

REQUIREMENTS AND GUIDELINES FOR INSTALLATION OF OFF-GRID SOLAR SYSTEMS FOR PUBLIC FACILITIES



Acknowledgements

This quality assurance framework was developed to support a new approach for the procurement, installation and long-term maintenance of off-grid solar electricity systems at public facilities, such as health clinics, schools, and public offices. The effort was funded by the World Bank's Lighting Africa program.

While much of the content of this document relies on literature sources, including International Electrotechnical Commission (IEC) documents and World Health Organization (WHO) guidance, many recommendations were informed by field research at over 60 health clinics and schools in Nigeria and Niger in 2017 and 2018. Additionally, insight was provided through consultation with representatives of the United Nations Foundation (UNF), the ECOWAS Center for Renewable Energy and Energy Efficiency (ECREEE), the Clinton Health Access Initiative (CHAI), and Global Sustainable Energy Solutions (GSES).

Authors and contributors include: Meg Harper, Tom Quetchenbach, Kristen Radecky, Jimento Aikhuele, Scott Toyama, Nick Lam, and Arne Jacobson (Schatz Energy Research Center) and Kevin Gauna (Sunbrothers).

The authors extend their gratitude to all those who kindly provided review and feedback on drafts of this document, including: Rahul Srinivasan and Mbusu Gwabila (World Bank), Luc Severi and Jem Pocomo (UNF / SE4All), Hamadou Tchiemogo and Collins Osae (ECREEE), Olakunle Owoeye, Geoff Stapleton (GSES), Jeff Lahl (Solar Electric Light Foundation, SELF), Simon Willans (Horizon Energy), Xavier Vallé (Trama TecnoAmbiental, TTA), Yoann Le Fol, (Victron Energy), Ray Gorman and Carolina Barreto (Tetra Tech), Gopal Nadadur (CHAI), and Saleban Omar (United Nations Development Programme, UNDP).

While all care has been taken to ensure this guideline is free from omission and error, no responsibility can be taken for the use of this information in the design, procurement, installation, or maintenance of any off-grid PV system.

Please send any comments or inquiries to Meg Harper at mjh80@humboldt.edu.

Requirements and Guidelines for Installation of Off-Grid Solar Systems for Public Facilities

Contents

- 1 Introduction 5
- 2 Scope 6
- 3 Terms and definitions 6
 - 3.1 Abbreviations and symbols 9
- 4 Use of this document 10
- 5 System design 11
 - 5.1 General 11
 - 5.2 Overall Design Considerations 12
 - 5.2.1 General 12
 - 5.2.2 Common Off-Grid, Stand-Alone System Configurations 12
 - 5.2.3 Overall System Efficiency 19
 - 5.2.4 Solar Resource 22
 - 5.2.5 Growth Factor 23
 - 5.2.6 PV Array Oversize Factor 23
 - 5.2.7 Days of Autonomy 24
 - 5.2.8 System Voltages 25
 - 5.2.9 Battery Depth of Discharge 27
 - 5.2.10 Maximum Instantaneous Power 27
 - 5.2.11 Discharge and Charge Rates of Battery 28
 - 5.2.12 Wiring and Protection 28
 - 5.2.13 Long-term remote performance monitoring 28
 - 5.2.14 Permits 29
 - 5.3 Component Selection Considerations 29
 - 5.3.1 General 29
 - 5.3.2 Batteries 29
 - 5.3.3 Inverter 31
 - 5.3.4 PV Modules 34
 - 5.3.5 Charge Controller 35
 - 5.3.6 Load limiters 36
 - 5.4 Elements to include in general specification 37
 - 5.5 Reporting Requirements 38
- 6 Component requirements 43
 - 6.1 General 43
 - 6.2 PV modules 44
 - 6.3 Batteries 44
 - 6.3.1 Requirements for all batteries 44
 - 6.3.2 Requirements for lead-acid batteries 44
 - 6.3.3 Requirements for lithium-ion batteries 45
 - 6.4 Inverters 45
 - 6.5 Charge controllers 46
 - 6.6 System loads: Lamps and luminaires 47

6.6.1	General.....	47
6.6.2	Safety requirements.....	47
6.6.3	Performance requirements	48
6.7	System loads: Ceiling fans.....	49
6.8	Electromagnetic compatibility (EMC) recommendations	51
6.8.1	General information	51
6.8.2	Recommendations for charge controllers and inverters	51
6.8.3	Recommendations for lamps and luminaires	51
6.8.4	Recommendations for ceiling fans	52
7	Installation and safety	52
7.1	General.....	52
7.2	Installer requirements	53
7.3	PV array mounting.....	53
7.3.1	General.....	53
7.3.2	PV array mounting structures.....	53
7.3.3	PV array orientation	54
7.4	Battery installations	54
7.4.1	General.....	54
7.4.2	Enclosure or room	55
7.4.3	Ventilation.....	55
7.5	Electrical cables and electrical connections	56
7.6	Electrical disconnects	57
7.7	Earthing.....	57
7.8	Protection against electric shock	58
7.9	Protection against thermal effects.....	58
7.10	Protection against overvoltage.....	59
7.11	Protection against overcurrent	59
8	Inspection, Testing and Commissioning.....	59
8.1	General.....	59
8.2	Built to plan.....	60
8.3	Construction inspection	62
9	Operations and Maintenance Planning	63
10	Service Delivery & Monitoring	64
10.1	General.....	64
10.2	Service Metrics	65
10.2.1	General.....	65
10.2.2	Available Energy (E_a).....	65
10.2.3	Low Voltage Disconnect (LVD)	66
10.2.4	Solar System Functionality (T_f).....	67
10.2.5	Peak Load (PL).....	67
10.2.6	State of Charge (SoC)	67
10.2.7	Depth of Discharge (DoD).....	68
10.2.8	Days Fully Charged (DFC).....	68
10.3	Minimum Allowable Performance (E_{min})	68
10.4	Missing and Invalid Data.....	69
10.5	Accessing Data from the Remote Monitoring System	69
11	Minimum energy service guidelines	70
11.1	General.....	70
11.2	Lighting.....	77
11.3	Circulation / Fans.....	77
11.4	Power outlets, load limiters and staff quarters.....	78

11.5	Vaccine Refrigerators	79
11.6	Additional medical appliances to consider	79
11.7	Additional appliances to consider for schools	80
11.8	Water Pumping	80
12	References	81

1 Introduction

This document outlines a quality assurance framework for the design, procurement, installation, and long-term operation and maintenance of off-grid solar electricity systems at public facilities, such as health clinics and schools. The approach involves quality standards for equipment, design, and installation, along with the innovative use of digital remote monitoring technology to ensure and verify the on-going performance of off-grid solar electricity systems against established key performance indicators. Using the quality assurance approach outlined in this document, companies in the off-grid solar sector could enter lease agreements or extended service contracts with government agencies to provide an agreed-upon level of electricity service in return for guaranteed payments. The payments could be designed to cover the capital costs of equipment and installation (or a percentage of these costs), along with the on-going operation and maintenance costs over the projected system life. By digitally monitoring the performance of the systems, a third party could verify that the operator is delivering the agreed electrical service and instruct the government agency to pay the monthly fee. Creating a payment system that explicitly includes a revenue stream for operation and maintenance costs (including equipment replacement over time) and keeping operators engaged to provide operations and maintenance (O&M) services is expected to improve the long-term performance of the systems and reduce the burden of capital (installation) cost on the government.

The proposed key performance indicators for monitoring system performance over time are:

- Available energy (E_a) per day > Minimum allowable performance (E_{min}) per day specified in the service agreement. (Note, to ensure the facility does not misuse the system, the energy the facility consumes each day should not exceed a maximum agreed upon value, which may be equal to or greater than E_{min} , and may vary throughout the year). This metric could also be evaluated as a certain number of days per month or percentage of time over a specified time period (month, quarter, 6-month period) that the operator is in compliance if 100 % compliance is not expected.
- System functionality > a minimum amount of time specified in the service agreement. The threshold may be specified as a number of days where the system has been functional for the minimum time, or the total number of minutes the system shall be functional during the reporting period.
- Peak load < a maximum power value specified in the service agreement. This metric is assessing the facility's compliance with the service contract and may indicate the need for intervention or education if the peak load is routinely exceeded.
- Depth of discharge (DOD) < maximum DOD recommended for the battery and specified in the service agreement.
- Days batteries are fully charged > minimum days of full charge specified in the service agreement. This metric is only critical for lead-acid batteries.

As described above, the core purpose of this document is to provide requirements and guidelines for systems that use monitoring methods to verify on-going performance. However, the guidelines for equipment, design, and installation are also appropriate to use to help ensure the initial installation of good quality systems in the absence of on-going monitoring.

Note that because this document is primarily intended for cases where the project implementer is also responsible for the long-term performance of the system, many of the design decisions, including component sizing and selection, are intentionally left open for the project implementer to decide. Alternatively, in the case that the project implementer will not be responsible for long-term maintenance, the project developer can use this section as guidance for writing design requirements for the general specification. In any case, the project developer should ensure systems are appropriately designed to meet the needs of the facility, installed in accordance with the design, codes, and the technical requirements in this document, and have a viable plan for the long term operations and maintenance of the systems. See Section 3 for definitions for key terms (such as project implementer and project developer). See Section 4 for more information about the structure of the quality assurance framework and this document.

2 Scope

The quality assurance framework described in this document is intended to assist with electrification efforts for a variety of public facilities. Specific recommendations are provided for health clinics (providing primary health care services) and schools.

This document is primarily intended for use with PV systems designed to power AC loads. Several other quality assurance frameworks are available for smaller DC systems, including the test methods and quality standards documented in [IEC TS 62257-9-5](#) and [IEC TS 62257-9-8](#) for plug-and-play solar home system kits up to 350 W, and a separate framework developed for the World Bank in 2020 for component-based systems up to 1 kW (Global Sustainable Energy Solutions, 2020).

Solar powered water pumps associated with the public facilities are not specifically addressed by this document, but are covered by a similar framework described that is currently under development.

The framework is intended to be applied to stand-alone solar electricity systems, though with some alterations, the guidance could be extended to assist with the installation of systems powered by different energy sources (e.g. wind, microhydro, diesel) or hybrid systems.

3 Terms and definitions

cycle life

The lifespan of a battery expressed in terms of the number of charge-discharge cycles (typically under standardized conditions) that results in a degradation of the battery's capacity to a specified level, typically 80 %.

days of autonomy

The number of days that the system can continue to power the design load with no recharging of the batteries.

depth of discharge DoD

The amount of ampere-hours removed from a fully charged cell or battery, expressed as a percentage of rated capacity (SEI, 2004).

extreme annual mean minimum design temperature

The lowest expected ambient temperature where an array is to be installed. This temperature can be used to calculate maximum voltage from a PV array using the manufacturer's temperature coefficients relative to the rating temperature of 25°C.

general specification

A specification prepared by the project developer providing minimum acceptable requirements, qualifications, and terms for the design, installation, and long-term maintenance of the off-grid solar electricity system. Project implementers would respond to this document by providing a bid.

growth factor

This value is used to account for near-term growth in energy demand at the facility by increasing the expected daily energy requirement before sizing the battery and PV array. The growth factor is expressed as a percentage of the daily energy needs.

maintenance contractor

The organization, corporate company, or person contracted by the operator for performing maintenance operations on the installation (IEC TS 62257-3, 2015).

maximum power

P_{\max}

The power output by a PV module or PV array when operating at the maximum power point.

maximum power point current

I_{mp}

The current produced by a PV module or PV array when operating at the maximum power point.

maximum power point voltage

V_{mp}

The voltage of a PV module or PV array when operating at the maximum power point.

open-circuit voltage

V_{oc}

The maximum voltage of a PV module or PV array, identified at open circuit when no current is flowing.

operator

The organization, company, or person in charge of system operations, management and maintenance. The operator may also be the project implementer (IEC TS 62257-3, 2015).

project developer

The organization, company, or person who defines and promotes the off-grid solar electricity project, assigns the project implementer, determines compliance with the specifications and is also responsible for obtaining resources for financing the project. The project developer may dictate the system design (or aspects of it), or assign the responsibility of system design to the project implementer. This can include local regulatory bodies and/or other government and non-government organizations with a primary role in facilitating the planning, purchase, and maintenance of the system. There can be more than one project developer for a single off-grid solar electricity system installation.

project implementer or general contractor

The organization, company or person entrusted by the project developer to perform the work (which may include system design) or have this work performed pursuant to the general specification, possibly through some subcontractors (IEC TS 62257-3, 2015).

purchaser

the entity purchasing the electric power system and related services (such as insurance, installation, training and initial maintenance). The purchaser could be the project developer, the user, or a separate entity such as an implementing agency working on behalf of a government or development organization.

PV oversize factor

This value is used to increase the size of the array beyond the minimum energy requirement for a single day. Oversizing the PV array is primarily used to ensure that the battery bank can routinely fully charge. On days that the batteries are able to charge sufficiently to support the design loads and the PV array can still provide additional electricity, the oversized array could also power additional loads that are expected to be used only during the day. The PV oversize factor is expressed as a percentage of the daily energy needs after all efficiency losses and growth factors have been considered.

short-circuit current

I_{sc}

The maximum current produced by a PV module or PV array, identified at short circuit when the module or array voltage is zero.

state of charge SoC

The available capacity remaining in a cell or battery, expressed as a percentage of the rated capacity. For example, if 25 amp-hours have been removed from a fully charged 100 amp-hour cell, the state of charge is 75 percent (SEI, 2004).

user

A person or organization that makes use of the off-grid solar electricity system to satisfy their energy demand (IEC TS 62257-3, 2015).

3.1 Abbreviations and symbols

AC	alternating current
AFREA	Africa Renewable Energy Access Program
Ah	ampere hour
BLDC	brushless DC (type of electric motor)
BMS	battery management system
BS	British Standard
C	charge or discharge rate of a battery equal to the capacity in ampere hours divided by one hour
CCT	correlated color temperature
CFL	compact fluorescent lamp
CFM	cubic feet per minute
CHC	comprehensive health centre (Nigeria)
CMM	cubic metres per minute
CRI	color rendering index
CSI	Centre de Santé Intégrée (Niger)
DoD	depth of discharge
DC	direct current
DFC	days fully charged
E_a	available energy
ECOWAS	Economic Community of West African States
ECREEE	ECOWAS Centre for Renewable Energy and Energy Efficiency
E_{min}	minimum allowable performance
EPA	Environmental Protection Agency (United States government agency)
ESMAP	Energy Sector Management Assistance Program
GHI	global horizontal irradiation
GPS	global positioning system
HIV	human immunodeficiency virus
IEC	International Electrotechnical Commission
I_{mp}	maximum power point current (of a PV module)
I_{sc}	short-circuit current (of a PV module)
kVA	kilovolt ampere
kWh	kilowatt hour
LED	light-emitting diode
LVD	low-voltage disconnect
MPP	maximum power point (of a PV module)
MPPT	maximum power point tracking
NASA	National Aeronautics and Space Administration (United States government agency)
O&M	operations and maintenance
PCB	printed circuit board
PCE	power conversion equipment
PELV	protected extra-low voltage
PHC	primary health clinic (Nigeria)
PL	peak load
P_{max}	maximum power (of a PV module)
POWER	Prediction Of Worldwide Energy Resources (NASA project)
PV	photovoltaic
PWM	pulse-width modulation
SEI	Solar Energy International
SEIAPI	Sustainable Energy Industry Association of the Pacific Islands

SELV	separated or safety extra-low voltage
SoC	state of charge
STC	standard test conditions
TB	tuberculosis
T_f	solar system availability
THD	total harmonic distortion
UL	Underwriters Laboratories
UN	United Nations
UNF	United Nations Foundation
UV	ultraviolet
V_{mp}	maximum power point voltage (of a PV module)
V_{oc}	open-circuit voltage (of a PV module)
Wh	watt hour
WHO	World Health Organization

4 Use of this document

This document is intended to be used as guidance when developing a procurement process for the design, installation, and long-term maintenance of solar electricity systems at public facilities. Sections of this document may be referenced directly in general specifications, terms of reference, or similar procurement documents, while other sections provide recommendations related to materials that contracting agencies may include in such a document.

The document is divided into 6 sections:

- System Design** – This section provides general recommendations on system design and specifies a list of required information that should be provided by project developers and requested from project implementers at different stages of the procurement process. In cases where the project implementer designing and installing the systems is expected to also be responsible for the long-term operation and maintenance, many key design choices need not be specified, in order to provide the project implementer with flexibility to create a system they believe can be cost-effectively maintained over the long term. The project developer can use this section as guidance to crosscheck the implementer's designs and ensure that all aspects of the general specification have been addressed. Alternatively, in the case that the project implementer will not be the operator or maintenance contractor, the project developer can use this section as guidance for writing design requirements for the general specification. Agents preparing general specifications and reviewing submitted bids should have appropriate expertise in the design of off-grid PV systems to evaluate the proposed designs.
- Component Requirements and Installation and Safety** – These two sections may be referenced directly in a general specification and are intended to ensure good quality equipment is procured and properly installed. Project implementers and general contractors should follow these guidelines, where possible, unless an alternative is more appropriate for a specific application. As noted in the installation and safety section, the guidance is not comprehensive but is intended to provide some of the necessary requirements and recommendations to ensure a safe, properly functioning off-grid solar electricity system. Project implementers and general contractors are expected to comply with local or national building codes, referenced standards, and component installation instructions when designing and installing the system(s).

- **Commissioning** – This section provides a list of aspects that should be physically confirmed or measured following system installation. If requirements deviate from those described in the installation and safety section, the commissioning checklist should be updated appropriately.
- **Operations and Maintenance Planning** – This section provides recommendations for including operations and maintenance activities in procurement documents and contracts. To better ensure systems are maintained following installation, project developers should include some method of incentivizing proper O&M, such as through the long-term service agreement described in the introduction that relies on the performance metrics described in the service delivery and monitoring section. Additionally, project developers will need to define clear lines of ownership and responsibilities for equipment, which are not covered explicitly by this document. In particular, the handling of equipment failures outside of the warranty period and replacement of major components should be considered during the general specification development process.
- **Service Delivery and Monitoring** – This section describes metrics of electricity service provision that can be used to assess service agreement compliance by the user and operator. The section also provides information relating to the determination and reporting of the metrics.
- **Minimum Energy Service Guidelines** – This section provides recommendations regarding the lights and appliances (i.e. loads) needed to meet a facility’s basic energy service needs. This information is intended as guidance for use during the early stages of system design and planning; individual facilities may have specific needs that add to or differ from the list of recommended loads provided in this section.

The most recent editions of standards referenced in this document should be referred for designing, installing and maintaining the off-grid solar electricity systems. By convention, throughout the document, provisions that are required are typically specified with the word “shall”. Other provisions are given as recommendations and stated with the word “should”.

5 System design

5.1 General

The guidelines below are intended to highlight key elements of the design process. Many solar design manuals exist. This section does not serve as a replacement for these resources but should instead be used in conjunction with a reputable design manual or established design process.

In cases where the project implementer will also be the operator, many key design choices need not be specified to provide the project implementer with flexibility to create a system they believe can be cost-effectively maintained over the long-term. In cases where the project implementer is a separate entity from the operator and maintenance contractor (or if there is no identified operator or maintenance contractor), the project developer may instead choose to be more prescriptive and specify key design requirements, especially those relevant to the longevity of the system. The project implementer shall provide the project developer with a clear presentation of the design and all of the assumptions included in determining the expected performance of the system. The project developer can then assess whether a given design is likely to meet the required performance parameters. The project developer is also responsible

for defining any parameters or assumptions that need to be consistent across bids to ensure that bids are comparable. These elements have been identified below, though an individual project developer may choose to define other parameters as well, depending on the specific circumstances of the project.

This section is divided into four main parts:

1. Overall design considerations: identifies system-level factors to be considered when designing systems, such as efficiency values and days of autonomy. These factors are related to the system as a whole as opposed to any single component.
2. Component selection considerations: identifies important component considerations when selecting and sizing equipment.
3. Elements to include in a general specification: lists key items that should be included in a general specification when using this QA framework.
4. Reporting requirements: synthesizes documentation requirements for providing an initial system design and a full system design.

5.2 Overall Design Considerations

5.2.1 General

This section describes system-level factors to be considered when designing systems. These factors are related to the system as a whole as opposed to any single component. Much of the information presented below is intended to provide guidance both to those preparing the general specifications and those designing a system; however, some requirements are included regarding documentation that shall be provided and values that shall be assumed.

5.2.2 Common Off-Grid, Stand-Alone System Configurations

There are several different configurations available for PV stand-alone systems. Each has unique advantages and capabilities that can yield cost benefits to the project implementer and energy benefits to the operator and/or user if the system is properly chosen to match the energy needs of the project site. The system configuration selection process is complex and involves many different factors, including but not limited to the:

- Detailed energy performance requirements of the installation
- Budget restrictions
- Local availability of system components
- Planned future expansion
- Project designer experience with different system types
- Operator technical capabilities

System configuration should be chosen based on site needs and can be generally divided into three categories:

- DC-coupled
- AC-coupled
- Hybrid

The difference between DC- and AC-coupled is how the battery bank is charged in the system: DC-coupled systems charge the battery bank with DC power directly from the PV array, whereas AC-coupled systems convert DC power from the PV array to AC power, then convert this AC power back to DC power to charge the batteries. Hybrid systems include multiple generation sources, e.g. solar and back-up generator, and could be either DC-coupled, AC-coupled, or both.

Choosing between these three broad categories is the first step when designing a system. DC-coupled systems were historically the first to be developed and DC coupling is still the most common configuration for stand-alone systems that are not connected to an external grid. They can be used for any system size considered by this document and employ either PWM or MPPT charge controllers to charge the battery array.

The advent of grid-connected PV systems initiated the development of AC-coupled configurations. PV-based inverters supply power directly to a grid by inverting the PV array DC output, following and matching the AC grid frequency. These PV inverters will not operate without an active external AC (grid-forming) source. AC power generation (and battery charging) is accomplished with a separate inverter (with additional or integrated battery charger). In an off-grid system, this battery-based inverter provides the external grid-forming AC source needed to keep the PV inverters operational.

Hybrid systems can be either AC or DC-coupled and often offer backup generator power, e.g. with fuel-powered generator, potentially increasing the reliability of the system for critical loads. The addition of another power source may also influence the sizing of the PV and battery arrays. Hybrid systems may be more complex than PV-only systems, however, and care must be given to the integration, operation, and maintenance of the fuel-powered generator to ensure that it will properly operate when called upon. This document does not explicitly cover requirements for generators. If considering a hybrid system under the quality assurance framework described in this document, additional requirements should be included in the general specifications regarding generator standards, installation, and maintenance. Further, if the project implementer is responsible for the long-term performance of the system, the project implementer should be responsible for any power-generating equipment to be used with the system, including the generator. Otherwise, if a third-party generator were to damage the solar electric system, a dispute could arise regarding responsibility for the ongoing performance and maintenance of the system.

The growth of the PV industry has led to increased sophistication of both grid-tied and stand-alone solar electricity systems. Many different configurations are available to serve a host of different application requirements. To maximize the energy benefit to the user and optimize the dollar investment in the project, the project developer needs to have access to adequate technical expertise to best inform the decision on which system configuration to pursue. Additionally, the project implementer or general contractor must have experience designing and installing this type of system to increase the likelihood of a successful installation and properly functioning system.

In addition to the immediate considerations that must be addressed when selecting a system configuration, specific attention should be given to system expansion options if there could be a need for additional capacity or functionality in the future. Some system configurations are easier to expand than others, and specific components can be selected to allow the addition of more units if the relevant components are compatible. Many inverters are stackable, PV arrays can often be augmented with additional panels, and some battery array configurations can be expanded if certain conditions, manufacturer recommendations and component compatibility requirements are met. However, some configurations are not easily expandable; for instance,

combining old and new batteries in a single battery bank, or old and new PV modules in a single string could result in poor performance. Expansion options should be explored early in the project design phase if the project developer has reason to believe they will be required by the project.

Table 1 outlines some advantages and disadvantages between DC- and AC-coupled systems. Sites with critical loads may also consider a hybrid system with a back-up generator; however, this document does not focus on hybrid systems.

Table 1. Advantages and disadvantages between DC- and AC- coupled systems

Configuration	Advantages	Disadvantages
DC-coupled	<ul style="list-style-type: none"> • <u>More efficient battery charging</u> – there are fewer energy conversion steps between the PV modules and the battery bank • <u>Fewer inverters</u> – inverter(s) are needed only to convert energy from the DC bus into AC for loads, no inverters are needed if all loads are DC • <u>Closed-loop communications</u> – some equipment combinations between inverters, charge controllers, and batteries allow for dynamic control of the battery’s charge and discharge characteristics based on direct battery measurements and available solar to optimize performance 	<ul style="list-style-type: none"> • <u>No potential inverter redundancy between energy sources</u> – if the inverter fails, the site is no longer provided with AC power regardless of battery state of charge or solar forecast • <u>More difficult future expansion</u> – if the site requires a larger battery bank in the future, the inverter may need to be upgraded and likely other system components as well • <u>Higher wiring costs</u> – thicker cables may be needed for sites where the solar or battery bank is far from the rest of the system to reduce voltage drop
AC-coupled	<ul style="list-style-type: none"> • <u>May be more efficient for large daytime AC loads</u> – direct conversion of PV array power to AC power eliminates DC power conversion steps • <u>Inverter redundancy between energy sources</u> – if one inverter type fails or is under maintenance, the other inverter can still provide AC power to the loads • <u>Easier future expansion</u> - if the site requires a larger battery bank in the future, the site may need only to add another battery inverter and does not need to upgrade its solar inverters • <u>Lower wiring costs</u> – cable size does not need to be as thick for sites where the PV or battery bank is far from the rest of the system for voltage drop considerations 	<ul style="list-style-type: none"> • <u>Less efficient battery charging</u> – energy is converted from PV into AC through an inverter, and then converted back into DC to charge the battery bank • <u>More inverters</u> – inverter(s) are needed to convert PV power from DC to AC and inverter(s) are also needed to convert battery power from DC to AC • <u>Open-loop communication</u> – system may not recover from a low battery state of charge if there is no backup generator

Figure 1 through Figure 6 illustrate common system configurations for off-grid, stand-alone systems and presents the advantages, disadvantages, and applications of each.

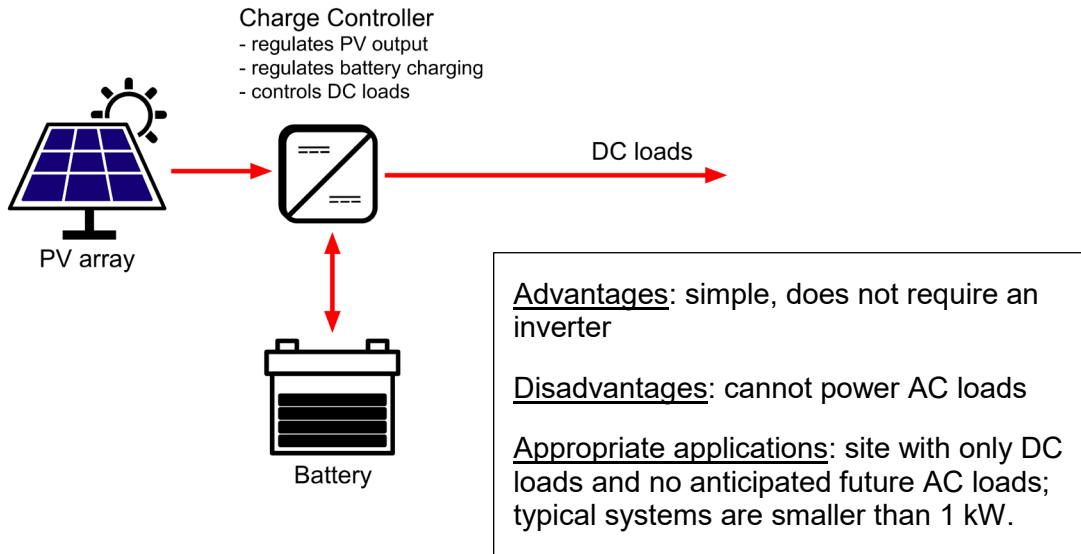


Figure 1. Off-grid, stand-alone system with charge controller, energy storage, and DC loads (DC-coupled)

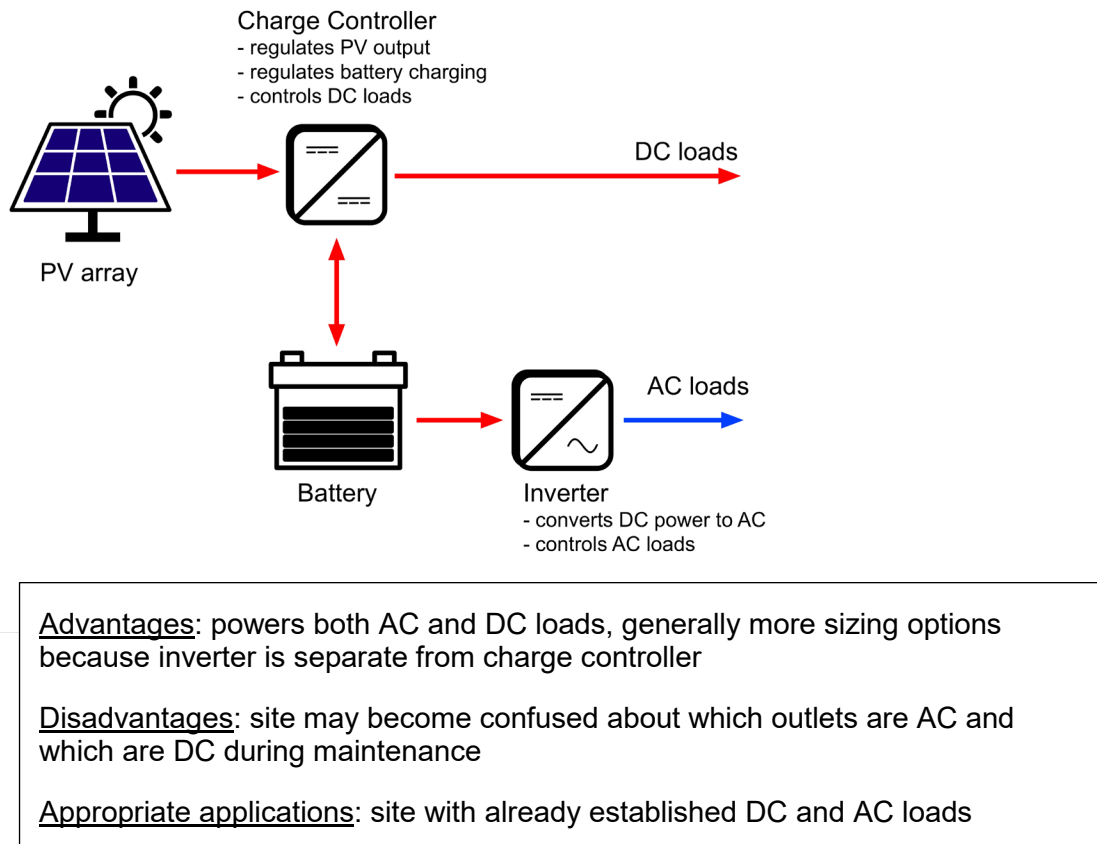
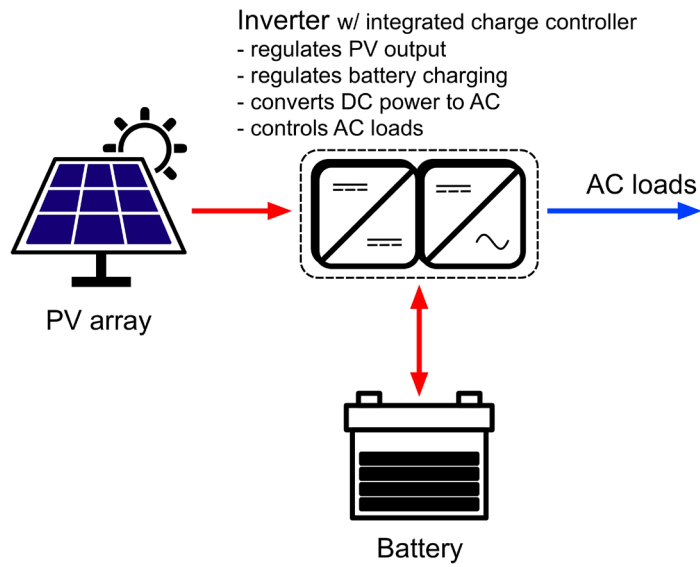


Figure 2. Off-grid, stand-alone system with charge controller, energy storage, and both DC and AC loads (DC-coupled). Configuration can also be designed with no DC loads.

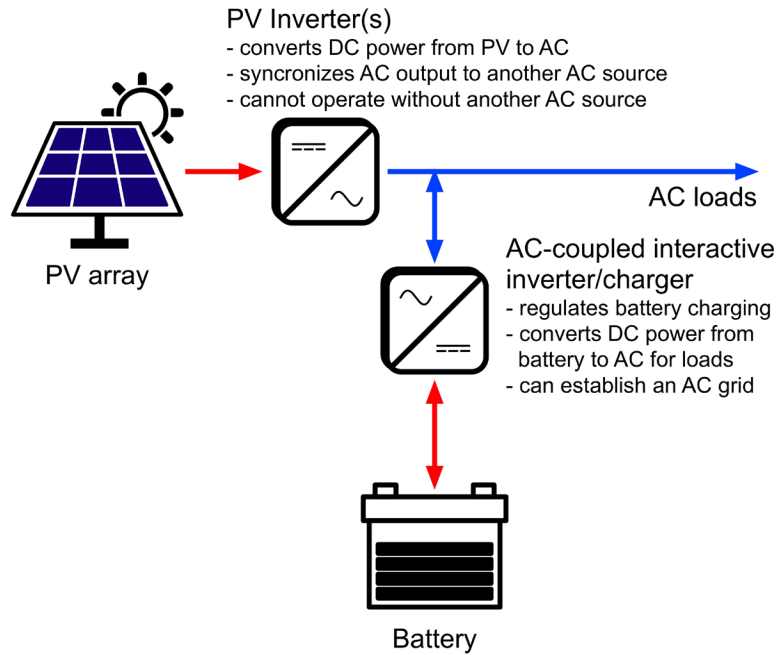


Advantages: fewer system components than Figure 2

Disadvantages: generally not as many sizing options because inverter is combined with charge controller

Appropriate applications: site that can be powered with PV and battery alone, all loads are AC, and appropriately sized equipment exists

Figure 3. Off-grid, stand-alone system with charge controller integrated into inverter, energy storage, and AC loads (DC-coupled)

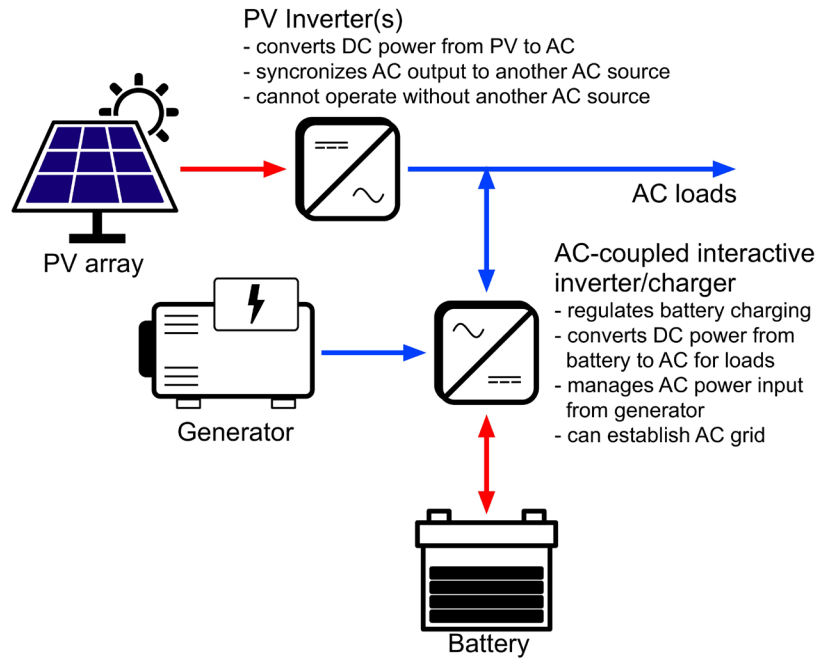


Advantages: can parallel multiple PV strings, more efficient for daytime loads

Disadvantages: requires separate PV inverter(s), less efficient for charging battery

Appropriate applications: site that may incorporate other AC generation sources in the future, e.g. AC generator, and all loads are AC.

Figure 4. Off-grid, stand-alone system with PV inverter having integrated solar charge controller, a second inverter with integrated battery charge controller, energy storage, and AC loads (AC-coupled)

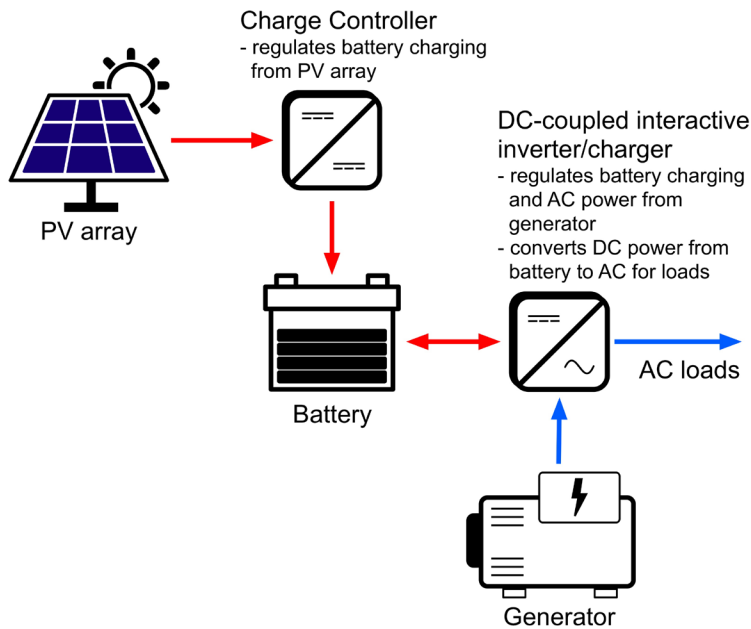


Advantages: can parallel multiple PV strings and AC sources, more efficient for daytime loads, generator provides on-demand power

Disadvantages: higher system complexity, less efficient PV battery charging

Appropriate applications: site that cannot be powered with PV/battery alone

Figure 5. Off-grid, stand-alone system with PV inverter having integrated solar charge controller, a second inverter with integrated battery charge controller that will accept multiple AC generation inputs, energy storage, and AC loads (AC-coupled)



Advantages: more efficient use of battery power, no PV inverters, generator provides on-demand power

Disadvantages: less efficient for daytime loads

Appropriate applications: site that cannot be powered with PV/battery alone

Figure 6. Off-grid, stand-alone system with charge controller, energy storage, inverter with integrated battery charge controller that will accept both AC and DC inputs, and AC loads (DC-coupled)

5.2.3 Overall System Efficiency

No energy generation system is 100 % efficient. Energy is lost through resistance in wires, when energy is stored in a battery, and when PV modules become soiled with dust. In addition, modules do not perform in their optimal conditions at all times and in all locations; some locations may be warmer yielding less energy generation and modules may be configured in a way that increases mismatch. These factors should be considered when designing the system(s).

Table 2 lists system efficiency values that shall be considered during design. The project implementer shall document efficiency values used for each contribution in the design and provide justification; multiple efficiency values may be used, such as in the case of the inverter (see inverter subsection below). In cases where efficiencies are not dependent on specific equipment choices, project developers may choose to specify efficiencies to be used for all bids to increase comparability between bids. The efficiency used in design calculations shall not exceed the maximum acceptable efficiency listed in Table 2. (This value is not intended as a

criterion in selecting components; it is intended to prevent the use of unrealistically high efficiency values in design calculations.)

Table 2. System efficiency values

Source of Efficiency Loss	Maximum Acceptable Efficiency (%)	Typical Range of Efficiencies (%)	Notes
Inverter (may include integrated charge controller)	99	88 - 98 ⁽¹⁾	<ul style="list-style-type: none"> • Multiple inverter efficiencies may be appropriate for design; see inverter subsection later in this section • Reference equipment documentation • AC systems only
Charge controller	99	93 - 99 (MPPT) ⁽²⁾	<ul style="list-style-type: none"> • Not required if integrated into inverter and the inverter spec provides a combined efficiency • Efficiency includes the loss due to the PV module operating at a voltage less than V_{mp}. This is not a physical energy loss in the system but a reduction in available production capacity due to suboptimal operation. • For non-MPPT charge controllers, efficiency ratings are generally not provided in documentation since the unit does not perform any power conversion. However, less energy from the PV array is generally harnessed with non-MPPT charge controllers (70-85 %),⁽³⁾ depending on how the PV array is sized relative to the battery bank. This efficiency may or may not be a factor in the calculations; for example, a typical sizing approach is to select the module voltage and number of modules in series based on the battery voltage, voltage drop between the PV array and battery, and the charge controller maximum voltage rating, and then select the number of module strings based on the battery capacity in ampere-hours. In this case, although the factors that contribute to energy loss in the charge controller are considered, the efficiency is not directly used in the design calculations.

DC wiring	99	97 - 99 ⁽¹⁾	<ul style="list-style-type: none"> Long conductor lengths may result in lower DC wire efficiency due to voltage drop. A voltage drop up to 5 % is generally reasonable. However, designers should ensure the voltage does not drop below acceptable ranges for equipment and that the conductors are safely sized to carry the expected current.
AC wiring	99.3	98 – 99.3 ⁽¹⁾	<ul style="list-style-type: none"> AC systems only
Battery	--	<p>Lead-acid: Coulombic: 85 - 90 Energy: 70 - 85</p> <p>Lithium: Coulombic: 99 Energy: 85 - 99*</p> <p>*some efficiency ratings may be lower than this range if additional loads such as cooling equipment or BMS are included in the rated battery efficiency</p>	<ul style="list-style-type: none"> Reference equipment documentation Note that batteries are often rated with both a coulombic efficiency (in reference to Ah) and an energy efficiency (in reference to Wh). When sizing the PV array for systems using switching or PWM solar charge controllers, the calculations are often based in Ah and coulombic efficiency is used. When sizing the PV array for systems using MPPT controllers, the calculations are often based on Wh and the energy efficiency is used. Battery efficiency will vary based on the battery chemistry and the specific battery. Various sources suggest the presented efficiency ranges for each battery type.^(4,5,6,7) In reality, the battery efficiency will depend on the state of charge and charge/discharge rates of the battery as well, though these variations are rarely considered in typical system design. All systems in the scope of this document include batteries
Shading	100	0 - 100 ⁽¹⁾	<ul style="list-style-type: none"> Provide site-specific shading images, solar path graphs, and monthly shading loss analyses to support shading efficiency value(s)
Soiling	99.5	30 - 99.5 ⁽¹⁾	<ul style="list-style-type: none"> May be site-specific
Diodes and connections	99.7	99 - 99.7 ⁽¹⁾	--
Module mismatch	99.5	97 - 99.5 ⁽¹⁾	--

Module power tolerance	100	80 - 105 ⁽¹⁾	--
Module degradation (derate) factor	--	Degradation of 0.5 – 1 % per year ⁽⁸⁾	<ul style="list-style-type: none"> • Module power will decrease over time and losses over the expected lifetime of the system should be considered. The suggested degradation rates are for individual modules, degradation of arrays can be greater due to increased mismatch losses as modules degrade. • For example, if a system was designed with a 20-year lifetime, the impact of module degradation could be accounted for by using an efficiency of 90 % (this is calculated by assuming a 0.5 % degradation each year over 20 years, which results in a 10 % total degradation, or 90 % efficiency).
<p>(1) Solar Energy International. 2013. Photovoltaic fundamentals and applications. Second edition. (2) Range determined by surveying datasheets of 24 MPPT charge controllers currently on the market in 2020. (3) Range determined through online research and discussions with three leading charge controller manufacturers in 2020. (4) May, G., A. Davidson and B. Monahov. 2018. Lead batteries for utility energy storage: A review. Journal of Energy Storage, vol.15, pp 145-157. (5) Büngeler J., E. Cattaneo, B. Riegel, and D. Uwe Sauer. 2018. Advantages in energy efficiency of flooded lead-acid batteries when using partial state of charge operation. Journal of Power Sources, vol. 375, pp. 53-58. (6) Beaudin M., H. Zareipour, A. Schellenberg, and W. Rosehart. 2015. Energy storage for smart grids, Chapter 1 – Energy storage for mitigating the variability of renewable electricity sources, pp. 6-8. (7) Global Sustainable Energy Solutions. 2020. Off grid PV systems system design guidelines: Includes stand alone PV systems and hybrid systems comprising PV and fuel generators. Draft guidelines prepared for Ugandan Rural Electrification Agency and World Bank. (8) Jordan, D. and S. Kurtz. 2012. Photovoltaic degradation rates — An analytical review. National Renewal Energy Laboratory (NREL).</p>			

5.2.4 Solar Resource

To ensure comparability of bids, the project developer should specify the solar resource data to be used for the system design. This data can be specified by stating a data source and specific site locations, or by directly providing the data to be used. Typically, to ensure reliability throughout the year, designs are based on the monthly minimum solar irradiation for a typical year, determined using long-term monthly average data for the global horizontal irradiation (GHI). If available, the long-term monthly average surface albedo should also be considered when determining the solar resource. Designs should account for shading at the site and the angle of installation.

Care should be taken to ensure the chosen data source is accurate and is available to all interested bidders. Several organizations provide estimates of monthly average solar radiation including:

- NASA POWER database (<https://power.larc.nasa.gov/data-access-viewer/>) [Note, in this database, GHI is referred to as “All Sky Insolation Incident on a Horizontal Surface.”]
- European Commission’s Photovoltaic Geographical Information System (http://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#MR), and
- SolarGIS (<https://solargis.com/about-us/>). [Note, for the SolarGIS database, most monthly average data, including global horizontal irradiation, must be purchased. However, the long-term monthly average of potential photovoltaic electricity production (PVOU) in kWh/kWp, is available for free as a GIS data layer. This data could be used for sizing, though typically, GHI data is preferred.]

Additional sources including IRENA (<https://irena.masdar.ac.ae/gallery/#tool/9>) and the Global Solar Atlas (<https://globalsolaratlas.info/map>) provide annual average data for free, though annual data is not sufficient for sizing a specific system. Other companies also offer average and time series solar data for a fee. Outdated data sets (e.g. datasets that end in 2005) and data based on very short time periods (e.g. data averaged over 1 or 2 years) are also available, but should be avoided. If referencing data from another source, the cost of the data, the reported accuracy of the data, duration of the underlying data used in the average, and the ease of access should all be considered.

Example: The project developer could state, “All project implementers shall use the monthly average ‘All Sky Radiation Incident on a Horizontal Surface’ and ‘Surface Albedo’ from the NASA POWER database (<https://power.larc.nasa.gov/data-access-viewer/>). Designs shall be based on the monthly minimum solar radiation period, after shading and angle of installation is taken into account. A table of latitude and longitudes for each of the sites is provided below.”

5.2.5 Growth Factor

Unless specified by the project developer, project implementers should apply an upgrade or growth factor to account for future load growth and shall document justification for the selected growth factor. A reasonable system growth factor is application specific, so determination for a given system should consider existing and future loads. Growth factors of 10 % – 30 % are often built into systems for clinics and schools in off-grid contexts, but the growth factor for any system should be justified using application-specific information, such as anticipated loads that may be added and/or expected population growth for the region (AFREA, 2010). Experience from past projects varies; in some cases systems were built to provide power for equipment that never arrived, while in other cases donations of equipment arrived as soon as reliable electricity was available. When estimating anticipated loads, project developers or implementers should consider potential increases in both the primary loads for a site (such as medical equipment for a clinic), as well as auxiliary loads that may serve to help with staff retention (such as a TV or computer for the staff housing).

5.2.6 PV Array Oversize Factor

By sizing the PV array larger than what would be required to meet the daily energy needs, the array can better recharge the batteries after cloudy or rainy periods. Oversizing the PV array is also a strategy to address load growth over time, and can be used to help meet electricity needs during the day (rather than at night).

Recommended PV oversize factors range between 20 % - 100 % (SEI-API, 2012) for systems with no backup generator. The chosen PV oversize factor will depend on the expected days of autonomy, which will determine the ratio between the daily energy production of the PV array and the total energy capacity of the battery bank. The type of battery will also influence the decision, as lead-acid batteries need to regularly receive a full charge to avoid irreversible capacity degradation (sulfation), while lithium-based batteries with active balancing (see 5.3.2) will not be damaged if not allowed to charge fully for long periods. While oversizing is generally encouraged, the PV array size should be limited to ensure the charge current is appropriate for the battery bank (or for the charge controller if the charge controller is limiting the current to the battery bank); too high of a charge current can reduce the capacity and cycle life of batteries.

Unless specified by the project developer, documentation stating the oversize factor applied to the solar array and justification for its selection shall be provided.

5.2.7 Days of Autonomy

Days of autonomy typically range from 3 to 5 days (SEI-API, 2012; SEI, 2013; World Bank, 2014; WHO, 2018), but may be 7 days or more (SEI-API, 2012; WHO, 2018) and some practitioners recommend as few as 1.5 – 2 days in cases where critical loads are not present. The key considerations for both the minimum and typical days of autonomy are enumerated below.

- Maximum energy deficit and poor weather conditions (climatic cycles), such as cloudy days, precipitation, and daily solar radiation should be considered during the determination of days of autonomy (WHO, 2018; SEI, 2013). Weather conditions differ according to the geographical area.
- In many systems, if an alternative power source such as a backup generator is available to charge the system batteries, the required days of autonomy could be reduced (SEI, 2013). However, if considering a hybrid system under the quality assurance framework described in this document, the operator should also be responsible for any power-generating equipment to be used with the system. Otherwise, if a third-party generator were to damage the solar electric system, a dispute could arise regarding responsibility for the ongoing performance and maintenance of the system.
- Design considerations such as array oversizing (PV array oversize factor) may influence the chosen days of autonomy. Oversizing an array could justify a reduction in the recommended number of days of autonomy by enabling the batteries to charge faster in a single day or in cases of low insolation (University of Southampton, 2011). Array oversizing is also be advisable to ensure that the entire battery bank will receive a full charge. This practice is especially important for lead-acid batteries which will be permanently damaged if not fully charged at routine intervals.
- The presence of critical loads may require an increase in the days of autonomy (or other measures to ensure electricity availability) to better ensure that the loads will not face a power outage. To reduce overall system costs, a separate system with a battery bank that can provide a higher number of days of autonomy can be used to power critical loads, while the system powering the non-critical loads is designed with fewer days of autonomy. In the case of vaccine refrigerators, WHO guidelines require these be powered with separate systems to better ensure the reliability of the refrigerator.
- The type of facility and its respective need for reliable power will influence the required days of autonomy. For instance, the recommendation of 3 – 7 days may be appropriate for a health clinic that needs consistent power to provide reliable service, while a

recommendation of less than three days may be appropriate for non-critical loads at a health center or a school that can still adequately conduct classes if power is unavailable for several days during the rainy season. The chosen days of autonomy will directly impact the size of the battery bank and therefore both the overall cost of the system and the on-going replacement costs of the batteries. The tradeoff between reliability and cost must be carefully considered when determining the required days of autonomy.

Unless specified by the project developer, the project implementer shall provide the project developer with the data and method used to determine the desired days of autonomy. If the service metrics described in Section 10 are used for assessing on-going system performance, the days of autonomy should be sufficient to ensure the system will provide the required “available energy” with the agreed level of reliability. In this case, the project developer should specify the number of days per month or percentage of time over a specified time period (month, quarter, 6-month period) that the system is required to provide the “available energy” to be in compliance with the service agreement.

5.2.8 System Voltages

5.2.8.1 General

A single system can have multiple voltages at different points in the system. The DC system voltage is typically defined by the type of battery and the number of cells in series. The DC system voltage refers to the battery voltage, the output of the charge controller and input of the inverter. It is important to note that the system voltage is a “nominal” voltage; the actual voltage will vary depending on the load and state of charge of the battery.

For systems with lead-acid batteries, 12 V, 24 V, and 48 V are the most common DC system voltages. Systems with lower voltages have higher currents and, therefore, larger wire sizes to deliver the same amount of power. Therefore, 12 V should be used only for the smallest systems, with a maximum instantaneous power of 1 kW or less. A system voltage of 24 V or 36 V is appropriate for systems with maximum instantaneous power up to 3 kW, and 48 V should be used for higher values of maximum instantaneous power¹. Note that higher voltages (e.g. 48 V) can be appropriate for systems below 4 kW in some cases. Also, some very small systems, such as certain solar vaccine refrigerators, can use voltages lower than 12 V (e.g. 6 V). Additionally, systems that use non-lead-acid batteries (e.g. lithium ion batteries) may have different system voltages than those based on lead-acid batteries.

Tip: some designers use batteries that cannot directly power appliances with common voltages, e.g. 12 V nominal, to avoid batteries being stolen or borrowed for personal use.

For systems with DC outputs, the output voltages can be the same as the battery voltage or can be different depending on the design of the system. For systems with AC outputs, the voltage and frequency of the AC output will depend on the inverter and should be chosen to be typical for AC systems in the local area (e.g. 120 V or 230 V; 50 Hz or 60 Hz) and compatible with the intended loads. The AC output voltage should be within 10 % of the nominal voltage, and the frequency should be within 3 Hz of the nominal value.

¹ SEI-API (2012) suggests that a system voltage of 24 V is appropriate for systems with maximum instantaneous power up to 4 kW, and 48 V should be used for higher values of maximum instantaneous power. Other experts suggest the broader ranges specified within this document.

5.2.8.2 Matching the Battery and PV Array Voltages

To fully utilize the capacity of the PV array, it is important to match the PV array and battery voltages, taking into account the operating temperature of the PV modules as well as any voltage drop in the wiring and charge controller.

For example, Figure 7 shows the current-voltage (I-V) curves of two different PV modules, one with 60 cells and one with 72 cells, as well as the typical operating voltage range of a 24 V lead-acid battery. At 25 °C, either PV module can charge the batteries with acceptable performance. However, at 50 °C, the 60-cell module performs poorly—the current drops by more than 40 % as the battery charges—while the performance of the 72-cell module is essentially unchanged.

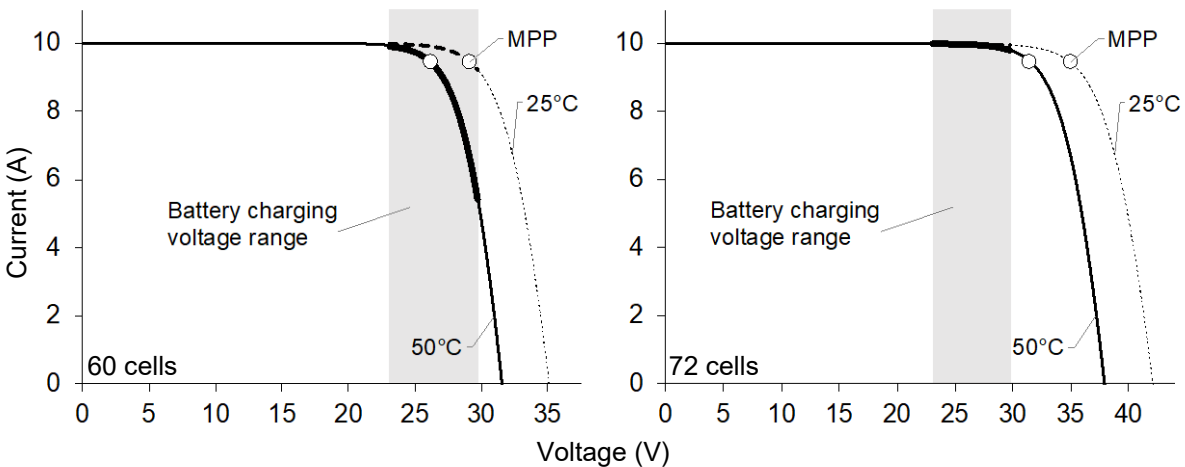


Figure 7. Example I-V curves of a 60-cell module and 72-cell module used with a 24 V lead-acid battery. At 50 °C, the 60-cell module charges the battery at a reduced rate.

In systems with PWM charge controllers, the voltage of the PV array is typically several volts higher than the DC system voltage to ensure that the PV module will work in the optimal portion of its IV curve, at a voltage less than V_{mp} . A value of V_{mp} less than the battery voltage will result in poor performance, as shown in Figure 7. Conversely, a value of V_{mp} much greater than the battery voltage will result in underutilization of the PV array capacity. For example, in Figure 8, the PV module can supply 300 W, but the battery receives at most 150 W.

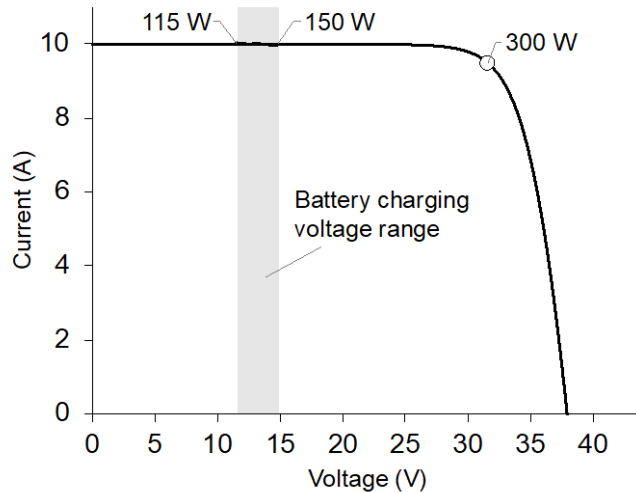


Figure 8. Example I-V curve of a 72-cell module used with a 12 V lead-acid battery. The battery can only utilize half of the power available from the PV module.

In systems with MPPT charge controllers, the PV array voltage should be selected in accordance with the charge controller manufacturer's instructions. Typically, as with PWM charge controllers, it is necessary for the PV module voltage to be greater than the battery voltage, but with an MPPT charge controller the PV operating voltage is not directly related to the battery voltage as it is in a PWM charge controller.

5.2.9 Battery Depth of Discharge

The depth of discharge for design calculations shall be selected in accordance with the battery manufacturer's specifications and associated battery test results. For lead-acid batteries, a value between 40 % and 60 % is typical. For lithium-based batteries, a value between 70 % - 90 % is typical. For both battery chemistries, a higher depth of discharge correlates with fewer cycles of useful life, so when assuming a depth of discharge, the project implementer should consider the long-term performance of the system and replacement intervals for the battery.

5.2.10 Maximum Instantaneous Power

Documentation shall be provided stating the assumed maximum instantaneous power, or peak load, of the system and how it was determined. The determination of peak load should consider existing and future loads, their duty cycles, and their associated power factors. An upper estimate of the peak load, for example, could be made by assuming that all loads become active simultaneously. Alternatively, a more conservative determination of peak load might identify the time of day when the total load is greatest. Consideration should be given to appliances and other loads with large and non-uniform power cycles, specifically those that require more power during brief periods of their operation, such as motors and refrigerators. Further, software or hardware in the system could help to guarantee an estimate of peak load. For example, load limiters (see 5.3.6) can be used on outlets or branches of the system to prevent large, unauthorized loads, or security lights could be controlled by light sensors and turned off during the day. As discussed in 5.3.3, when sizing inverters, the maximum surge current, or inrush current, shall also be considered.

5.2.11 Discharge and Charge Rates of Battery

The storage capacity of a battery is typically specified at a particular discharge rate. The battery capacity assumed in the design should align with the expected discharge rate of the battery. The discharge rate of the battery is dependent on the power usage profile of connected loads over the course of an average day as well as on the size of the battery bank. For some battery types, especially lead-acid batteries, the battery capacity is lower with a higher battery discharge rate. For example, a lead-acid battery's capacity rating for a 10-hour discharge is higher than for a 1-hour discharge – the slower energy is removed from the battery, the more energy is able to be removed from the battery.

Systems should be designed to avoid discharging the batteries at too high a rate to avoid reducing battery lifetime. A typical maximum discharge rate for lead-acid batteries is a 10-hour discharge (C/10 or 0.1C rate) and some experts suggest a 5-hour discharge (C/5 or 0.2C rate). Lithium-based batteries can typically sustain faster discharge rates without long-term damage. A typical surge rate for lead-acid batteries is a 1C discharge rate; surges are generally quick and last less than a minute. Specifications from the battery manufacturer should be considered when establishing the maximum discharge rate for a system.

Note that in addition to battery capacity, a battery's cycle life may be reduced when discharged at higher rates, especially for lead-acid batteries.

A battery's charge rate is an additional design criterion. The system's battery bank should not be charged at too high or too low a rate. Ensure the charge rate is within the battery manufacturer's specifications.

The criteria used in specifying the systems' discharge rates, surge rates and durations, charge rates and associated capacities shall be provided by the project implementer.

5.2.12 Wiring and Protection

A description and diagram showing all wiring, cables, connectors, disconnects, earthing, and protections shall be included with the full design package. Detailed requirements for these elements are included in Section 7.

If AC outlets or sockets are to be installed as part of the system, the socket type and voltage range should be typical for AC systems in the local area and compatible with the intended loads. If both DC and AC sockets are provided, the sockets should be significantly different to prevent connecting incorrect appliances.

5.2.13 Long-term remote performance monitoring

Equipment to log data and enable long-term performance monitoring shall be included in the system and specified in both the initial bid and full design. Monitoring equipment may be included as part of the charge controller or inverter or may be a stand-alone device. Unless already considered in the efficiency rating of a component, the power requirements of the monitoring equipment shall be included in the design load.

Whenever feasible, this equipment shall enable remote monitoring of the system (e.g. via a cellular connection). In circumstances where this is not possible or reliable, a description of an alternate method of monitoring and reporting data shall be provided.

Monitoring equipment shall be able to record all of the metrics described in Section 10 within the specified range of accuracy. Monitoring equipment may record or present other metrics that are

useful to the operator or site hosts, though all parties need to agree to the collection of additional metrics. All metrics proposed for monitoring shall be listed in the bid.

5.2.14 Permits

The project implementer or general contractor is responsible for identifying and obtaining all applicable permits for the system. Permitting requirements may vary between countries, regions, and systems. Local requirements may include items such as company registration, licensing of contractors, installers, operators, and designers, structural calculations, equipment import requirements, and an environmental impact assessment. Documentation verifying that all permits have been obtained or are in the process of being obtained and are likely to be granted, shall be submitted with the full design package. Occasionally, it may be appropriate for the project implementer to seek waivers or exemptions from the appropriate authorities for certain permits. Not obtaining a permit or waiver/exemption from the relevant permitting agency can result in significant unplanned delays in system installation.

5.3 Component Selection Considerations

5.3.1 General

This section identifies important component considerations when selecting and sizing equipment. Much of the information presented below is intended to provide guidance both to those preparing the general specifications and those designing a system; however, some requirements are included regarding documentation that shall be provided by the project implementer at either the initial bid stage or full design stage. Note, for all components, in addition to the technical requirements, the price and availability should be considered. In certain locations, acquiring or importing the best technical option could be impractical. Further, ensuring that spares and replacement parts will be available could influence the decision of which components to use.

5.3.2 Batteries

This document considers lead-acid and lithium-ion batteries. Other battery chemistry types, including nickel-metal hydride, are also available and can be used with stand-alone photovoltaic systems, but are beyond the scope of this document. In addition, it is important to understand that “lithium-ion” is a broad category that includes a number of chemistries with different characteristics, including operating temperature range, energy density, cycle life, and safety characteristics.

Documentation, including a specification sheet and warranty information, shall be provided for the batteries by the project implementer at the initial bid stage. Additionally, the following shall be considered and where indicated, documented when selecting the battery:

- **Battery chemistry:** Lead-acid and lithium-ion (including lithium iron phosphate) batteries are the two most common chemistry types. Lead-acid batteries are a mature technology and can be part of a reliable and economical system, but they are heavy and present hazards if disassembled or recycled improperly. Lithium-ion batteries can have better energy density and cycle life, but they may come at a higher cost. In addition, lithium-ion batteries can have better round-trip energy efficiency than lead-acid batteries, and can tolerate greater depth of

discharge. This can allow for cost savings in other system components (e.g. a smaller PV array).

- Cycle life: For lead-acid batteries, cycle life is strongly influenced by depth of discharge. In addition, cycle life of lead-acid batteries is very sensitive to temperature; an increase of 8 °C to 10 °C can halve the cycle life. The battery replacement intervals shall be estimated based on the rated cycle life at the design depth of discharge and temperature, and shall be presented with the bid. Assume 365 cycles per year for this calculation.
- Valve-regulated vs. vented (flooded) lead-acid batteries: Valve-regulated lead-acid batteries are generally more expensive, are less tolerant of overcharging, and can have a shorter cycle life than well-maintained vented batteries. However, vented batteries do require regular maintenance, including watering with distilled water, typically a monthly basis, and equalization in accordance with the manufacturer's recommendations. Infrequent or improper maintenance (such as using tap water), can lead to early battery failure. Improper handling, installation, or maintenance can also lead to spillage of electrolyte, presenting a hazard to health or environmental safety. A battery maintenance schedule shall be included with each bid and shall follow the manufacturer's recommendations.
- Activation of lead-acid batteries: Vented lead-acid batteries can be shipped dry by the manufacturer; the battery is then activated (filled with acid and charged) by a distributor or the installer. Failure to follow the correct procedure during activation can result in loss of up to 20 % - 30 % of battery capacity or premature battery failure. If poor past experiences with batteries from particular brands or distributors raise doubts about whether the activation procedure has been performed correctly, ensure that batteries purchased from these sources have been activated by the manufacturer.
- Balancing for lithium-ion batteries: Lithium-ion battery systems shall incorporate balancing to ensure that all cells are charged equally. (The balancing function may be incorporated into the battery or an external component.) There are two general types of balancing: passive and active. In passive balancing, switched resistors are connected in parallel with the cells to dissipate excess energy; a cell's resistor is switched on during charge if that cell has a higher voltage than the others. In active balancing, energy is transferred from one cell to another using various techniques. Passive balancing can be less efficient (since excess energy is dissipated as heat), and since the balancing only operates during charge, a long period without full charges can allow the cells to get further out of balance; this reduces the usable capacity. Therefore, active balancing should be used for lithium-ion batteries.
- Battery management system: Lithium-ion batteries shall be used only with a battery management system meeting the battery manufacturer's specifications. Some lithium-ion battery systems require integration with other system components, such as the inverter and charge controller; these systems shall be used according to the manufacturer's requirements. The battery management system shall be designed to prevent any cell in a series string from exceeding safe voltage limits.
- Disposal: Provisions should be made for proper disposal of batteries of all types; lead-acid batteries are particularly problematic due to their toxicity.
- Series and parallel connections: All batteries or cells connected in parallel or series shall be of the same type (manufacturer, model, and series). New cells should not be used in combination with old cells.
- Hot locations:
 - Battery capacity and cycle life can also be impacted by use in warm and unventilated locations. Battery manufacturer specifications should be reviewed to determine if the

battery size and/or charge control set points should be adjusted based on the expected temperature of the installation. In some cases, it can be more economical to install an efficient air conditioning system for the battery room, plus extra PV capacity to power it, than to accept a poor battery cycle life due to high temperatures.

- For lithium-ion batteries, the manufacturer's recommendations regarding the operating temperature range should be followed. Operation above the manufacturer's specified maximum temperature can reduce the battery's cycle life and result in a risk of fire. The BMS should be designed to prevent operation outside the manufacturer's specified temperature ranges for charging and discharging if such temperatures are expected.
- Humid locations: High humidity can also be detrimental to lithium-ion battery performance.
- Cold locations:
 - If necessary, the depth of discharge for lead-acid batteries should be selected to prevent freezing of the electrolyte when the battery is at a low state of charge. This is only relevant for locations where the battery bank will experience temperatures less than 0 °C.
 - Many types of lithium-ion batteries cannot be charged at low temperatures. The BMS should be designed to prevent operation outside the manufacturer's specified temperature ranges for charging and discharging if such temperatures are expected.
- Warranty duration: Battery warranties often depend on the battery chemistry. While lead-acid batteries typically carry slightly shorter warranties (1 – 7 years), lithium-based batteries tend to come with 5 - 10-year warranties. Note, some battery companies will offer a longer "pro-rated" warranty that will provide partial compensation for the battery after the initial 1 – 5 year full replacement warranty period ends. The warranty may also be written in terms of the cycle life, which is dependent on the depth of discharge of the battery.

The battery design temperature used in cycle life and capacity calculations shall be reported and should be the annual mean temperature at the site, unless air conditioning is used or more site-specific data are available.

5.3.3 Inverter

Documentation including a specification sheet and warranty information for the inverter shall be provided by the project implementer at the initial bid stage. Additionally, the following shall be considered and, where indicated, documented when selecting the inverter:

- Efficiency curve:
 - Inverter efficiency is mainly a function of load. It is important to consider the facility's load during all hours of the day when selecting an inverter.
 - The facility's load profile shall be documented based on power ratings and estimated use times for each appliance, direct measurement from logging the facility's load data over a period of time, or a combination of both.
 - The inverter efficiency value(s) shall be documented, along with an explanation of how these values were considered when making the design calculations.
 - Additional factors should also be considered that affect inverter efficiency, such as temperature. An inverter's rated output can notably decrease when performing in an environment, e.g. outdoors or within an enclosure, with temperatures that reach higher than standard conditions associated with the inverter's rating, e.g. 25°C.

Example: If the facility's load profile is similar to the load profile plot below (Figure 9), the facility's total power generally ranges between 0.2 kVA and 0.7 kVA. However, this facility's maximum power draw is 1.0 kVA. If an inverter is selected with an efficiency plot as shown below (Figure 10), the inverter runs at 95 % efficiency when all the facility's loads are being used simultaneously; however, this is not typical according to the example load profile. Based on the example facility's load profile, the specified inverter would typically run at an efficiency closer to 80 % when paired with the facility.

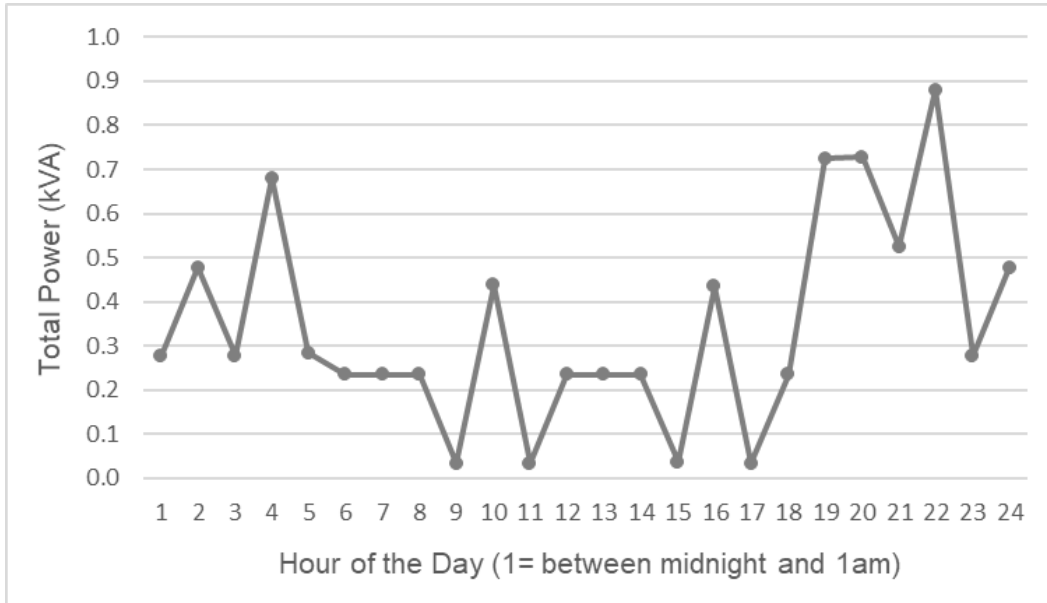


Figure 9. Example load profile for a hypothetical facility.

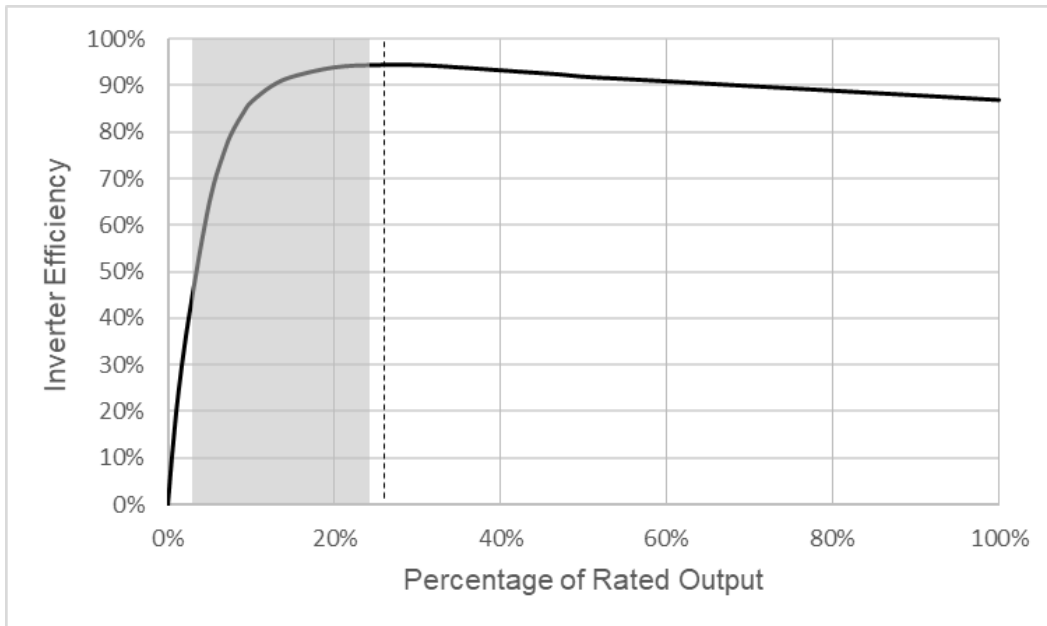


Figure 10. Example inverter efficiency curve for a typical 4 kVA inverter; the gray box identifies efficiency during typical use according to the hypothetical example load profile, and the black dotted line identifies efficiency when all the loads are used simultaneously (1 kVA or 25 % of the rated output).

- Inverter type: There are several types of inverters, and the terms used to identify them vary. Most of these terms are from [IEC TS 61836](#).
 - Stand-alone inverter: an inverter that is designed to operate independently from the utility grid, using battery power, and cannot operate in parallel with the grid. Most systems within the scope of this document will use this type of inverter.
 - Grid-dependent inverter: an inverter that is designed to operate in parallel with the utility grid and cannot operate independently. Alone, these inverters are not suitable for stand-alone systems within the scope of this document; however, they can be used together with one or more grid-interactive inverters in an AC-coupled system. Subtypes of grid-dependent inverter include:
 - Central inverters, which receive power from multiple PV strings.
 - String inverters, which receive power from a single PV string.
 - Module inverters or microinverters, which receive power from a single PV module.
 The AC outputs of multiple string or module inverters are connected in parallel in systems with more than one string or module.
 - Grid-interactive inverter: an inverter that is designed to operate either as a stand-alone inverter or in parallel with the utility grid. These inverters are used to build systems that can export power to the utility grid and provide backup power when the grid is offline. Some grid-interactive inverters are also designed to function in “hybrid mini-grids” with multiple AC-coupled generation sources. Grid-interactive inverters are sometimes called “hybrid inverters.”
 - Inverter/charger: an inverter that incorporates a battery charger capable of charging the batteries from an AC power source—either the utility grid or a backup generator—and a transfer switch to allow either the inverter or the AC source to supply power to the system.
 - The term “grid-tie inverter,” “grid-tied inverter,” or “grid-connected inverter” can refer generally to inverters capable of operating in parallel with the utility grid, or more specifically to grid-dependent inverters.

Most systems within the scope of this document will use stand-alone inverters; systems with backup generators or intermittent utility power can use inverter/chargers or grid-interactive inverters. This document does not include safety requirements for grid-connected systems.

- Power factor: Appliance power factors contribute to the facility’s maximum demand (SEI-API, 2012). For example, a 180 W load having a power factor of 0.8 requires 225 VA of power from an inverter. The power factor values for included and anticipated appliances and equipment used with the system shall be stated and power factors for any appliances that individually or collectively contribute to 10 % or more of the total load shall be documented. The total apparent power of the facility’s loads in units of Volt-Amperes (as opposed to its real power in units of Watts) shall be used when sizing an appropriate inverter.
- Output waveform: Not all inverters provide the same AC power output waveform, and some appliances will not function without the pure sine wave AC power. Inverter waveforms are categorized as sine wave, modified sine wave, and square wave. True sine wave inverters are expected. The inverter shall meet the requirements stated in 5.3.3 and 6.4, and the AC requirements of all the existing and expected future appliances of the facility.
- Surge requirements: Appliances can require an inrush current upon starting. An inverter’s surge overload capacity shall meet the existing and/or expected future anticipated maximum

surge power for the facility, e.g. power draw when all appliances that are expected to be turning on at the same time (SEIAPI, 2012); this is not necessarily all appliances at the facility.

The facility's expected max surge requirement shall be documented; specify surge power for appliances included in the expected max surge.

- System voltage: Be sure the inverter input voltage range matches the battery bank voltage and the output voltage matches the desired AC output for the location (e.g. 120 V or 230 V).
- Inverter idle power consumption: When no loads are operating, the inverter still consumes some power. When loads are operating, this consumption is incorporated into the inverter efficiency, described above. However, during times when no loads are operating, the idle power consumption of the inverter shall be taken into account when determining the overall electricity consumption of the facility.
- Sleep or search mode: When no loads are present, some inverters enter "sleep mode" or "search mode," in which the inverter does not operate continuously. This feature decreases the idle power consumption of the inverter, but it cannot be used if any loads require continuous power. If this feature is used, all personnel at the site shall be trained on how to "wake up" the system or the sensitivity shall be adjusted so that sleep mode does not interfere with the operation of any loads. (That is, turning on any load shall be sufficient to wake the inverter from sleep mode.) If sleep mode is disabled, the increased idle power consumption shall be considered in the design calculations.
- Load shedding: Some inverters are equipped with the capability of load shedding or cutting off certain loads to prioritize power for critical loads. Load shedding may be an appropriate strategy to maintain critical loads at certain sites. (Note that according to WHO requirements, vaccine refrigerators should be provided with a separate PV system rather than operated as a critical load on a larger PV system.)
- Settings and set points: Many inverters require programming of settings. Set points include conditions, measurements, or baselines associated with the energy system that informs the inverter how to operate. Settings that are programmed may include: PV system size, battery size and voltage, maximum battery charge rate, inverter type. These settings, if used, shall be provided. Set points related to battery charging and discharging shall be compatible with the battery manufacturer's specifications. Programmed set points shall be checked in the commissioning stage (8.3).
- Warranty duration: Inverter warranties typically range from 5 - 10 years, with some as long as 25 years.

Note that it is not always desirable to run inverters up to their rated capacity. Even though an inverter may specify a continuous apparent power rating, running it continuously at its limit may reduce its life or require repairs sooner than expected, e.g. cooling fan replacement.

5.3.4 PV Modules

The following factors should be considered when selecting PV modules. Documentation including a specification sheet and warranty information for the PV modules shall be provided by the project implementer at the initial bid stage.

- PV module efficiency: More efficient modules can reduce the area required for a given PV array power output, although the cost for high efficiency modules may be higher than the cost for modules with a more typical efficiency value.

- Power tolerance: The tolerance in the maximum power rating should be taken into account in the selection of PV modules and the design of the system.
- Temperature coefficients: the voltage (and hence the power output) of modules varies with the operating temperature. In hot climates, a smaller temperature coefficient for variations in voltage and/or power can result in more energy production.
- PV module technology: Monocrystalline silicon PV modules can be more efficient than polycrystalline silicon and have better performance at high temperatures and under low-light conditions but are typically more expensive. These differences are often insignificant in practice, so it is important to consider the specifications of the particular PV module under consideration. Thin-film PV modules can be less expensive than either crystalline PV module type, but they are often significantly less efficient and can degrade faster than crystalline silicon. Cadmium telluride (CdTe) modules typically have high conversion efficiencies but also contain toxic materials and proper disposal is required.
- Warranty duration: PV module manufacturers typically provide warranties for workmanship and for maximum power output. Common warranties for large modules offer a minimum of 10 years and often extend to 20 – 25 years. PV module warranties can specify the expected maximum power at the warranty date (e.g. at least 80 % of original maximum power at 25 years).
- Matching: All PV modules in a series string shall be of the same type, model, and manufacturer.

5.3.5 Charge Controller

Documentation including a specification sheet and warranty information for the charge controller shall be provided by the project implementer at the initial bid stage. Additionally, the criteria used for charge controller selection shall be provided.

This section primarily discusses solar charge controllers, which are used in DC-coupled systems to regulate the flow of power from the PV module to the battery. These units are also sometimes called “solar controllers.” Solar charge controllers are not used in AC-coupled systems, in which the PV module is connected to the AC bus through a PV inverter, and the battery is charged from the AC bus by a charger. Often, the battery charger is combined with an inverter, in which case the combination is typically called an inverter/charger.

For solar charge controllers, the following should be considered:

- Voltage limits: Typical operating voltage (either V_{mp} or the nominal voltage, depending on the configuration of the charge controller) and maximum voltage (V_{oc}) of the array in relation to the charge controller minimum required battery charging voltage and maximum voltage limit.
- Current limits: The PV module short circuit current (I_{sc}) in relation to the charge controller current limit. The charge controller should be capable of carrying 125 % of the array short circuit current. Oversizing the charge controller even further can be appropriate if the array size is likely to be increased in the future (SEI-API, 2012).
- Set points: The relevant set points include low-voltage disconnect (LVD), maximum charge current, and overcharge protection limits. These limits, along with a description of how the charge protection is implemented, shall be provided. Charge controller set points shall be compatible with the battery manufacturer’s specifications. Many charge controllers require programming to set the correct set points for the battery; this programming is checked in the commissioning stage (8.3).

- Temperature compensation: To ensure optimum charging of lead-acid batteries, the charge voltage set points should be adjusted to compensate for battery temperature. Generally, lower temperatures require higher charge voltages to allow complete charging, while higher temperatures require lower charge voltages to prevent overcharging. Similarly, lithium batteries may have a limited temperature range over which they can be charged, yet these limits may be included in the battery management system rather than a separate charge controller.
- Charge controller type: The choice of a maximum power point tracking (MPPT) or pulse width modulated (PWM) or other non-MPPT charge controller will often depend on the size of the system. Most larger systems will benefit from an MPPT charge controller (SEI, 2013). If an MPPT charge controller is used, the maximum power of the PV array will also be important in properly sizing the controller.
- Efficiency and self-consumption: As presented in Table 2, charge controllers are not 100 % efficient; some power is used for the charge controller's operational purposes, or lost when the PV module does not operate at its maximum power point. Ideally a charge controller will have a high efficiency and a low self-consumption.
- Warranty duration: Charge controller warranties typically range from 2 - 5 years.

Inverter/chargers or separate battery chargers shall have appropriate voltage set points, as described above. In addition, parameters such as the maximum charging current, battery size, type, and voltage shall be configured according to the charger and battery manufacturers' requirements. Programmed settings shall be checked in the commissioning stage (8.3).

In addition, some inverters include an integrated solar charge controller and/or battery charger, in which case the system would not need an additional solar charge controller unit and/or battery charger unit.

Note that it is not always desirable to run charge controllers up to their rated capacity. Even though a charge controller may specify a maximum input current, supplying it with PV strings at a maximum current near this limit may reduce its life, e.g. due to sustained heating of the charge controller's electronics.

5.3.6 Load limiters

Load limiters can be installed to prevent overuse of non-critical circuits, such as those in staff housing. If any related equipment is included with the proposed systems, specification sheet and warranty information for the equipment shall be provided by the project implementer at the initial bid stage.

Many types of load limiters exist, including:

- Circuit breakers (either thermal, magnetic, or electronic)
- Devices incorporating PTC thermistors (also called resettable fuses)
- Energy meters that incorporate load-limiting functionality (some of these incorporate additional features, such as prepayment capability)

Load limiters should comply with applicable standards relating to safety and accuracy, if such standards are available. (For some types of load limiters, it is possible that no international or national standards exist.)

Load limiters shall be used in accordance with the manufacturer’s specifications and installation instructions.

Load limiters should be tamper-evident and tamper-resistant. Load limiters that do not require user interaction (such as PTC devices) can be installed in a user-inaccessible location to reduce the risk of tampering; however, the device should remain accessible for maintenance.

5.4 Elements to include in general specification

In cases where the project implementer is responsible for the design of systems, the general specification prepared by the project developer needs to provide adequate information about the facilities and should define any parameters or assumptions that need to be consistent across bids to ensure that bids are comparable. Table 3 provides a list of the key elements that should be included in the general specification. If the project developer is responsible for the design of the systems, the project developer should still provide the information in Table 3 in the general specification, but will also need to provide details about the system design and component specifications.

One key assumption that should be provided by the project developer is the daily energy requirement for each system in kWh/day. The daily energy requirement of the system should be based on the anticipated loads required to be covered by the system and should be conducted in consultation with representatives from health ministries and the health facilities. Typically, the initial system sizing will be conducted by the project developer in order to specify the daily energy requirement and load profile for the design, regardless of which entity is responsible for the detailed system design. See Section 11 for more detail on determining the energy requirement for a facility.

Depending on the type of bid process used, e.g. single-stage or multi-stage, enabling applicants to visit sites prior to an initial bid submission may or may not be necessary. If the bid is a single stage (i.e., very competitive and risky for each applicant), applicants should not be expected to visit sites to make their own assessments prior to bid. If the bid is multi-stage or otherwise limited to a few applicants, selected applicants could visit the sites or an example site prior to submitting a final bid to improve the quality and accuracy of their proposals. In this case, it may be appropriate for the project developer to compensate applicants submitting proposals to cover their time spent preparing the bid. This practice can also help improve the quality of the submitted bids.

Table 3. Key elements to include in general specification

Element	Information Required
Facility type and energy needs	Outline of the estimated facility energy service needs for each facility, including: <ul style="list-style-type: none"> • Facility classification • Daily energy requirement in kWh • Average demand in kW • Maximum (peak) loads in kVA • Facility load profile assumptions (see Section 11). These detailed assumptions should cover the expected loads, power consumption, and hours of use, along with notes regarding provisions for staff housing, priority loads, security posts, vaccine refrigerators, water pumping, facility hours of operation, and any other special conditions. • List of any loads that are expected to be installed by the project implementer with the system (such as lights, fans, or water pumps)

	Project developers may want to allow some flexibility for project implementers to adjust these default assumptions based on their insight either during or after the bidding process.
Solar resource	Data source for solar resource and specific site locations, or the specific average monthly insolation data to be used for each site (see 5.2.4).
Site data	Geolocation for each facility or meteorological data for each site to ensure chosen equipment and designs are appropriate for the facilities in terms of temperature, humidity, wind, and extreme weather. If available, pictures, blueprints, and any other site-specific data should be made available to those designing the systems. Information on the existing wiring, installed loads, and construction (i.e., roof quality) of each facility is also valuable.
Efficiency values	Assumed values for any efficiencies that are not dependent on specific equipment or installation choices should be stated to increase comparability between bids. These include values for shading and soiling at each site, as well as losses to assume for module mismatch , module power tolerance , and module degradation .
Factors related to system sizing	The project developer may choose to specify the growth factor , PV array oversize factor , and required days of autonomy for each system. Alternatively, if the project implementer is responsible for the long-term operation of the system which will be monitored for compliance, it may be appropriate to leave these design decisions to the discretion of the project implementer. Expectations regarding designing for potential system expansion should also be stated.
Performance monitoring metrics and requirements	The project developer should state the metrics with which the systems will be assessed. Recommended metrics are presented in Section 10. Reporting intervals, specific compliance criteria, and associated penalties for non-compliance will need to be stated in the general specifications or procurement contract. Similarly, equipment ownership and responsibilities, including the replacement of major components outside of the warranty period should be stated.
Warranty periods	Required minimum warranty periods for each component
Operations and maintenance requirements	The project developer should state expectations regarding operations and maintenance (O&M) for the system, training of users and technicians, and e-waste/end-of-life management. Additional details are discussed in Section 9.
Financial assumptions	The project developer should state any assumptions that prospective project implementers should use in their cost estimates to ensure estimates are comparable across bids.
Exceptions or additions to the requirements of this document	Design, component and installation requirements are described in Sections 5.3, 6, and 7. If the project developer chooses to reference these sections in the general specifications, but wants to require additional elements or make exceptions to these requirements, those changes should be clearly noted.

5.5 Reporting Requirements

This section provides lists of materials that shall be provided or documented by the project implementer or operator. Table 4 identifies materials that shall be provided initially, typically at the bid stage. Table 5 identifies materials that shall be provided with the full designs, typically after the project implementer is under contract, but prior to approval of the design and before any purchases are made.

Table 4. Documents at bid stage

Subsection	Manufacturer Documents Required	Design Information Required
Overall system efficiency	<ul style="list-style-type: none"> Equipment datasheets (when not specified to be provided in the subsequent rows of this table) 	<ul style="list-style-type: none"> Document efficiency values used for each component in the design and provide justification for choice; multiple efficiency values may be used, such as in the case of the inverter, when clearly explained
Solar Resource	<ul style="list-style-type: none"> None specified at this time 	<ul style="list-style-type: none"> Document solar resource values used including any impact due to array tilt, orientation, and shading Site-specific shading images, solar path graphs, and monthly shading loss analyses, or other similar documentation to support shading efficiency value. Note, in some regions, where trees, tall buildings, and other obstructions are not present, shading analysis may not be necessary.
Growth factor	<ul style="list-style-type: none"> None specified at this time 	<ul style="list-style-type: none"> State growth factor used in design and provide justification for choice
PV oversize factor	<ul style="list-style-type: none"> None specified at this time 	<ul style="list-style-type: none"> State PV oversize factor used in design and provide justification for choice
Days of autonomy	<ul style="list-style-type: none"> None specified at this time 	<ul style="list-style-type: none"> State days of autonomy used in design and provide justification for choice
Battery depth of discharge	<ul style="list-style-type: none"> Plot showing battery life vs. depth of discharge Expected cycle life based on proposed depth of discharge 	<ul style="list-style-type: none"> State battery depth of discharge used in design and resulting cycle life and provide justification for choice
System voltages	<ul style="list-style-type: none"> Equipment datasheets 	<ul style="list-style-type: none"> State design system voltages and confirm that all equipment is compatible with these voltages
Maximum instantaneous power	<ul style="list-style-type: none"> Appliance and inverter datasheets 	<ul style="list-style-type: none"> Document peak load value in design and provide justification for choice

Subsection	Manufacturer Documents Required	Design Information Required
Discharge rate of battery	<ul style="list-style-type: none"> • Battery datasheet that confirms the battery can tolerate the specified discharge rate 	<ul style="list-style-type: none"> • Document maximum allowable battery discharge rate used in design and provide justification for choice
Charge rate of battery	<ul style="list-style-type: none"> • Battery datasheet that confirms the battery can tolerate the specified charge rate 	<ul style="list-style-type: none"> • Document maximum allowable battery charge rate used in design and provide justification for choice
Battery	<ul style="list-style-type: none"> • Equipment datasheet • Warranty • Documentation (see 6.1) showing battery meets requirements in Section 6.3 	<ul style="list-style-type: none"> • Battery replacement intervals • Battery maintenance schedule • System voltage and total Ah size; indication of how batteries will be connected in series and parallel
Inverter	<ul style="list-style-type: none"> • Equipment datasheet • Efficiency curve • Warranty • Documentation (see 6.1) showing inverter meets requirements in Section 6.4 	<ul style="list-style-type: none"> • Facility load profile • Power factors for all appliances • Facility's expected max surge power, specifying surge power for included appliances
Charge controller	<ul style="list-style-type: none"> • Equipment datasheet (if function is not included in inverter) • Warranty • Documentation (see 6.1) showing charge controller meets requirements in Section 6.5 	<ul style="list-style-type: none"> • None specified at this time
PV modules	<ul style="list-style-type: none"> • Equipment datasheet • Warranty • Documentation (see 6.1) showing PV modules meets requirements in Section 6.2 	<ul style="list-style-type: none"> • Total kW size • Total voltage • Total current • Indication of how modules will be strung together and connected to the inverter

Subsection	Manufacturer Documents Required	Design Information Required
PV mounting hardware	<ul style="list-style-type: none"> Equipment datasheet(s) 	<ul style="list-style-type: none"> State mounting plan (pole, roof, tracking, etc.) and specify hardware to be used Designs with adjustable arrays should include a schedule for making the seasonal adjustments Designs with tracking arrays should provide details on the tracking mechanism or software If roof mounted array, provide analysis of the roof that suggests it can support the load If pole mounted array, provide plans for stabilizing the pole and any associated soil analysis
Protections	<ul style="list-style-type: none"> Equipment datasheet(s) 	<ul style="list-style-type: none"> Indication of protection devices planned to be used and where
Remote Monitoring	<ul style="list-style-type: none"> Equipment datasheet(s) 	<ul style="list-style-type: none"> Description of how metrics presented in Section 10 will be measured, along with recording intervals and method of retrieving data
Additional equipment	<ul style="list-style-type: none"> Equipment datasheet(s) If lights or fans are included with the system, documentation (see 6.1) showing they meet requirements in Sections 6.6 and 6.7, as applicable. 	<ul style="list-style-type: none"> None specified at this time
Cost estimate (optional)	<ul style="list-style-type: none"> Table itemizing system costs, including materials, labor, and equipment and operations and maintenance (O&M) costs (see Table 5 for additional details) 	<ul style="list-style-type: none"> Depending on the bidding process, it may be appropriate to request a cost estimate at the initial stage, or may be appropriate to wait until the full-design stage.

Table 5. Documents at full-design stage

Document	Description
Overall design layout	<ul style="list-style-type: none"> High-level layout showing major components and connections Major component brand and model numbers should be specified

Document	Description
Civil design layout	<ul style="list-style-type: none"> • Layout that shows all civil work, e.g. trenching • Control and battery room layout showing required clearances and ventilation • Ventilation and thermal calculations, if applicable • Additional design sheets showing details should be included as needed
PV mounting information	<ul style="list-style-type: none"> • Confirmation of or adjustments to mounting plan and equipment submitted at the bid stage • If roof-mounted array where the combined weight of the PV array and mounting hardware is 100 kg or more, provide stamped approval of the structural design by an accredited engineer.
Electrical design layout	<ul style="list-style-type: none"> • Layout that shows all electrical work, e.g. wire runs and circuit protection • Additional design sheets showing details should be included as needed
Single line and full, e.g. power wiring or three line, electrical diagrams	<ul style="list-style-type: none"> • Illustrates all electrical components and their connections without spatial scale and using symbols for components • Includes monitoring and communication components and connections • Includes AC and DC protection devices and their ratings • Includes earthing and surge protection
Calculations	<ul style="list-style-type: none"> • Show all sizing and equipment selection calculations • Include maximum number of modules per string, maximum voltage and current per PV string, and the extreme annual mean minimum design temperature • If sizing the system to power all loads of the facility, include facility's load profile as well as power and surge factors considered • Structural analysis calculations
Equipment schedule	<ul style="list-style-type: none"> • Specify type, manufacturer, model, quantity, and relevant notes for each piece of equipment included in the system. Include all components in balance of system, e.g. mounting hardware, racking, charge controllers, inverters, remote monitoring equipment, disconnects, transfer switches, combiner boxes, and overcurrent protection devices.
Conduit and wire schedule	<ul style="list-style-type: none"> • Specifies required conduit and wire sizes for each power and communications circuit • Specifies wire type, including material, maximum voltage and rated temperature • Specifies conductor maximum ampacity, overcurrent protection device sizes per circuit • Calculations for determining wire and conduit sizes, including ampacity, voltage drop, one-way length, temperature derate, conduit fill derate, and percent of maximum conduit fill • Describes method for mounting wiring (e.g. in-the-wall vs. surface wiring)
Earthing diagram	<ul style="list-style-type: none"> • Illustrates major equipment and system earthing connections

Document	Description
Cost estimate	<ul style="list-style-type: none"> • Table itemizing system costs, including materials, labor, and equipment • Additionally, expected operations and maintenance (O&M) costs for the next 15 years (or an alternate period specified by the project developer), including any expected replacement costs, should be provided either for each individual system, or for the overall project including the full fleet of systems covered by the project. The replacement interval of the batteries should take into consideration the rated cycle life of the battery at the expected operating temperature and the charge/discharge voltages. Any financial analyses should state all assumptions included in the analysis and should be presented in simple terms without considering the time value of money (i.e., should not use discounted cash flows) unless otherwise instructed by the project developer.
Permits	<ul style="list-style-type: none"> • Table presenting required permits and identifying which permits have already been acquired and outlining plan for acquiring any remaining permits
Materials submittals	<ul style="list-style-type: none"> • Datasheets for all equipment and materials that will be purchased • Table including model numbers and count for each proposed purchase • Each submittal should be approved by the project developer prior to purchase

6 Component requirements

6.1 General

Components shall be selected and installed in compliance with all manufacturer's instructions. Care should be taken to comply with any instructions related to interoperability of components to ensure that the components selected are capable of operating when combined into a complete system. Components shall be rated for the anticipated ambient temperature considering both the local climate and the specific operating environment of the equipment location.

The project implementer shall provide a valid test certificate or other evidence of meeting the requirements in this section. Tests to meet the requirements listed in this section should be conducted at a third-party test laboratory that has demonstrated competence, metrological traceability, and impartiality, for example by accreditation to [ISO/IEC 17025](#) by an ILAC MRA signatory; however, depending on the component and the market, internal test results may be acceptable in certain cases. When the requirements of this document are met through a safety marking such as the CE Marking, proof of the validity of the marking (for example, a certificate or declaration of conformity) shall be provided. The authenticity of the submitted documents should be checked.

The use of alternate standards, where permitted, is subject to approval by the facility owner and project developer.

Requirements are provided for select PV system loads, including lamps, luminaires, and fans because these are loads that are often procured and installed with the PV system. If other loads

are procured with the PV system, additional requirements beyond the scope of this document will likely apply. In the case of vaccine refrigerators, typically a separate PV system should be designed to independently operate the vaccine refrigerator and WHO specifications should be followed for procurement, design, and management.²

6.2 PV modules

PV modules shall meet the requirements of [IEC 61215](#) (all parts). Modules shall meet the requirements of [IEC 61730](#) (all parts) class II or class III according to [IEC 61730-1](#) and shall not be used in applications inconsistent with their class rating. Modules of class III shall not be used if the PV array maximum voltage, calculated according to [IEC 62548:2016](#), 7.2, exceeds 35 V, and shall not be used in parallel with other PV modules or energy sources unless the combination provides protection from reverse current and overvoltage protection.

Note: Class II and class III of [IEC 61730-1:2016](#) correspond to application classes A and C, respectively, of IEC [61730-1:2004](#).

The UL 61215 and UL 61730 series may be used in place of the corresponding IEC standards. In addition, for modules tested prior to December 4, 2019, [UL 1703](#) may be used in place of IEC 61730 or UL 61730. (The requirements related to class II or class III rating do not apply to UL 1703.)

If a PV module is rebranded (for example, if a local company uses a PV module from an international manufacturer but labels the module with its own brand), the project implementer shall provide a valid test certificate (or other evidence of compliance meeting the requirements of 6.1) with relevant information (e.g. company name, model number, electrical ratings) matching the information marked on the PV module. Alternatively, a declaration from the PV module manufacturer (i.e. the company whose name is on the certificate) that the two modules are identical except for the branding may be accepted.

6.3 Batteries

6.3.1 Requirements for all batteries

Batteries shall be marked with the name of the manufacturer or supplier and the date of manufacture (which may be in code) or a serial number that allows this information to be traced.

6.3.2 Requirements for lead-acid batteries

The provisions of one or more of the following standards shall apply to lead-acid batteries used in the off-grid solar electricity system:

- [IEC 61056-1](#) (valve-regulated, portable)
- [IEC 60896-11](#) (valve-regulated, stationary)
- [IEC 60896-22](#) (vented, stationary)

² Current WHO specifications for solar power systems for vaccine refrigerators are available at: http://apps.who.int/immunization_standards/vaccine_quality/pqs_catalogue/catdocumentation.aspx?id_cat=17

- [IEC 61427-1](#)
- [UL 1973](#)
- [UL 1989](#)
- Appropriate alternate standard

In addition, the lead-acid battery shall have a rated cycle life of at least 1100 cycles down to 50 % depth of discharge. This rating may be at a standard temperature, typically 20 °C to 25 °C, and need not be corrected for temperature as described in 5.3.2. Rated cycle life (also referred to as minimum cycle life or end of life) is defined as the number of cycles resulting in a 20 % capacity loss (i.e. the battery retains 80 % of its initial rated capacity).

6.3.3 Requirements for lithium-ion batteries

Lithium-ion batteries of all types shall be used only in combination with a battery-management system (BMS) approved by the battery manufacturer. Lithium-ion batteries shall meet the requirements of at least two safety standards:

one that focuses on safety during transport:

- [UN 38.3](#) or
- [IEC 62281](#)

and one that focuses on safety during use:

- [IEC 62619](#) or
- [UL 1973](#).

Safety tests in at least one category shall cover both the individual cell and the fully assembled battery pack (these may be two separate test reports or certificates or one single test report or certificate for both cell and battery). [IEC 62619](#) and [UL 1973](#) cover batteries for stationary applications. [IEC 62133-2](#), [UL 62133-2](#), or [UL 2054](#) may be an appropriate alternate requirement, though these standards are typically applied to portable batteries for use in devices that can be hand-carried. There is significant overlap between [UN 38.3](#) and [IEC 62133-2](#), [UL 62133-2](#), or [UL 2054](#), so a project developer may elect not to require [UN 38.3](#) for portable batteries meeting these standards; however, shipping carriers generally require [UN 38.3](#) for all batteries.

Safety tests shall be conducted at a third-party test laboratory that has demonstrated competence, metrological traceability, and impartiality, for example by accreditation to [ISO/IEC 17025](#) by an ILAC MRA signatory.

"Similar" batteries in which the number of cells differs between models but all other characteristics are the same would still need to carry the above certificates for all models. Note, however, that some test methods do allow for smaller units (i.e., sub-packs of cells similarly assembled into packs and then connected), to be tested as representative of the larger battery enabling reduced testing for the larger battery.

6.4 Inverters

The provisions of one or more of the following shall apply to inverters and inverterchargers in the off-grid solar electricity system:

- [IEC 62109-1](#) and [IEC 62109-2](#)
- [UL 1741](#)

As an alternative, battery inverters or inverter/chargers may comply with [IEC 62477-1](#), but this standard is not appropriate for PV inverters in AC-coupled systems where there is no battery connected to the DC input.

The following types of inverters are permitted, provided that they meet the standards listed above (see also 5.3.3):

- Stand-alone (off-grid) inverters
- Inverter-chargers (i.e. inverters that incorporate an AC charger that can charge the battery bank from the utility grid)
- Grid-interactive inverters (i.e. inverters that can operate in grid-connected or stand-alone mode)
- Grid-dependent inverters (i.e. inverters that can only operate when connected to the grid), in conjunction with other inverter types in an AC-coupled system.

Inverters that establish the voltage waveform shall have true sine wave output with total harmonic distortion (THD) of the voltage waveform not exceeding 7 % at 40 % load and 5 % at the nominal power rating. (This requirement does not apply to grid-dependent inverters, as they do not determine the voltage waveform.)

6.5 Charge controllers

The provisions of one or more of the following shall apply to charge controllers or battery chargers (other than inverter/chargers) used in the off-grid solar electricity system:

- [IEC 62109-1](#)
- [IEC 60335-1](#) and [IEC 60335-2-29](#)
- [IEC 62509](#)
- [IEC 62477-1](#), only for battery chargers with AC input (no DC power input from PV array)
- [UL 1741](#)
- Appropriate alternate safety standard

Alternatively, the charge controller may carry one of the following safety markings:

- UL (Underwriters Laboratory) Listing and Classification Mark
- CE (Conformité Européenne) marking
- Appropriate alternate safety marking

The charge controller shall comply with all requirements specified by the battery manufacturer, including but not limited to specifications for voltage set points.

The charge controller shall be marked with the manufacturer name and either the date of manufacture (which may be in code) or a serial number that allows this information to be traced.

The charge controller and inverter may be combined into a single unit, in which case, the requirements of both Sections (6.4 and 6.5) apply.

Such combined units may also include a battery; in this case, the combined unit (battery, charge controller, and possibly inverter) shall comply with one of the following combinations of standards:

- [IEC 62109-1](#) and [IEC 62619](#). In addition, systems containing inverters shall comply with [IEC 62109-2](#). For [IEC 62619](#), the entire unit shall be tested as a battery system.
- Only for units without DC input from the PV array: [IEC 62477-1](#) and [IEC 62619](#). For [IEC 62619](#), the entire unit shall be tested as a battery system.
- [IEC 62040-1](#) and [IEC 62040-3](#). In addition, systems having DC output shall comply with [IEC 62040-5-3](#).
- [ANSI/CAN/UL 9540](#)

The battery in a combined unit, and any spare or replacement batteries, shall comply with the requirements of Section 6.3. In addition, spare or replacement batteries shall be of a type approved by the manufacturer of the combined unit. The other functions of the combined unit (e.g. inverter, charge controller) need not comply with the requirements in this document for the individual components if the combined unit meets the requirements of this section.

Note: Combined units including a battery are relatively new and uncommon. In the future, alternative testing requirements could be identified that might supersede those listed above.

6.6 System loads: Lamps and luminaires

6.6.1 General

Lighting loads often represent a significant energy service demand for off-grid solar electricity systems. Efficient lighting technologies consume substantially less energy than inefficient technologies and can also be more robust and offer longer service life, reducing maintenance costs. The higher upfront cost of efficient lights will, in many cases, be entirely offset by the reduced cost of the extra energy generation required for inefficient lights. For these reasons, it is strongly recommended that any pre-existing low-efficiency lighting in a PV facility be replaced by more efficient lighting technologies. In practice this means that incandescent or T-12 fluorescent lamps should be replaced by more efficient linear fluorescent lamps, CFLs, or LED lamps that meet the performance requirements in this section.

The local availability of replacement lamps should also be assessed for newly installed luminaires to ensure that the facility will be able to replace lamps and/or luminaires when they fail.

Pre-existing lamps and luminaires in the facility need not be replaced or brought into compliance with the requirements of this document. However, the power consumption of these lamps and luminaires shall be taken into account in the sizing of the PV and battery arrays. Pre-existing lamps and luminaires should be checked to ensure safety.

The following requirements for lighting apply to newly installed lamps and luminaires in the PV system.

6.6.2 Safety requirements

Lamps and luminaires shall be rated for safe operation. Lamps and luminaires in the off-grid solar electricity system shall be safety tested and carry one of the following safety markings:

- UL (Underwriters Laboratory) Listing and Classification Mark
- CE (Conformité Européenne) marking
- Appropriate alternate safety standard

6.6.3 Performance requirements

The successful performance of the off-grid solar electricity system is greatly dependent on the efficiency of installed lighting in the facility. LED lighting technologies in general offer the highest levels of efficiency and should be used whenever possible. Incandescent lighting typically offers the lowest efficiency and should be avoided to the extent possible.

These performance requirements do not apply to the following:

- Emergency lighting that is automatically turned off during normal building operation, and
- Lighting that is integral to medical equipment or specifically designed for use only during medical or dental procedures.

Lamps and luminaires in the system shall carry ratings for lumen output, input power, correlated colour temperature (CCT), and colour rendering index (CRI).

Lamps and luminaires shall meet the energy efficiency requirements of one or more of the following:

- The lamp or luminaire shall carry a valid European Union energy label (energy efficiency index) rating of A+ or A++.
- The lamp or luminaire shall carry a valid US Energy Star label
- The lamp or luminaire shall carry a valid China Energy Efficiency label with an Energy Label Class 2 or better level.
- The lamp or luminaire shall have a luminous efficacy of at least 75 lm/W.

Lamps and luminaires shall meet the power factor requirements in Table 6. Compact fluorescent lamps, LED lamps, and LED luminaires may be assumed to meet this requirement if they comply with one of the following standards or regulations:

- European Commission regulation 244/2009 (non-directional household CFLs)
- European Commission regulation 1194/2012 (LED lamps and luminaires, directional CFLs)
- Indian Standard IS 16102-2
- US Energy Star

Other countries' energy labels may be used to verify compliance with the luminous efficacy and power factor requirements stated above. However, the requirements for different countries' energy labelling schemes can vary significantly. Before accepting an alternative energy label, the project developer should carefully evaluate the requirements for the label to ensure that lamps or luminaires with the label will meet the requirements above.

Table 6. Minimum power factor for lamps and luminaires

Lamp/luminaire type	Power range	Minimum power factor
Fluorescent	$P < 25 \text{ W}$	0.5
	$P \geq 25 \text{ W}$	0.9
LED	$2 \text{ W} < P \leq 5 \text{ W}$	0.4
	$5 \text{ W} < P \leq 25 \text{ W}$	0.5
	$P > 25 \text{ W}$	0.9

Photometric and power measurements shall be made according to one of the following test methods:

- [IEC 62612](#) (for self-ballasted LED lamps)
- [IEC 60969](#) (for self-ballasted fluorescent lamps)
- The applicable part of [IEC 62722](#) (for luminaires)
- Approved test methods for one of the specific energy labelling schemes listed above
- [IEC TS 62257-12-1](#)
- A recognized test method that is substantially equivalent to one or more of those listed above.

Measurements should be made by a laboratory that has demonstrated competence, metrological traceability, and impartiality, for example by accreditation to [ISO/IEC 17025](#) by an ILAC MRA signatory, or is approved to conduct tests for one of the specific energy labelling schemes listed above.

Recommendations regarding the minimum requirements for ambient lighting (in lux) are provided in Section 11.2.

6.7 System loads: Ceiling fans

Ceiling fans circulate air within a room to provide occupant comfort. The blade size, shape, fan speed, and motor type affect the efficiency of the fan and the amount of air moved. If included in a system, ceiling fans should be appropriately sized and positioned to maximize air movement. The ceiling fan size chart listed below is based on research in Nigeria and Niger along with recommendations from commercial websites and the US EPA Energy Star program website.

Existing efficiency standards for fans generally do not include minimum power factor requirements. However, since fans can be a significant percentage of a system's load, the power factor should be taken into account in the system design.

Ceiling fans used in PV systems shall meet all of the requirements for one of the following two options. In cases where facilities are built "grid-ready" and already have ceiling fans installed, it may be appropriate to replace the fans with more energy efficient fans that meet the requirements of either option 1 or option 2, depending on the efficiency of the existing fans and the fans available in the market.

OPTION 1:

- Meet or exceed the minimum efficiency and airflow requirements for the fan size and type as presented in Table 7. Efficiency and airflow specifications shall be confirmed through third-party test results or similar evidence.
- Meet or exceed the minimum airflow requirements for a room (specified by the project developer)

Table 7. Minimum efficiency and air speed requirements for option 1

Requirements using English units			
Distance from ceiling to lowest point on blades	Size (fan sweep diameter in inches)	Minimum Efficiency (CFM/W)	Minimum High-Speed Airflow (CFM)
> 10 in	$D \leq 36$ inches	$\geq 0.72*D + 41.93$	≥ 1767
	$36 \text{ inches} < D < 78$ inches	$\geq 2.63*D - 26.83$	$\geq 1.3635*D^2$
	$D \geq 78$ inches		≥ 8296
≤ 10 in	$D \leq 36$ inches	$\geq 0.31*D + 36.84$	≥ 1414
	$36 \text{ inches} < D < 78$ inches	$\geq 1.75*D - 15$	$\geq 1.0908*D^2$
	$D \geq 78$ inches		≥ 6637
Requirements using metric units			
Distance from ceiling to lowest point on blades	Size (fan sweep diameter in mm)	Minimum Efficiency (m ³ /min/W)	Minimum High-Speed Airflow (m ³ /min)
> 25.4 cm	$D \leq 914$ mm	$\geq 0.0008027*D + 1.1873$	≥ 50.04
	$914 \text{ mm} < D < 1981$ mm	$\geq 0.002932*D - 0.7597$	$\geq 0.00005985*D^2$
	$D \geq 1981$ mm		≥ 234.92
≤ 25.4 cm	$D \leq 914$ mm	$\geq 0.0003456*D + 1.0432$	≥ 40.04
	$914 \text{ mm} < D < 1981$ mm	$\geq 0.001951*D - 0.4248$	$\geq 0.00004788*D^2$
	$D \geq 1981$ mm		≥ 187.94
This table was derived from the US EPA Energy Star website: https://www.energystar.gov/products/lighting_fans/ceiling_fans/ceiling_fans_key_product_criteria The tables for English and metric units are included for convenience and should be equivalent. In the case of any discrepancies, the table using English units is the original version and should prevail.			

OPTION 2:

- Use brushless direct current (BLDC) motors (also called synchronous DC motors; note that fans that use AC power can have BLDC motors).
- Have a maximum power no more than 75 W.
- The blade diameter should be no less than the minimum value specified in Table 8.

Table 8. Minimum blade diameter recommendations for given room sizes

Room area (m ²)	Minimum blade diameter (mm)	Minimum blade diameter (in)
<7	750	29
7-14	900	35
14-21	1200	47
21-33	1400 or 2 fans (1200 mm or larger each)	55 or 2 fans (47 in or larger each)
>33	At least 2 fans (1200 mm or larger each)	At least 2 fans (47 in or larger each)

6.8 Electromagnetic compatibility (EMC) recommendations

6.8.1 General information

Project developers may choose to establish requirements for electromagnetic compatibility. The following recommendations may be used as a guide; however, the project developer should consider particular national requirements. (For example, certain frequency bands are regulated in some countries but not in others.)

In general, field experience has shown that electromagnetic interference is unlikely to be a significant concern in schools and basic health facilities, but could be an important consideration in larger facilities or those using more sophisticated medical equipment.

6.8.2 Recommendations for charge controllers and inverters

Inverters and charge controllers should meet the requirements of a standard that addresses emissions of potentially harmful electromagnetic interference and a standard that addresses immunity to interference. Acceptable standards include:

- [IEC 62920](#) (emissions and immunity)
- [CISPR 32](#) or [CISPR 22](#) (emissions)
- [IEC 61000-6-3](#) (emissions)
- [CISPR 35](#) or [CISPR 24](#) (immunity)
- [IEC 61000-6-1](#) (immunity)
- Appropriate alternate standard

Note: CISPR 22 has been withdrawn and replaced with CISPR 32, but many countries have not yet adopted this change. CISPR 35 is planned to replace CISPR 24 but both are currently considered valid.

Alternatively, the inverter or charge controller may meet one of the following national or regional electromagnetic compatibility standards or regulations:

- United States Federal Communications Commission (FCC) regulations ([Title 47 of the US Code of Federal Regulations, Part 15](#))
- [Industry Canada ICES-003](#)
- [The European Commission EMC Directive](#)
- Appropriate alternate standard or national regulations

Combined units including a battery and charge controller in a single housing, as described in 6.5, may alternatively comply with [IEC 62040-2](#).

6.8.3 Recommendations for lamps and luminaires

Lamps and luminaires should meet the requirements of any of the following EMC standards or regulations:

- [CISPR 15](#)

- Any of the national or regional requirements listed in 6.8.1
- Appropriate alternate standard

6.8.4 Recommendations for ceiling fans

Ceiling fans should meet the requirements of any of the following EMC standards or regulations:

- [CISPR 14-1](#) and [CISPR 14-2](#)
- Any of the national or regional requirements listed in 6.8.1
- Appropriate alternate standard

7 Installation and safety

7.1 General

These installation guidelines and safety requirements of the off-grid solar electricity system represent best practices in many circumstances. They are not comprehensive but are intended to provide some of the necessary requirements and recommendations to ensure a safe, properly functioning electrical system. Designers and installers are expected to comply with available local or national building codes, referenced standards, and component installation instructions when designing and installing the system. Designers and installers may use other recognized standards not mentioned in this document that are appropriate to off-grid solar electricity systems described herein. British, French, Canadian, and American standards are typically used in the absence of other appropriate local or national standards.

The off-grid solar electricity system shall comply with the design requirements specified in [IEC 62548](#), [IEC 62124](#), [IEC 60364-7-712](#), and/or other referenced standard or local electrical codes. The following sections in this document contain information and standards references to highlight specific issues that are relevant to a particular subject area, but these are not intended to serve as comprehensive installation guidelines. The project implementer or general contractor shall refer to [IEC 62548](#), [IEC 60364-7-712](#), equipment manufacturer installation instructions, and/or other appropriate standards documents or local electrical codes when selecting, designing, and installing the PV system. The design and installation shall provide security measures against tampering, theft, or accidental contact by unauthorized persons, such as lockable enclosures, fencing, and security lighting, as appropriate.

Different system architectures will have different requirements for earthing, the interconnection of electrical components, and the use/placement of disconnects and electrical protection devices. Unless otherwise specified by a referenced standard or local electrical code, the installation should follow instructions provided by the component equipment manufacturer(s). Significant deviations from these instructions shall be noted in the installation commissioning checklist.

National/local building and electrical codes (local codes) or other relevant standards (alternate standard) may be used in lieu of IEC standards listed here if:

- The local code or alternate standard contains requirements that provide for a safe and properly functioning electrical system.

- The local code or alternate standard is well established and recognized as legitimate by the country of installation.
- The local code or alternate standard regulates the same technical elements as those found in the IEC standard that it replaces.

The use of an alternate standard or local code to replace a referenced IEC standard in this document is subject to approval by the facility owner and project developer.

7.2 Installer requirements

The installation of the off-grid solar electricity system shall be performed by a qualified technician. A qualified technician shall be licensed or otherwise carry accreditation to perform the work by the country or local jurisdiction where the system is installed. Installers should follow any relevant occupational health and safety guidelines for electrical/PV installation.

Though not a requirement, experience from prior projects suggests that involving local technicians in the installation may be beneficial for the long-term functionality of the system. Familiarizing those who may later be involved in servicing the system can help avoid mistreatment of the system.

7.3 PV array mounting

7.3.1 General

The provisions of one or more of the following shall apply to the mechanical mounting of the PV array:

- [IEC 62548:2016](#), 5.2 *Mechanical design*
- Appropriate alternate standard or local code

7.3.2 PV array mounting structures

All PV array support structures and module mounting configurations shall comply with applicable building codes, local regulations, and module manufacturer's mounting requirements to ensure a safe and stable structure. This shall include:

- All PV arrays and associated structures shall be capable of supporting anticipated structural loads, e.g. dead load, accumulated debris or snow loads, and wind loading for the region.
- All PV arrays shall have security fencing, theft-deterrent mounting hardware, and/or other means to guard against theft.
- PV modules mounted on a roof shall be permanently fixed to an appropriate mounting structure or rack. The roof surface shall be appropriate to support the array mounting system, including any mounting feet from racks and all rail and other fastener systems used by the panel mounts.
- For roof mounted systems, the roof shall be inspected prior to PV installation to confirm the roof surface has adequate structural integrity to support the proposed PV equipment loads. Hazardous materials (i.e. asbestos or other hazardous materials) shall be noted and

appropriate design mitigation shall be implemented to prevent exposure of people to hazardous materials.

- The roof-mounted array design shall be approved by an accredited engineer unless the combined weight of the PV array and mounting hardware is less than 100 kg. For arrays below 100 kg, the decision to seek approval from an engineer may be made by the project implementer and/or general contractor.
- The PV array structure shall be able to withstand extreme weather events such as tropical cyclones, wind storms, rain storms, etc., as appropriate to the region. The PV array mounting system and structural hardware shall be wind rated in accordance with relevant wind loading standards. The maximum wind speed that the PV array is expected to experience during its lifetime shall be reported. Wind speed data and/or structural design requirements can be referenced from local building codes, meteorological agencies, or other appropriate sources recognized as legitimate by the country of installation.
- In regions that have experienced wind speeds of 119 km/h or more, the PV array shall use single-module clamps to affix PV modules to the PV array frame. Dual-module clamps, where a single clamp affixes two adjacent PV modules to the array frame, shall not be used.
- All metal supports, brackets, screws, and other parts shall be of similar materials or stainless steel to minimize corrosion. Dissimilar metals (based on their galvanic ratings) shall be electrically separated by rubber or polymer materials. Where wood materials are used, they shall be suitable for long-term outdoor exposure.
- The PV array structure shall not trap water against the roof or wall or allow water to penetrate the roof or wall.

7.3.3 PV array orientation

Whenever possible, PV arrays should be oriented to optimize energy collection during the month with the lowest solar radiation. Fixed PV arrays are permanently mounted to a roof of a building or the ground and are not configured to allow seasonal adjustments of the tilt angle. Adjustable arrays can allow seasonal adjustment of the array tilt angle to increase the energy input. When specified, designs with adjustable arrays should include a schedule for making the seasonal adjustments. Tracking arrays automatically adjust the array tilt and azimuth to follow the sun's path. Tracking arrays involve added complexity that increases the possibility of mechanical failure, and may offer little or no cost benefit when compared to a fixed array. When specified, designs with tracking arrays shall include specifications of the programming, mechanism, and maintenance requirements for the tracking system.

7.4 Battery installations

7.4.1 General

The provisions of one or more of the following shall apply to batteries and battery arrays in the off-grid solar electricity system:

- [IEC 62485-1](#) and [IEC 62485-2](#)
- Appropriate alternate standard or local code

7.4.2 Enclosure or room

Safety considerations and hazards associated with the area or enclosure where batteries are installed include:

- Explosion due to a spark in the presence of hydrogen build up (flooded lead-acid batteries)
- Excessive currents caused by battery shorts
- Overheating and explosive ignition of lithium battery chemistries due to overcurrent, overvoltage, low or high temperature, or other abusive conditions as described by the battery manufacturer or other lithium battery safety information sources.
- Leakage of corrosive electrolytes (battery acid)

Batteries shall be appropriately installed to prevent hazardous conditions that can result in injury, fire, or explosion. Batteries shall be located in a dedicated room or, when appropriate, within a dedicated enclosure:

- All battery types shall be installed according to manufacturer instructions
- Access to the batteries shall be restricted to authorized personnel only
- No electrical equipment shall be installed above corrosive and/or gas emitting batteries
- For flooded lead-acid arrays, the battery enclosure or room shall have adequate ventilation to prevent the buildup of hazardous gases as defined below.
- All battery equipment should be readily accessible for maintenance.
- Batteries shall be raised off the ground (e.g. on a pallet) or otherwise installed in a way that minimizes risk of damage in case of flooding.
- Batteries should be installed with adequate spacing (e.g. 2 cm or more) between adjacent units to allow airflow and heat dissipation.
- The battery enclosure or room should be vermin proof.
- The battery room should be designed to avoid exposing the battery to extreme temperatures (see 5.3.2), for example by providing adequate ventilation and avoiding direct sun exposure. Air conditioning can be considered for larger systems.
- For lithium battery arrays, the battery room or enclosure shall be configured according to the battery manufacturer's requirements and recommendations.

7.4.3 Ventilation

For flooded lead-acid battery arrays, ventilation of battery enclosures or rooms areas shall be provided to prevent the buildup of hazardous gases. When possible, inlet vents should be positioned low near the floor of the enclosure and outlet vents should be positioned high near the top of the enclosure. Vents should be placed on opposite ends of the enclosure to allow cross ventilation.

The provisions of one or more of the following shall apply to ventilation of the battery enclosure or room for all batteries, excluding gas-tight sealed batteries:

- [IEC 62485-2:2010](#), 7 *Provisions against explosion hazards*
- Appropriate alternate standard, local code, or battery manufacturer instructions

For gas-tight sealed batteries, the battery manufacturer's ventilation instructions shall be followed.

7.5 Electrical cables and electrical connections

Each electrical cable in the off-grid solar electricity system shall be properly rated to handle the electric current and environmental conditions that the cable will experience in normal operation. Preexisting electrical cables and electrical connections shall be inspected prior to use to determine if they are appropriate for use in the new system. Any existing electrical infrastructure shall be assessed to determine if repair or replacement is necessary. Local or national electrical codes may be used to determine current-carrying capacities and insulation requirements for cables in the system.

The provisions of one or more of the following shall apply to all electrical cables and electrical connections in the off-grid solar electricity system:

- [IEC 62548:2016](#), 7.3.7 *Cables*
- [IEC 60364-7-712:2017](#), 712.52 *Wiring systems*
- [IEC 62852](#) (for PV module connectors)
- Appropriate alternate standard or local code

Cables used to connect different components in the system should meet the requirements of the equipment manufacturer(s) AND shall meet the following requirements:

- All exposed cables shall be mechanically supported with clips and appropriate strain relief hardware. Cables shall be arranged to prevent trip hazards and inadvertent stress (pulling) on cable connections and plugs.
- Cables insulation and jacket materials shall be appropriate for use in the specific application and their physical environment. Cables shall have appropriate temperature ratings and, when used outside or otherwise exposed to the elements, shall be rated for outdoor exposure including UV resistance.
- Cables shall be protected from damage by sharp edges.

In the design process the sizing of cables within the off-grid solar electricity system affects the voltage drop in those cables under load. This can be particularly significant in systems with low PV output voltage and high output currents from the PV array and the battery. Project implementers should consider these voltage drops during the design phase and choose cable sizes to keep voltage drops within the system, under load, to the following levels:

- The voltage drop between the PV array and the battery bank should never exceed 5 %
- The voltage drop between the battery bank and any DC loads should never exceed 5 %
- The voltage drop between the PV array and charge controller should never exceed 3 %
- The voltage drop between the PV array and inverter should never exceed 3 %

Ohm's Law and cable resistance (ohms per metre multiplied by total cable length) may be used to calculate voltage drops based on the maximum expected current.

7.6 Electrical disconnects

The provisions of one or more of the following shall apply to all electrical disconnectors, isolation, and switching in the off-grid solar electricity system:

- [IEC 62548:2016](#), 7.3.6 *Disconnectors and switch-disconnectors*
- [IEC 62548:2016](#), 7.4 *Location and installation requirements*
- [IEC 60364-7-712:2017](#), 712.536 *Isolation and switching*
- Appropriate alternate standard or local code

Unless otherwise specified by manufacturer instructions, referenced standard(s), or local electrical codes, the following requirements apply:

- Protective earthing conductors shall not have installed disconnects.
- PV arrays shall be provided with a suitable disconnect to interrupt all conductors of the PV array connected to system PCEs.
- Battery arrays shall be provided with a suitable disconnect to interrupt the electrical connection of the battery array to the system charge controller or other PCEs.

7.7 Earthing

The provisions of one or more of the following shall apply to all elements of the earthing configuration of the off-grid solar electricity system:

- [IEC 62548:2016](#), 7.4.2 *Earthing and bonding arrangements*
- [IEC 60364-7-712](#). Earthing requirements are found in the following sections:
 - [IEC 60364-7-712:2017](#), 712.31.101.1.1 *PV Installation architectures*
 - [IEC 60364-7-712:2017](#), 712.4 *Protection for safety*
 - [IEC 60364-7-712:2017](#), 712.5 *Selection and erection of electrical equipment*
 - [IEC 60364-7-712:2017](#), 712.54 *Earthing arrangements and protective conductors*
- Appropriate alternate standard or local code

The configuration of system earthing is dependent on the system design and PCE component selection. Some PV array designs and PCEs require functional earthing to operate properly while others do not. In addition, the electrical separation of the DC and AC sides in the electrical system will determine the configuration of earthing components. Installers should follow the earthing recommendations and requirements of the PV module and PCE manufacturers. Refer to [IEC 60364-7-712:2017](#), Annex A, for example wiring diagrams showing various earthing configurations.

All exposed conductive parts of the PV array and PCEs shall be equipotentially bonded to the main earthing terminal of the installation with a protective earthing conductor. Additional earthing electrodes may be used in the system provided they are equipotentially bonded to the main earthing terminal with an earthing conductor. Earthing electrode equipment and installation shall meet applicable local electrical code requirements.

7.8 Protection against electric shock

The provisions of one or more of the following shall apply to the protection against electric shock measures in the off-grid solar electricity system:

- [IEC 62548:2016](#), 6.2 *Protection against electrical shock*
- [IEC 60364-7-712:2017](#), 712.41 *Protection against electrical shock*
- [IEC 60364-4-41](#) *Low-voltage electrical installations - Part 4-41: Protection for safety - Protection against electrical shocks*
- Appropriate alternate standard or local code

[IEC 62548](#) and [IEC 60364-7-712](#) reference [IEC 60364-4-41](#) to define the protection against electric shock requirements for low voltage PV based systems. Each standard requires that systems shall use one or more of the following protection provisions on the direct current (DC) side of the system:

- Double or reinforced insulation
- Separated/safety extra-low voltage (SELV) or protected extra-low voltage (PELV)

The use of extra-low voltage systems (SELV or PELV) requires that the maximum open circuit voltage of the PV array ($U_{oc\ MAX}$) shall not exceed 60 V. Calculation of $U_{oc\ MAX}$ shall be performed according to one of the following:

- [IEC 62548:2016](#), 7.2 *PV array maximum voltage*
- [IEC 60364-7-712:2017](#), Annex B
- Using the formula

$$U_{oc\ MAX} = 1.2n \cdot U_{oc\ STC}$$

where

$U_{oc\ MAX}$	is the maximum open-circuit voltage of the PV array
n	is the number of series modules in the PV array
$U_{oc\ STC}$	is the open circuit PV module voltage at STC (from the manufacturer).

Note: In this formula, the symbol U_{oc} is used instead of V_{oc} to match the referenced IEC standards.

7.9 Protection against thermal effects

The provisions of one or more of the following shall apply to the protection against thermal effects measures in the off-grid solar electricity system:

- [IEC 62548:2016](#), 6.3 *Protection against thermal effects*
- [IEC 60364-7-712:2017](#), 712.42 *Protection against thermal effects*
- Appropriate alternate standard or local code

[IEC 62548](#) and [IEC 60364-7-712](#) both require protection from insulation faults within the system. The protection mechanisms will depend on the specific configuration of the PV array and PCEs

used in the system. Protection mechanisms can include insulation monitoring devices and/or residual current monitoring. This protection is often provided by the system inverter.

7.10 Protection against overvoltage

The provisions of one or more of the following shall apply to the protection against overvoltage measures in the off-grid solar electricity system:

- [IEC 62548:2016](#), 6.6.2 *Protection against overvoltage*
- [IEC 60364-7-712:2017](#), 712.44 *Protection against voltage disturbances and electromagnetic disturbances*
- Appropriate alternate standard or local code

7.11 Protection against overcurrent

The provisions of one or more of the following shall apply to the protection against overcurrent measures in the off-grid solar electricity system:

- [IEC 62548:2016](#), 6.5 *Protection against overcurrent*
- [IEC 60364-7-712:2017](#), 712.43 *Protection against overcurrent*
- Appropriate alternate standard or local code

All fuses and circuit breakers, including fuse holders and circuit breaker panels, shall be appropriate for use in the system. Fuses shall comply with the requirements in at least one of the following:

- [IEC 62548:2016](#), 7.3.5 *Fuses*
- [IEC 60364-7-712:2017](#), 712.533 *Devices for protection against overcurrent*
- Appropriate alternate standard or local code

Circuit breakers shall comply with the requirements in at least one of the following:

- [IEC 62548:2016](#), 7.3.4 *Circuit Breakers*
- [IEC 60364-7-712:2017](#), 712.533 *Devices for protection against overcurrent*
- Appropriate alternate standard or local code

8 Inspection, Testing and Commissioning

8.1 General

Once construction of the project has been completed, commissioning of the system shall be performed and documented by a qualified inspector. A qualified inspector shall be licensed or otherwise carry accreditation to perform the work by the country or local jurisdiction where the system is installed and shall be associated with either the project developer or a third party. The commissioning of the system includes confirming that the system was built to plan and inspecting the quality of the installation.

Inspection and commissioning of the off-grid solar electricity system shall be documented in a commissioning report. All sections of the commissioning report shall be accompanied by pictures documenting any physical evidence to support the report (e.g. equipment specs, component placement, wiring, etc.). The commissioning report shall be reviewed to determine compliance with the requirements of this document and/or additional requirements specified by the project developer. Non-compliance issues shall be corrected by the project implementer as directed by the project developer.

The project developer shall define who is responsible for reviewing the commissioning report. For example, the project developer could specify that the project implementer is responsible for reviewing the commissioning report and correcting any deviations from the requirements, but the project developer reserves the right to review the commissioning reports for a subset of projects to confirm that the commissioning was performed correctly and that any deviations were addressed.

Unless otherwise specified by the project developer, the commissioning report shall include the following:

- The built to plan information outlined in Section 8.2
- The construction inspection report outlined in Section 8.3
- A system connection diagram or wiring schematic of the installed off-grid electricity system that includes all electrical connections and electrical ratings of the following, as applicable: PV array, battery bank, charge controllers, inverters, all overcurrent devices and switches, and other electrical equipment
- An operation manual for the operator and/or user providing sufficient information to allow for the safe operation of the off-grid electrical system
- System and equipment warranty information
- A maintenance manual and suggested maintenance schedule
- Shutdown and isolation procedures for emergencies and maintenance
- Equipment manufacturer's documentation and handbooks for all equipment supplied
- Engineering certificates, building permits, and/or other documentation required by the design
- A declaration of compliance from the project implementer confirming that the installed off-grid electricity system conforms to the specifications of the full-design stage documentation (5.4 Table 5) provided by the project implementer. Deviations of the installed system from the full-stage design shall be noted by the project implementer and subject to approval by the project developer

8.2 Built to plan

This section of the commissioning report shall record the following:

- Project site name
- Project site address
- Project site coordinates (GPS coordinates)
- Name of person(s) commissioning the system

- Inspector's title and relevant license or accreditation
- Commissioning date
- Commissioning time
- Ambient temperature and current weather conditions

This section shall record and verify the following match the plans:

- Project site coordinates
- Number of PV modules in each array
- Number of PV modules in each string
- Tilt of each PV module array if ground or pole mounted (degrees from horizontal)
- Azimuth of each array if ground or pole mounted (where due south is 180°)
- Range of possible tilt and azimuth angles for each PV array if tracking or adjustable system
- Current tilt and azimuth angle of each PV array if tracking or adjustable system
- Manufacturer, model, rated P_{max} , V_{mp} , I_{mp} , V_{oc} , and I_{sc} of PV modules
- Number, manufacturer, and model of charge controllers, if not included within inverters
- Number, manufacturer, and model(s) of inverters
- Inverter specifications (maximum power, maximum DC voltage, MPP voltage range, minimum DC voltage, maximum input current, number of MPP trackers, AC nominal power, max current output, etc.)
- Number, manufacturer, and model of batteries
- Battery bank voltage, number of series and parallel battery strings in the battery bank
- Battery enclosure ventilation size
- Conductor size and type, and insulation type of all wires
- Conduit type and size
- Number of conductors in each conduit, including ground
- Disconnect locations, if applicable
- Disconnect signage, if applicable
- Earthing conductor location(s), size(s), depth(s)
- Bus bar rating(s)
- All fuse, circuit breaker, and switch disconnect voltage and amperage ratings
- Ground mount material type (e.g. stainless steel or galvanized)
- PV array anti-theft provisions (fencing, mounting hardware)
- Warning label location(s)
- Manufacturer and model of any additional installed equipment

8.3 Construction inspection

This section of the commissioning report shall verify values are as expected for the design and record the following:

- Measured V_{oc} of all PV strings
- Polarity of all PV strings
- Sufficiency of wire management (e.g. conductors do not touch the roof)
- Inverter or inverter/charger settings and set points, if applicable, e.g. battery charger settings based on battery manufacturer recommendations
- Charge controller set points, if applicable
- Battery bank voltage versus inverter voltage reading
- Assessment of roof and wall penetration waterproofing, if applicable

The commissioning report shall also confirm and record the following:

- System is free of earth faults (i.e. no non-earthed conductor has continuity with earth)
- No faults (short circuits) between independent conductors (e.g. positive and negative PV conductors)
- Load shedding, if present, is functional, and critical loads remain operational when non-critical loads are disabled
- Remote monitoring interface, if applicable, is functional
- Remote monitoring system is outputting the correct GPS coordinates or project location, if applicable
- PV modules, racking systems, and metallic conduit are bonded
- All other metal equipment is bonded
- Neutral return path is present, if applicable
- No galvanically dissimilar metals are in contact with each other
- Disconnects are functional
- All loads (lamps, fans, water pumps, etc.) are functional
- All outlets are functional
- DC outlets, if present, are significantly different from the AC outlets to prevent connecting incorrect appliances
- Load limiters, if present, are functional and operate at the correct current or power set point
- All live parts of system are adequately insulated.

This section of the commissioning report should include the results of the following (if conducted):

- Insulation resistance testing
- Thermal imaging pictures of PV modules

9 Operations and Maintenance Planning

The long-term performance of a system depends in part on the proper installation of good quality equipment, but it also relies substantially on on-going operations and maintenance (O&M) activities and associated budgets. To better ensure systems are maintained following installation, all contracts should include some method of incentivizing proper O&M. Two primary options include:

1. Include an O&M contract for 10 – 20 years as part of the initial contract (or as a separate accompanying contract). The O&M service could be offered by the same entity providing the installation, or by a separate entity subcontracted or partnering on the project. (If the O&M contract is with a separate entity, it is advisable to include terms in the installation contract regarding responsibility for early equipment failure due to poor quality equipment or poor installation.) Ideally, the O&M service should include provisions for replacement of any system components expected to need replacement within the 10 – 20 year system service life.

Payment of the O&M contract could be dependent on continued performance, as verified by a third party through data logging, remote monitoring, or routine site visits/surveys of system users. If possible, data logging or remote monitoring should be used to assess system performance; however, if data logging is not feasible, alternate methods of determining system performance could be employed including routine visits to the site to confirm function of the system, and/or phone surveys of system users. If data logging or remote monitoring is feasible, the recommended indicators are described in 10.2. If data are transferred via cellular networks, the cost of data charges should be accounted for in the O&M contract, and should be considered when determining the required reporting frequency.

2. The contract could be designed as a lease agreement or extended service contract to provide an agreed-upon level of electricity service in return for guaranteed payments. The payments could be designed to cover the capital costs of equipment and installation (or a percentage of these costs), along with the on-going O&M costs over the projected system life. Funding for replacement costs should also be considered, though these payments may need to be set aside in a shared savings or escrow account to ensure they are available for use when needed.

As in Option 1, a third party could verify that the operator is delivering the agreed electrical service as verified through data logging, remote monitoring, or routine site visits/surveys of system users, using the indicators described in 10.2.

The two options are listed in order of complexity in terms of developing the initial contract. However, the second option may be of particular interest because of its potential to help ensure long-term performance by using a payment structure that explicitly includes a revenue stream for O&M costs (including equipment replacement over time) and keeps entities engaged to provide O&M services over time.

In addition to including provisions for O&M in the initial contract, additional measures may be considered to help ensure long-term system health. These include:

- Training local technicians and/or including local technicians in the installation of the system to familiarize them with the system. With training, they may be a useful resource to help service the system as needed.

- Recommending that the main system components are field-serviceable and that key replaceable parts of the main components (such as PCBs for inverters) are purchased and stocked at the start of the project.
- Using locally available components and appliances where applicable to better ensure that spare parts and service expertise will be available.
- Ensuring users are trained on operation, basic maintenance, and system limitations. This training should ideally be substantive and involve periodic refresher trainings, as short, one-time trainings often provide only very limited benefits which are lost over time without reinforcement. Staff turnover should also be considered when planning user training.

An additional long-term issue that should be addressed in the initial contract is the treatment of e-waste when replacing components or decommissioning the system. The batteries generally constitute the most significant source of waste in the system. Lead-acid batteries can introduce lead, a toxic heavy metal, into the environment if they are not disposed of properly. Recycling infrastructure may be available in some markets, but is not ubiquitous, so responsibility for proper disposal needs to be clearly determined. Lithium batteries are less toxic alternatives, but should still be disposed of properly. Inverters, charge controllers and other system components also include electronics that should be recycled or disposed of properly. Though PV modules are expected to have the longest useful life of any component in the system, proper disposal of the PV modules should also be considered at the outset of the project. Management of e-waste in the off-grid sector is still evolving, additional resources related to e-waste management are available at: <https://globalleapawards.org/e-waste>.

10 Service Delivery & Monitoring

10.1 General

This section describes metrics of electricity service provision that can be used to assess service agreement compliance by the customer and operator if using a service delivery model. The section also provides information relating to the determination and reporting of the metrics.

While this section describes metrics that can be used to assess performance, the project developer will also need to specify terms and penalties in the service contract to clearly describe what happens if either the project implementer, contractor, or operator, or the facility are not in compliance with the agreed upon terms. For instance, if the performance metrics indicate that the operator is out of compliance, will a given payment be delayed, pro-rated, or forfeited? Similarly, if the performance metrics indicate that a facility is exceeding the peak allowable load, will the operator still be responsible for meeting all the requirements? Additionally, project developers will need to define clear lines of ownership and responsibilities for equipment, which are not covered explicitly by this document. In particular, the handling of equipment failures outside of the warranty period and replacement of major components should be considered during the contracting process.

Note, some of the metrics in 10.2 also include requirements that the energy consumption and peak load of the facility not exceed a maximum quantity stated in the service agreement. While meeting this requirement is ultimately the responsibility of the facility, it is critical that the project developer, project implementer, and operator take the difficulty of limiting communal energy consumption into consideration and ensure that facilities are adequately trained in the use of the

system and measures such as load limiters are installed where appropriate (see 5.3.6 and 11.4). Repeated facility misuse of the system should be addressed quickly so facility non-compliance does not become an excuse for operator non-compliance.

The metrics in 10.2 only assess whether the power system is functioning as expected, but do not assess performance at the level of individual appliances. As described in Section 11, this document does not provide specific requirements for systems supporting vaccine refrigerators, as these should be powered with a separate, stand-alone system that meets WHO requirements. However, if a vaccine refrigerator, or similar high-priority appliance were included as part of a system, real-time data collection (such as the temperature of the vaccine refrigerator) could be useful to include as a service metric to ensure these appliances are receiving power and functioning as expected.

These service metrics, along with any other system information of interest, should ideally be compiled in a single platform which consolidates and analyzes incoming data and allows interested parties to review and make decisions regarding payment and contract compliance.³

This section is critically important for systems that use monitoring methods to verify on-going performance. However, if the guidelines in this document are being used solely to ensure the initial installation of good quality systems in the absence of on-going monitoring, this section is not relevant.

10.2 Service Metrics

10.2.1 General

The following service metrics shall be used to assess service agreement compliance by the user and operator. Descriptions of these metrics, as well as information relating to their determination and reporting, are provided below. The contract or service agreement will need to specify all thresholds and tolerances needed to determine compliance.

10.2.2 Available Energy (E_a)

- a. **Metric Description:** The amount of energy used and stored that is available to power loads.
- b. **Determination Method:** E_a shall be determined using one of two approaches⁴:
 - i. **Direct:** Direct assessment of E_a shall be performed by summing the energy consumed (E_c) each day and the energy stored that is available to power loads (E_s) at the end of the day. Determination of E_s shall be performed by measuring the battery state of charge (SoC, see below) and applying adjustments for system losses so that the E_s reflects only energy available to power loads. Assumptions used in the estimation of system losses shall be documented.

³ Several inverter/charge controller manufacturers offer remote monitoring with consolidated dashboard interfaces for systems using their technology, while some of these can integrate data from other companies' technology as well. Additionally some third-party companies offer web-based services to consolidate data from one or more inverter/charge controller technologies.

⁴ For initial pilot testing of these service metrics, we recommend assessing this metric using both the direct and indirect methods to compare the results and verify that the indirect method can sufficiently assess compliance.

- ii. **Indirect:** An indirect assessment of E_a shall be performed by assessing the quantity of energy consumed (E_c) each day and whether the battery had reached the low voltage disconnect (LVD) at any point during the evaluation period.

Note: In either scenario, the maximum allowable value of E_c need not be a fixed quantity, but could vary, for example, according to the solar resource or on a monthly basis. The maximum allowable value of E_c should be clearly defined in the service agreement to ensure the customer is aware of their obligations and limitations.

- c. **Units:** kWh (direct); kWh & yes/no for LVD (indirect)
- d. **Evaluation Period:** 24 h (e.g. midnight to midnight)
- e. **Documentation & Reporting Requirements:** Documentation shall document the measurements and equipment used to determine components of E_a and assumptions used in the conversion between stored energy to energy available to power loads (direct).
- f. **Determination of Compliance (if applicable):**

Compliance is dependent on the method and on the value of E_{min} , which shall be stated in the service agreement and adjusted as described in 10.3.

- i. **Direct:** E_a shall be equal to or greater than E_{min} (operator in compliance)
- ii. **Indirect:** E_a is compliant if either:
 - a. the battery has not reached the LVD and E_c is greater than 0, or
 - b. the battery has reached the LVD and E_c is equal to or greater than E_{min} (operator in compliance)

For both the direct and indirect methods, E_c shall not exceed the service agreement maximum quantity (facility in compliance).

This metric could also be evaluated as a certain number of days per month or percentage of time over a specified time period (month, quarter, 6-month period) that the operator is in compliance if 100 % compliance is not expected.

10.2.3 Low Voltage Disconnect (LVD)

- a. **Metric Description:** Assessment of whether the battery discharge has been stopped to protect the battery (i.e., the battery has reached its LVD).
- b. **Determination Method:** The LVD will be determined by identifying periods when the battery voltage is at or below the LVD, as indicated by voltage measurements or “flags” provided by the remote monitoring system.
- c. **Unit:** minutes per day or voltage (V)
- d. **Evaluation Period:** 24 h (midnight to midnight)
- e. **Documentation & Reporting Requirements:** Criteria and system flags used to determine if the battery reached the LVD shall be provided. Flags or voltage should be logged at a frequency of at least 15 min intervals.
- f. **Determination of Compliance (if applicable):** Not applicable, used to assess 10.2.2 Available Energy (E_a). If voltage is logged, may be used to assess safe operation of battery to ensure LVD is within safe limits for the particular battery.

10.2.4 Solar System Functionality (T_f)

- a. **Metric Description:** The amount of time the system is available to power loads.
- b. **Determination Method:** The solar system functionality will be determined by identifying periods of system error, as indicated by “flags” provided by the remote monitoring system. Errors on both the PV (DC) side and the loads (AC) side of the system should be logged.
- c. **Unit:** minutes per day
- d. **Evaluation Period:** 24 h (midnight to midnight)
- e. **Documentation & Reporting Requirements:** Criteria and system flags used to determine if the system was offline shall be provided. Flags should be logged at a frequency of at least 15 min intervals.
- f. **Determination of Compliance (if applicable):** T_f shall be compliant if equal to or greater than the T_f specified in the service agreement (operator in compliance). T_f may be specified as a number of days where the T_f has exceeded a certain value, or the total number of minutes the system shall be functional during the reporting period.

10.2.5 Peak Load (PL)

- a. **Metric Description:** The maximum instantaneous power required by loads during an evaluation period.
- b. **Determination Method:** PL shall be determined by measuring the maximum power required over the evaluation period. PL should be determined using power measurements logged at a frequency of at least 15 min intervals, with a maximum recorded over each 24 hr period.
- c. **Unit:** watts
- d. **Evaluation Period:** 24 h (midnight to midnight)
- e. **Documentation & Reporting Requirements:** Reporting should include daily PL; documentation should include description of how PL was determined from data logged by the monitoring system.
- f. **Determination of Compliance (if applicable):** Peak load does not exceed agreed upon values (facility in compliance).

10.2.6 State of Charge (SoC)

- a. **Metric Description:** The available capacity remaining in a cell or battery, expressed as a percentage of the rated capacity. If the state of charge is 100 %, the battery is fully charged.
- b. **Determination Method:** SoC shall be determined by taking the maximum SoC recorded over the evaluation period. SoC should be determined from measurements logged at a frequency of at least 15 min intervals, with the minimum and maximum reported over each 24-h period.
- c. **Unit:** percentage
- d. **Evaluation Period:** 24 h (midnight to midnight)
- e. **Documentation & Reporting Requirements:** Documentation describing how SoC is determined shall be provided, including protocols for recalibration of the monitor used to track SoC.

- f. **Determination of Compliance (if applicable):** Not applicable, used to assess 10.2.2 Available Energy (E_a) and 10.2.8 Days Fully Charged (DFC), and may be used to determine 10.2.7 depth of discharge (DoD).

10.2.7 Depth of Discharge (DoD)

- a. **Metric Description:** The amount of ampere-hours removed from a fully charged cell or battery, expressed as a percentage of rated capacity. If the depth of discharge is 100 %, the battery is fully discharged.
- b. **Determination Method:** DFC shall be determined by recording the maximum DoD recorded over the evaluation period. This metric should be determined from measurements logged at a frequency of at least 15 min intervals.
- c. **Unit:** Percentage
- d. **Evaluation Period:** 24 h (midnight to midnight)
- e. **Documentation & Reporting Requirements:** Documentation describing how DoD is determined shall be provided, including protocols for recalibration of the monitor used to track DoD.
- f. **Determination of Compliance (if applicable):** DoD shall not exceed the DoD specified in the service agreement (operator in compliance). (See Section 5.2.9 for recommended DoD for various battery chemistries).

10.2.8 Days Fully Charged (DFC)

- a. **Metric Description:** The number of days over the evaluation period which the battery reached a full charge. (This metric is only applicable to lead-acid batteries, as their useful life will be reduced if not routinely fully charged).
- b. **Determination Method:** DFC shall be determined by summing the number of days that the battery has reached a state of charge of 100 %. This metric should be determined from measurements logged at a frequency of at least 15 min intervals.
- c. **Unit:** Percentage of days in the month
- d. **Evaluation Period:** 24 h (midnight to midnight)
- e. **Documentation & Reporting Requirements:** Documentation describing battery characteristics, including full charge, shall be provided.
- f. **Determination of Compliance (if applicable):** DFC will be compared to the minimum DFC specified in the service agreement (operator in compliance). E_c shall not exceed the service agreement maximum quantity (facility in compliance).

10.3 Minimum Allowable Performance (E_{min})

The minimum allowable performance (E_{min}) for a system is the agreed upon level of energy available to power loads and is used as a threshold for determining compliance with the key metric of Available Energy (E_a). This value should be used as the basis for original system design and be clearly stated in the service agreement.

In cases of non-compliance with E_a , if any party believes the cause for non-compliance is due primarily to the actual insolation or environmental conditions differing from the average historical values used for system design, procedures can be used to adjust the expected value of E_{min} to

account for the change in insolation or temperature. E_{min} shall be adjusted by using design software with the actual system specifications as inputs, along with real-time insolation and weather data taken on site or from satellite-based datasets, to estimate the amount of energy the system should produce given the new insolation or temperature. The design software and input values used for this assessment shall be agreed upon by all parties.

To complete this analysis, recent time-series solar data will be required. One option to attain this data is for systems to include pyranometers on site to monitor actual insolation at the site. However, these pyranometers would also require routine maintenance and calibration, and data could not be adjusted for issues that routine O&M should manage, such as keeping the pyranometer clean and ensuring that surrounding trees are not shading the site. Another option is to use data from local meteorological stations. However, in many regions, these sites are limited, calibration of equipment is not guaranteed, and real-time or recent data can be expensive. The third and most viable option is to use satellite data. Two organizations were identified that offer near real-time solar insolation data based on satellite observations for a fee: SolarGIS (<https://solargis.com/>) and Copernicus Atmosphere Monitoring Service (CAMS, <http://www.soda-pro.com/>). These sites use ground observations to calibrate the satellite measurements; SolarGIS claims an accuracy of +/- 8 % GHI and +/- 12 % DNI between the satellite-modeled data and the actual measured data on the ground. CAMS claims a bias of only 1.7 %, but this comparatively better accuracy may be attributed to the fact that CAMS has fewer reference sites in equatorial regions, which are considered more difficult to accurately model. The pricing for these services depends on the number of sites and the number of requests, with the option of annual subscriptions to receive data for specific sites, and ranges from several hundred to several thousand dollars. Due to the cost of real-time data, it is recommended that this calculation is only conducted in the case of a plausible dispute.

10.4 Missing and Invalid Data

It is important to address missing and invalid data when calculating service metrics. Treatment of missing or lost data may be required if, for example, the monitoring system loses power temporarily, causing gaps in the data record. Procedures for notifying monitoring system failures shall be clearly identified in the service agreement. If data were missing or lost during a reporting period, these time periods shall be clearly identified, and the specific treatments used to address them provided and justified. The selected method of treatment for missing or invalid data will vary depending on the parameter and quantity of lost data. Missing or invalid data may be treated in one of the following ways (adapted from [IEC 61724-1](#)):

1. The invalid or missing data may be replaced by values estimated from the valid data recorded before and/or after the invalid or missing data
2. The invalid or missing data may be replaced with an average value for the analyzed interval
3. The data may be treated in a manner specified in a valid contract, performance guarantee document, or other specification covering the installation
4. The analyzed interval may be treated as missing or invalid

10.5 Accessing Data from the Remote Monitoring System

Data for calculating service metrics should be transferred wirelessly over internet or cellular networks. If for any reason wireless methods become unavailable, a record of the same data shall be available on a local storage device, which can be manually downloaded and processed

to generate the necessary service metrics. If the locally stored data are different from what is transferred over the wireless system, procedures for calculating the service metrics from the locally stored data shall be provided. The device used to store data locally shall have no less than 6 months of available storage before overwriting. This locally stored data should also be able to be automatically transferred wirelessly if/when the remote connection is restored.

Transfer of data via a cellular network will require on-going data charges that can be sizeable depending on the amount and frequency of data required. While more frequent data will provide a better picture of the function of a system, for many of the metrics above, a single maximum or minimum measurement each day may be sufficient for determining compliance. The operator, in consultation with all other parties will need to determine the correct balance between receiving near real-time data (i.e., every 1 – 15 minutes) and receiving small snapshots of system performance a few times a day.

11 Minimum energy service guidelines

11.1 General

This section provides guidance regarding the lights and appliances (i.e. loads) needed to meet a facility's basic energy service needs. This information is intended as guidance for use during the early stages of system design and planning; individual facilities will likely have specific needs that add to or differ from the list of recommended loads provided in this clause. The tables in this section provide example loads for three types of facilities: primary health clinics (PHC), comprehensive health centres (CHC), and schools. Additional information on select loads is provided after the tables.

The nomenclature for the types of health clinics is based on the public health system in Nigeria, but the recommendations can be transferred to similar facilities in other countries.

Primary health clinics (PHC) are often the first point of contact with the formal health system and serve a population of up to approximately 5000 people. A PHC is typically staffed with personnel trained as midwives and community health workers and offers services including vaccinations and treatment of common diseases (TB, HIV, malaria), nutrition counseling, and maternal and child health care. PHC are analogous to Centre de Santé Intégré (CSI) Type I in Niger and health centers in Ghana.

Comprehensive health centres (CHC) offer a wider range of services and serve a broader population up to approximately 20,000. They are often staffed with at least one doctor or medical officer. CHC are loosely analogous to CSI Type II in Niger and poly clinics in Ghana. Though a CHC is often equipped to offer additional laboratory services and to handle more complicated issues than a PHC, many severe and complex cases will still be referred to secondary or tertiary care facilities, such as hospitals.

In some countries, there are even more basic entry points for health care, referred to in various countries as health posts, health clinics, case de santé, or dispensaries. These sites are not addressed by the tables in this section as their needs are likely best met with a small DC solar home system or similar portable solar power unit, such as those distributed by We Care Solar (<https://wecaresolar.org/>).

Further, it is important to note that the services and level of care offered is not always reflected in the name of the facility. In fieldwork in Nigeria, there were PHCs that offered services equivalent to most CHCs. Again, it is essential to conduct a load assessment at each clinic prior to finalizing a solar system design.

All recommendations and values are based on a combination of field research at over 60 health clinics and schools in Nigeria and Niger in 2017 and 2018; consultation with representatives of the United Nations Foundation (UNF), the ECOWAS Center for Renewable Energy and Energy Efficiency (ECREEE), and the Clinton Health Access Initiative (CHAI), and other literature sources, including:

- World Health Organization (WHO). (2014). Access to modern energy services for health facilities in resource-constrained settings: a review of status, significance, challenges and measurement.

- World Health Organization (WHO). (2016). Interagency list of priority medical devices for essential interventions for reproductive, maternal, newborn and child health.
- National Primary Healthcare Development Agency (NPHCDA). (2015). Minimum Requirement of Health Centers in Nigeria
- South African National Standard. (2016). Photovoltaic systems for use in individual homes, schools and clinics – Part 1: Standardized requirements applicable to off-grid individual homes, schools, and clinics, SANS 959-1.
- Note, the recommendations in Table 10 and Table 11 do not consider the potential need for additional medical equipment in response to the COVID-19 outbreak. Information regarding the energy needs for COVID-19 response efforts is available from several organizations; the Sustainable Energy for All (SE4All) website is compiling a useful list of resources here: <https://www.seforall.org/interventions/energy-and-health/covid-19-response-powering-health-facilities> . To date, most COVID response efforts have focused on larger hospitals in urban areas, though the resources may provide guidance if support for rural areas becomes feasible.

Prior to finalizing a design for a facility, project developer and/or project implementer should meet with all relevant government agencies (including, but not limited to the Ministry of Health or Education or equivalent, as appropriate for the system in question), facility staff, and other end users to complete a load assessment in which the appliances, number of appliances and hours of use of each appliance are discussed. These values can be used to calculate the power and energy needs for the facility and estimate the system size. Typically, the initial system sizing will be conducted by the project developer in order to specify the daily energy requirement and load profile for the design, regardless of which entity is responsible for the detailed system design. Best practice would include an audit of each facility, including:

- an assessment of existing and planned appliances and energy systems,
- determination of whether the facility meets country health service standards (in terms of equipment, staffing, and operational hours),
- evaluation of the likelihood that the facility will be upgraded in the future (in terms of services, equipment, staffing, hours, buildings, electricity access)⁵

If the resulting system size is greater than the budget for the system, the project developer or project implementer should work with the facility staff or government agency to determine where adjustments can be made to the number of appliances and hours of use to reduce the overall system cost but still provide adequate services to the facility.

Note: The system budget should consider the life cycle cost of the system, including the capital expenditure, and operations and maintenance costs, including replacement costs. Depending on the method of financing the system, the initial capital expenditure could be spread over multiple years to reduce the upfront cost of the system.

This process can be used to educate end users about the systems and set expectations with respect to the system's power and energy limitations.

Energy efficiency should be considered across all stages of design, including the replacement of existing lights, fans, and other appliances with more efficient alternatives that would allow for an overall lower system cost. Transitioning to energy efficient appliances can significantly reduce the overall size of the solar installation, but it is difficult to design for these energy efficient alternatives if they are not procured in conjunction with the solar system. Further, there are an increasing number of portable medical appliances that are designed to use low-voltage DC power. When designing the system, the possibility of providing DC outputs for DC loads or not

⁵ As discussed in 6.1.5, it may be appropriate to include an upgrade or growth factor. Often after reliable electricity is available, equipment is donated or acquired. However donations and purchases may be uncoordinated (and not always energy efficient) so accounting for some unplanned growth is advisable.

offering AC outputs at all could be considered.⁶ Appliances that the facility plans to acquire in the future could be procured along with the solar electric system. Procurement during this stage has several benefits: A) ensures that the system is sized appropriately for the new appliances, and B) improves the likelihood that energy efficient appliances are purchased. In particular, the health sector is beginning to show interest in the development of energy efficient appliances, especially for resource-constrained settings. If appliances cannot be purchased in conjunction with the system, an alternative method of ensuring that large loads are not used with the system is to install load limiters that use either hardware or software to restrict the current available on certain circuits or outlets. Additionally, during the design stage and after installation, the project implementer should provide an estimate of the maximum power or number of additional appliances that can be connected to the system to properly set user expectations and enable smart purchasing decisions.

High energy demand appliances will often increase both system size and cost significantly. The project developer or project implementer may decide to exclude these appliances from the system. Such appliances include, for example, autoclaves, air conditioners, and resistive heaters. In some cases, facilities may already possess such equipment (though the equipment may never have been used) and they will need to either agree to no longer use the equipment or to power the equipment from a power source other than the solar system.

When conducting a load assessment to determine the energy requirements of a facility, the power of each appliance, in watts (W), is multiplied by its expected daily hours of use. The daily energy requirement is expressed in watt hours (Wh) or kilowatt hours (kWh). Certain appliances, like refrigerators, do not draw a constant power, but instead turn on for a period, and then off for a period. For these appliances, the duty cycle, or percentage of time that the appliance actually draws power, should be multiplied by the power and expected hours of use to determine the daily energy requirement. Other devices, such as computers and wireless routers also cycle between high and low power modes, and the average power is typically used when estimating the energy requirements of these appliances. Note that the rated or nameplate power of an appliance is often the maximum power the appliance may require, which is typically higher than the average power.

To assist with sizing the battery bank, charge controller and inverter, the maximum power at any one moment will also need to be calculated based on the total power of all the loads that could be on at one time. The most conservative approach is to assume that all loads may be on at the same instant; however, if it is unlikely that all loads will be used at the same time, either a careful accounting or statistical model can be used to estimate the total power that should be used for the design. Some loads, especially loads with motors, draw a higher current at start-up. This is known as a surge current, and should be accounted for when choosing an appropriately sized inverter. For AC loads, power factors should also be considered for inverter sizing.

Table 9 provides estimates of power, duty cycle, surge factor, and power factor for common appliances in health clinics and schools.⁷ If measured values or reliable manufacturer specifications are available, these should be used in place of the example values in this table.

⁶ As discussed in 11.5, including a DC outlet may also be appropriate for emergency back-up of a vaccine refrigerator in case the stand-alone solar system for the refrigerator is compromised.

⁷ The surge current of an appliance is calculated by multiplying the surge factor by the current of the appliance. The apparent power (or maximum demand) in volt-amps (VA) is calculated by multiplying the power factor by the appliance power (in W). Surge factors indicated in the table as ">1.00" are suspected to be greater than 1, but an

Table 9. Estimated power, duty cycle, surge factor, and power factor of common appliances

Load	Duty cycle	Power (W)	Surge factor	Power factor
General Appliances				
Ceiling Fan	--	Efficient: <60 Inefficient, but common: 70 - 100	1.10	0.9
Computer (laptop)	--	60	1.00	0.7
General Purpose Refrigerator/ Freezer	39 %	130	2.2	0.65
USB Modem	--	2.5	1.00	0.7
Lighting (interior)	--	10 (bulb) 18 (tube) [assuming 90 lm/W LEDs]	1.00	0.7
Lighting (outdoor/security)	--	10	1.00	0.7
Mobile Phones	--	10 (smart phone)	1.00	0.7
Printer	--	100	1.00	0.7
Remote Monitoring	--	5	1.00	0.7
Television	--	100	1.00	0.7
Medical Appliances				
Procedure Light	--	50 (LED)	1.00	0.7
Centrifuge	--	110	>1.00	0.9
Electric Microscope	--	30	1.00	0.7
Fetal Heart Monitor	--	3	1.00	0.7
Oxygen Concentrator	--	200	>1.00	0.9
Portable Ultrasound	--	28	1.00	0.7
Suction Apparatus	--	185	>1.00	0.8

Table 10, Table 11, Table 12, and Table 13 provide example loads for three types of facilities: primary health clinics (PHC), comprehensive health centres (CHC), and schools. For each facility, a “basic” (Table 10 and Table 12) and “improved service” (Table 11 and Table 13) profile are provided – the basic profile represents a minimal system design with restricted hours for loads and basic equipment needs; the improved service profile considers longer operation hours and a broader set of appliances. If choosing a more minimal system design (similar to that presented in Table 10 and Table 12), it is strongly recommended that the system be designed in a way to allow for future expansion. The “basic” example systems offer very restricted hours of use and limited equipment beyond lights and fans. Additional discussion regarding specific loads follows the tables.

In some cases, an accelerated schedule for the delivery of energy service equipment will require a phased approach to the system installation. Other system designs may anticipate the growing energy needs of the facility over time or the use of the power system to provide additional local services, in which case additional power generating capacity will be desired and

estimate of the surge factor was not identified through literature or field research. The appliance current is not listed, but assumed to be the appliance power divided by the system voltage (typically 120 V or 230 V). Note that the power values are given for AC appliances; the power required for equivalent DC appliances may differ.

grid interactivity features may be needed. These needs should be addressed in the initial project design and procurement stages to avoid equipment conflicts during expansion. Project developers may consider adding system expansion planning requirements to accommodate future energy service growth beyond the immediate needs of the client facilities. See the discussion in 5.2.2 for additional guidance.

Table 10. Example Health Facility (Basic) -- Primary health care facility and comprehensive health care facility (CHC)

This basic profile represents a minimal system design with restricted hours for loads and basic equipment needs

Load	Number of Units: PHC	Number of Units: CHC	Hours of Use (h)
General Appliances			
Ceiling Fan	If appropriate for the climate and culture, include at least one 50" - 60" (1270-1530 mm) ceiling fan per 33 m ² of room area or circulate at least 230 CMM per 100 m ³ of room volume Include staff housing. Exclude certain rooms - toilet, kitchen, laboratory, hallway, entry, storage	Same as PHC	most rooms: 4 lab: 2 rooms with beds: 8
Computer (laptop)	--	1	4
General Purpose Refrigerator/ Freezer	--	1	24
USB Modem	--	1	4
Lighting (interior)	Include lighting based on size of rooms, including staff housing, at a ratio of 162 lumens/m ² For security posts, ensure at least 1 light can be on for 10 h, but this could be included as 2 lights for 5 h each, etc., depending on the layout of the site.	Same as PHC	most rooms: 4 bathrooms/ storage: 1
Lighting (outdoor/security)	4 per building (1 per side)	Same as PHC	10
Mobile Phones	1 charge/day per staff member	Same as PHC	1
Remote Monitoring	1	1	24
Medical Appliances			
Procedure Light	1	2	2
Centrifuge	--	1	2
Electric Microscope	--	1	2
Fetal Heart Monitor	1	1	2
Oxygen Concentrator	--	1	4
Portable Ultrasound	1	1	1
Suction Apparatus	--	1	5

Table 11. Example Health Facility (Improved) -- Primary health care facility and comprehensive health care facility (CHC)

This improved service profile considers longer operation hours and a broader set of appliances than that suggested in the basic table

Load	Number of Units: PHC	Number of Units: CHC	Daily Hours of Use (h)
General Appliances			
Ceiling Fan	Same as "Basic" system	Same as PHC	most rooms: 6 rooms with beds: 12
Computer (laptop)	1	1	6
General Purpose Refrigerator/ Freezer	1	1	24
USB Modem	1	1	6
Lighting (interior)	Same as "Basic" system	Same as PHC	most rooms: 6 bathrooms/ storage: 2
Lighting (outdoor/security)	4 per building (1 per side)	Same as PHC	10
Mobile Phones	1 charge/day per staff member	Same as PHC	1
Remote Monitoring	1	1	24
Television	1 per staff bedroom	Same as PHC	4
Medical Appliances			
Procedure Light	1	2	4
Centrifuge	--	1	2
Electric Microscope	--	1	2
Fetal Heart Monitor	1	1	2
Oxygen Concentrator	1	1	4
Portable Ultrasound	1	1	1
Suction Machine	--	1	5

Table 12. Example School Facility (Basic) – Primarily intended to enable provision of night classes
This basic profile represents a minimal system design with restricted hours for loads and basic equipment needs

Load	Number of Units	Daily Hours of Use (h)
Ceiling Fan	If appropriate for the climate and culture, for 3 rooms, include at least one 50" - 60" (1270-1530 mm) ceiling fan per 33 m ² of room area or circulate at least 230 CMM per 100 m ³ of room volume Exclude: toilet, kitchen, laboratory, hallway, entry, storage	4
Lighting (interior)	Only include lighting for 3 classrooms and/or offices in school, based on size of rooms at a ratio of 162 lumens/m ²	most rooms: 4 bathrooms/ storage: 1
Lighting (outdoor/security)	4 per building (1 per side)	10
Mobile Phones	1 charge/day per staff member	1
Remote Monitoring	1	24

Table 13. Example School Facility (Improved) – electrified for both day and night use
This improved service profile considers longer operation hours and a broader set of appliances than that suggested in the basic table

Load	Number of Units	Daily Hours of Use (h)
Ceiling Fan	Same as "Basic" system, but include for all classrooms, offices, and staff housing (except toilet, kitchen, laboratory, hallway, entry, storage)	most rooms: 6 rooms with beds: 12
Computer (laptop)	1	6
USB Modem	1	6
Lighting (interior)	Same as "Basic" system, but include for all classrooms, offices, and staff housing	most rooms: 6 h bathrooms/ storage: 2 h
Lighting (outdoor/security)	4 per building (1 per side)	10
Mobile Phones	1 charge/day per staff member	1
Printer	1	2
Remote Monitoring	1	24
Television	1 per staff room	4
Laboratory Equipment	Consult with the school or ministry of education to determine if there is additional laboratory equipment that the school could likely acquire if provided with adequate electricity	--

11.2 Lighting

Lighting installations are typically included as part of the solar system procurement for off-grid facilities. Some health and school facilities could have multiple old, off-grid installations that included lighting, and some facilities are built to be “grid-ready” where AC lighting is already wired in the building even in the absence of a power source. Project implementers will need to decide whether to use the existing lighting and wiring as faulty wiring could compromise the quality and safety of the new installation. Additionally, as noted in 11.1, energy efficiency should be considered, which may require replacing existing high wattage incandescent or fluorescent bulbs with more efficient lighting.

The World Health Organization recommends a minimum illuminance of 162 lux (note: one lux is one lumen per square metre) for general lighting in health facilities (WHO, 2014).⁸ This value is a very low lighting requirement in comparison to lighting recommendations in the US or Europe, even for low-light rooms. However, 162 lux is higher than some minimum recommendations for off-grid lighting in low-income countries (Alstone, 2010; Johnstone, 2009, ESMAP, 2015). Further, the estimate of 162 lux is given for general lighting in health facilities; specialized rooms such as operating theatres require more light and often directional light, which could be provided through overhead and/or task lighting.

Additionally, in the original sources, the illuminance recommendation of 162 lux is intended to indicate the illuminance on a working surface.⁹ However, Table 10, Table 11, Table 12, and Table 13 suggest using this value to estimate the amount of light required based on the area of a room. This method likely underestimates the number of lights needed to provide the recommended illuminance on a working surface. However, this method can serve to enable project implementers to make an initial estimate of the required lighting, in the absence of higher national, state, or local codes.

The procedure lights listed in Table 10 and Table 11 are very bright task lamps that can be used as needed for medical procedures, including obstetrics. The 50 W rating for this lamp assumes an LED task lamp that can provide on the order of 20,000 lux at 100 cm distance. In addition to these lamps, health facilities could also make use of battery-powered headlamps, which can assist with deliveries, but these would only be included as part of the estimated load for a solar system if the batteries were rechargeable.

All power estimates in the table assume the use of LED lighting, with a minimum efficacy of 90 lm/W. LED technology is rapidly evolving, and more efficacious bulbs are already on the market, so this value could be updated (increased) according to align with technology trends and local availability of lighting products.

11.3 Circulation / Fans

Recommended ceiling fan characteristics are based on site assessments of existing facilities in Nigeria and Niger. This research indicated that many facilities included at least one ceiling fan

⁸ In Annex 5 of “Access to modern energy services for health facilities in resource-constrained settings,” the authors state that this illuminance rating is based on is based on an Indian hospital building code (United States Agency for International Development/India ECO-III, 2011).

⁹ The illuminance on a working surface refers to the amount of light present on a surface, such as a desktop or page of a book.

with blade diameter of 50 – 60 in (1270 – 1530 mm), that was rated to circulate 230 – 285 cubic metres per minute (CMM) for every 33 m² of floor area (or 100 m³ of room volume). This recommendation also aligns with the guidance for minimum blade diameter based on room area that is provided in the Section 6.7.

These recommendations are for air circulation, which is largely intended for comfort, not for ventilation or as a full HVAC system. Air exchange and ventilation standards for hospitals exist to control the spread of disease, but there are no clear standards for circulation. Circulation expectations can vary significantly across different regions, cultures and climates. Additionally, measurement of air circulation is difficult to conduct and rated values are often inaccurate or non-existent, making it difficult to set a recommendation based on air circulation alone.

It should be noted that some practitioners and health professionals caution against the inclusion of ceiling fans in clinics for several reasons. For instance, fans may be excluded from a laboratory or ward to minimize the spread of airborne disease, or excluded from a neo-natal ward to ensure that babies are kept in a warm environment. From an energy practitioner's perspective, fans are often left on in empty rooms and can quickly deplete the batteries in an off-grid system.

Despite these concerns, many facilities and government agencies expect ceiling fans to be included in an electricity system to help maintain the comfort of all occupants. The decision on whether or not to include ceiling fans should be made in consultation with the relevant facility staff and government agency early in the design process. Fans can constitute a substantial fraction of the total load of a system so adding them into a system as an afterthought could require system redesign or lead to system failure.

If fans are included in a system, installing timers or occupancy sensors to limit their use may be appropriate. Another alternative may be to not provide ceiling fans with the system, but instead include outlets and size the PV system to provide some energy for standing fans that can be used as needed and are less likely to be left on indefinitely. If a decision is made to not include ceiling fans on the PV system, but facilities are built "grid-ready" and already have lights and fans installed, some practitioners recommend either removing the fans, wiring the system to exclude the existing fans, or replacing the fans with more efficient fans.

11.4 Power outlets, load limiters and staff quarters

Many public facilities, especially health clinics, can have priority loads that are considered essential to the function of the facility. Care should be taken in the design of systems to ensure that adequate energy is available for these priority loads. Some options include installing load limiters / miniature circuit breakers on selected outlets that supply non-priority loads using separate circuits for priority loads to enable either the power or energy to be limited for the non-priority loads, or putting outside security lighting on a dusk-to-dawn cycle with the use of timers or photocells. These considerations are especially important if loads like televisions or resistive heaters are likely to be used on a system that is not designed to support them. Additionally, the number and placement of outlets should be considered carefully to minimize the number of outlets that are accessible to the public.

Close attention should be paid to the staff housing when present in remote health and school facilities. Providing power for staff is important, particularly to ensure staff retention in an already highly rotational staffing model of remote facilities. However, in addition to ensuring electricity use for staff housing is included in the initial load estimate, practitioners also recommend

installing load limiters, timers, energy meters, or similar measures in staff housing to minimize the risk of staff using more energy than that allotted for their personal use. Training of staff on the limitations of the system, and providing similar written guidance that can be posted for incoming staff can also help alleviate over consumption.

11.5 Vaccine Refrigerators

Current WHO guidance requires vaccine refrigerators to have standalone, dedicated solar power systems. For this reason, vaccine refrigeration is not included as a recommended load in Table 10 and Table 11. The purpose of a stand-alone system is to ensure that the electricity available for the vaccine refrigerator is never compromised by competing loads.

If vaccine refrigerators are already present at a site, or if they are being procured at the same time as the solar system, a separate solar system can be designed to support the vaccine refrigerator. The design of the system will be dependent on the specific model of vaccine refrigerator, which could be a direct-drive DC unit (i.e. DC refrigerators that use ice packs for energy storage and so do not require batteries) or either an AC or DC unit powered from a battery. In either case, WHO specifications should be followed.¹⁰ The management of the vaccine cold chain is typically a responsibility of a country's Ministry of Health, often with support of the WHO, UNICEF, and Gavi Alliance. Therefore any and all decisions affecting vaccine refrigeration at a site require buy-in and approval from those managing the vaccine cold chain for that facility.

Having realized that vaccine refrigeration systems are often able to provide more energy than what is required for the refrigerator, the WHO has released new specifications for vaccine refrigeration systems designed for "energy harvesting." These systems are able to provide power to other small loads, such as mobile phones and battery-powered lanterns/headlamps, at the facility once it is clear the daily needs of the vaccine refrigerator will be met.¹¹

Although vaccine refrigerators should be powered by a standalone, dedicated solar system, project implementers should consider including an additional outlet as part of the main solar system to power the vaccine refrigerator if the refrigerator's dedicated solar system is compromised. The outlet should be compatible with refrigerator in terms of voltage, maximum current, current type (AC or DC), and plug type. Practitioners also recommend ensuring that the main solar system is designed with enough additional capacity to provide back-up for the vaccine refrigerator. Further, the facility staff should be made aware of the possibility of using the main system as a back-up, and advised as to how powering the vaccine refrigerator will impact the available energy for other uses.

11.6 Additional medical appliances to consider

The medical appliances listed in Table 10 and Table 11 were identified as essential appliances for health clinics. However, these lists are still very limited, and it would not be surprising to find sites that either have or plan to obtain other medical appliances, especially if the facility wants to

¹⁰ Current WHO specifications for solar power systems for vaccine refrigerators are available at: http://apps.who.int/immunization_standards/vaccine_quality/pqs_catalogue/catdocumentation.aspx?id_cat=17

¹¹ Current WHO specifications for energy harvesting systems are available at: http://apps.who.int/immunization_standards/vaccine_quality/pqs_catalogue/catdocumentation.aspx?id_cat=36

offer specialized laboratory services. Some additional appliances that may be encountered are shown in Table 14 along with an estimate of their power consumption and daily hours of use. As noted in 11.1, care should be taken when considering the inclusion of high energy demand appliances as they can increase both system size and cost significantly. These can be appliances that require a high power input, or appliances with a relatively low power input, but are required to be used 24-hours per day to be effective. The project developer or project implementer may decide to exclude these appliances from the system. The WHO provides extensive listings of additional medical appliances relevant to a broad range of health facilities operating in resource-constrained settings (WHO, 2014; WHO, 2016).

Table 14. Characteristics of other appliances used by health facilities

Appliance	Daily Hours of Use (h)	Power (W)
Anesthesia machines	2	500 – 1500
Blood chemistry analyser	4	88
CD4 machine (for HIV testing)	5	200
Electrophoresis genotype machine	3	190
Hematology analyser	4	400
Patient monitor for vital signs	24	300
Photoelectric colorimeter	4	11
Phototherapy device	24	80 (LED)
Pulse oximeter (battery operated)	2	50

11.7 Additional appliances to consider for schools

The appliances listed in Table 12 and Table 13 for schools were identified as common appliances to either offer evening/night classes or improve the learning environment to better meet basic educational needs. A wide variety of other loads may be appropriate to include or design for depending on the school. For instance, innovative programs have provided schools with banks of palmtops, laptops, or tablets for students to increase their computer literacy. Additionally, schools with electricity may be able to access lab equipment that they otherwise would not have been eligible for. Laptops, projectors, televisions, and DVD players could also be considered for certain classrooms. Project implementers should consult with the school or education ministry to determine if there is equipment that the school could likely acquire if provided with adequate electricity.

Beyond the classroom, school offices may want to make use of additional computers, printers, copiers and general office equipment. Further, if the school includes a cafeteria, refrigeration may be a priority. Additional lighting may need to be considered for boarding schools with staff and students living on site.

11.8 Water Pumping

An additional need for most public facilities is the provision of clean water. Depending on the hydrology of the site, a borehole with a solar water pump can be appropriate. The pump can be included as an additional load on the main solar system for a site or be powered from a stand-alone solar array. There are advantages and disadvantages to each arrangement, and the cost-benefit is likely to be site specific, being affected by, for example, the distance of the pump to the main solar array, the reliability of the main system, and the water demand of the site, which

would influence the choice of an AC or DC pump. Recommended estimates for water demand and pumping energy are covered in a separate document which is under production.

12 References

Note: Hyperlinks are provided to the most recent versions of referenced documents at the time of publication of this document. Undated references refer to the most recent version of the document, which may be newer than the hyperlinked version.

Africa Renewable Energy Access Program (AFREA). 2010. [Photovoltaics for community service facilities: Guidance for sustainability](#)

Alstone, P. A. Jacobson, and E. Mills. 2010. [Illumination sufficiency survey techniques: In-situ measurements of lighting system performance and a user preference survey for illuminance in an off-grid, African setting](#). Lumina Project Research Note #7

Beaudin M., H. Zareipour, A. Schellenberg, and W. Rosehart. 2015. *Energy storage for smart grids, Chapter 1 – Energy storage for mitigating the variability of renewable electricity sources*, pp. 6-8

Büngeler J., E. Cattaneo, B. Riegel, and D. Uwe Sauer. 2018. *Advantages in energy efficiency of flooded lead-acid batteries when using partial state of charge operation*. Journal of Power Sources, vol. 375, pp. 53-58

[CISPR 14-1: Electromagnetic compatibility – Requirements for household appliances, electric tools and similar apparatus – Part 1: Emission](#)

[CISPR 14-2: Electromagnetic compatibility – Requirements for household appliances, electric tools and similar apparatus – Part 2: Immunity – Product family standard](#)

[CISPR 15: Limits and methods of measurement of radio disturbance characteristics of electrical lighting and similar equipment](#)

[CISPR 22: Information technology equipment – Radio disturbance characteristics – Limits and methods of measurement](#)

[CISPR 24: Information technology equipment – Immunity characteristics – Limits and methods of measurement](#)

[CISPR 32: Electromagnetic compatibility of multimedia equipment – Emission requirements](#)

[CISPR 35: Electromagnetic compatibility of multimedia equipment – Immunity requirements](#)

Energy Sector Management Assistance Program (ESMAP). 2015. [Beyond connections: Energy access redefined](#). Technical report 008/15

European Commission. 2014. [Directive 2014/30/EU: Electromagnetic Compatibility \(EMC\) Directive](#)

European Commission. 2020. [Photovoltaic geographical information system](#)

Global Sustainable Energy Solutions. 2020. Off grid PV systems system design guidelines: Includes stand alone PV systems and hybrid systems comprising PV and fuel generators. Draft guidelines prepared for Ugandan Rural Electrification Agency and World Bank.

[IEC 60335-1](#): *Household and similar electrical appliances - Safety - Part 1: General requirements*

[IEC 60335-2-29](#): *Requirements for special installations or locations - Solar photovoltaic (PV) power supply systems*

[IEC 60364-4-41](#): *Low voltage electrical installations - Part 4-41: Protection for safety - Protection against electric shock*

[IEC 60364-7-712](#): *Household and similar electrical appliances - Safety - Part 2-29: Particular requirements for battery chargers*

[IEC 60896-11](#): *Stationary lead-acid batteries – Part 11: Vented types – General requirements and methods of tests*

[IEC 60896-22](#): *Stationary lead-acid batteries – Part 22: Valve regulated types – Requirements*

[IEC 60969](#) (all parts): *Self-ballasted compact fluorescent lamps for general lighting services - Performance requirements*

[IEC 61000-6-1](#): *Electromagnetic compatibility (EMC) – Part 6-1: Generic standards - Immunity standard for residential, commercial and light-industrial environments*

[IEC 61000-6-3](#): *Electromagnetic compatibility (EMC) – Part 6-3: Generic standards - Emission standard for residential, commercial and light-industrial environments*

[IEC 61056-1](#): *General purpose lead-acid batteries (valve-regulated types) – Part 1: General requirements, functional characteristics – Methods of test*

[IEC 61215](#) (all parts): *Terrestrial photovoltaic (PV) modules - Design qualification and type approval*

[IEC 61427-1](#): *Secondary cells and batteries for renewable energy storage - General requirements and methods of test - Part 1: Photovoltaic off-grid application*

[IEC 61724-1](#): *Photovoltaic system performance – Part 1: Monitoring*

[IEC 61730](#) (all parts): *Photovoltaic (PV) module safety qualification*

[IEC TS 61836](#): *Solar photovoltaic energy systems – Terms, definitions and symbols*

[IEC 62040-1](#): *Uninterruptible power systems (UPS) - Part 1: Safety requirements*

[IEC 62040-2](#): *Uninterruptible power systems (UPS) – Part 2: Electromagnetic compatibility (EMC) requirements*

[IEC 62040-3](#): *Uninterruptible power systems (UPS) - Part 3: Method of specifying the performance and test requirements*

[IEC 62040-5-3](#): *Uninterruptible power systems (UPS) - Part 5-3: DC output UPS - Performance and test requirements*

[IEC 62109-1](#): *Safety of power converters for use in photovoltaic power systems - Part 1: General requirements*

[IEC 62109-2](#): *Safety of power converters for use in photovoltaic power systems - Part 2: Particular requirements for inverters*

[IEC 62124](#): *Photovoltaic (PV) stand alone systems - Design verification*

[IEC 62133-2](#): *Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for portable sealed secondary lithium cells, and for batteries made from them, for use in portable applications - Part 2: Lithium systems*

[IEC TS 62257-3](#): *Recommendation for renewable energy and hybrid systems for rural electrification – Part 3: Project development and management*

[IEC TS 62257-12-1](#): *Recommendations for renewable energy and hybrid systems for rural electrification - Part 12-1: Selection of lamps and lighting appliances for off-grid electricity systems*

[IEC 62281](#): *Safety of primary and secondary lithium cells and batteries during transport*

[IEC 62485-1](#): *Safety requirements for secondary batteries and battery installations – Part 1: General safety information*

[IEC 62485-2:2010](#): *Safety requirements for secondary batteries and battery installations - Part 2: Stationary batteries*

[IEC 62548:2016](#): *Photovoltaic (PV) arrays - Design requirements*

[IEC 62612](#): *Self-ballasted LED lamps for general lighting services with supply voltages > 50 V - Performance requirements*

[IEC 62619](#): *Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for secondary lithium cells and batteries, for use in industrial applications*

[IEC 62852](#): *Connectors for DC-application in photovoltaic systems - Safety requirements and tests*

[IEC 62722](#): *Luminaire performance - Part 1: General requirements*

[IEC 62920](#): *Photovoltaic power generating systems – EMC requirements and test methods for power conversion equipment*

Industry Canada. 2019. ICES-003: *Information technology equipment (including digital apparatus) – Limits and methods of measurement*

[ISO/IEC 17025](#): *General requirements for the competence of testing and calibration laboratories*

Johnstone, P., A. Jacobson, E. Mills, and K. Radecky. 2009. [Observed minimum illuminance threshold for night market vendors in Kenya who use LED lamps](#). Lumina Project Research Note #3

Jordan, D. and S. Kurtz. 2012. *Photovoltaic degradation rates — An analytical review*. National Renewal Energy Laboratory (NREL)

May, G., A. Davidson and B. Monahov. 2018. *Lead batteries for utility energy storage: A review*. Journal of Energy Storage, vol.15, pp 145-157

NASA. 2020. [POWER database](#)

National Primary Healthcare Development Agency (NPHCDA). (2015). *Minimum requirement of health centers in Nigeria*

Solar Energy International (SEI). 2013. *Solar Electric Handbook: Photovoltaic fundamentals and applications*. Second Edition

SolarGIS. 2020. [Download solar resource maps and GIS data for 200+ countries](#)

South African National Standard. 2016. *Photovoltaic systems for use in individual homes, schools and clinics – Part 1: Standardized requirements applicable to off-grid individual homes, schools, and clinics*, SANS 959-1

Sustainable Energy Industry Association of the Pacific Islands (SEIAPI). 2012. *Off-grid PV power systems design guidelines*

[UL 1741](#): *Standard for inverters, converters, controllers and interconnection system equipment for use with distributed energy resources*

[UL 1973](#): *Standard for batteries for use in stationary, vehicle auxiliary power and light electric rail (LER) applications*

[UL 1989](#): *Standard for standby batteries*

[UL 2054](#): *Standard for household and commercial batteries*

[ANSI/CAN/UL 9540](#): *ANSI/CAN/UL Standard for energy storage systems and equipment*

[UL 61215](#) (all parts): *Terrestrial photovoltaic (PV) modules - Design qualification and type approval*

[UL 61730](#) (all parts): *Standard for photovoltaic (PV) module safety qualification*

[UL 62133-2](#): *Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications*

[UN 38.3](#): *United Nations recommendations on the transport of dangerous goods, Manual of tests and criteria, sub-section 38.3: Lithium metal and lithium ion batteries*

United States Code of Federal Regulations. 2020. [47 CFR 15](#): *Radio frequency devices*

University of Southampton. 2011. *Performance quality safety (PQS) solar autonomy calculation method*

World Bank. 2014. *Deployment of renewable energy technologies (RETs) to enhance teacher training effectiveness in Bihar*. Draft Final Report

World Health Organization (WHO). 2014. [Access to modern energy services for health facilities in resource-constrained settings: a review of status, significance, challenges and measurement](#)

World Health Organization (WHO). 2016. [Interagency list of priority medical devices for essential interventions for reproductive, maternal, newborn and child health](#)

World Health Organization (WHO). 2018. [Performance quality safety specification: Solar power system for vaccine refrigerator or combined vaccine refrigerator and water-pack freezer](#)