USAID
FROM THE AMERICAN PEOPLE

POWERING HEALTH: PHOTOVOLTAIC (PV) SYSTEMS

PV systems generate electricity from sunlight collected by solar panels. This energy can be used directly or stored in batteries.

USAID

POWERING HEALTH

This document is provided as part of USAID's Powering Health toolkit. Health-care facilities require electricity to maintain perishable supplies and power life-saving technologies. Energy is essential for preventing child and maternal deaths, controlling the HIV/AIDS epidemic, and combating infectious diseases and pandemics.

Reliable electricity can mean life or death for patients in developing country health-care facilities. However, many of these facilities have little or no access to reliable electricity. USAID supports partner countries in understanding the energy needs of their health-care facilities over the long term. This challenge requires local capacity for careful planning, a commitment to maintenance, and dedicated funding.

USAID uses its experience at the nexus of the health and energy sectors to help international development practitioners and health-care administrators design programs that meet the energy needs of health-care facilities. By applying international best practices and lessons learned, stakeholders can help ensure that health-care facilities are able to power standard appliances, such as lights, life-saving equipment, blood and medicine refrigerators, ventilators, laboratory diagnostic tools, and technology that monitors patients' vital signs.

INTRODUCTION

Photovoltaic (PV) systems generate electricity from sunlight collected by solar panels. Energy collected in this manner can be used to supply power to electrical equipment, or it can be stored in batteries to provide backup power.

PV systems have been successfully deployed all over the world for decades in a variety of applications, including power for remote weather stations and telecommunications towers, residential installations, community micro-grids, and grid-scale power plants. Perhaps the greatest advantage of PV technology in meeting such a wide range of applications is scalability. PV systems can be designed to meet nearly any power requirements and can work in conjunction with diesel generators, the grid, battery banks, or any other power source to provide stable, continuous power. A competitive marketplace for photovoltaics and a diverse set of commercially available PV technologies provide consumers with a variety of options when considering system cost and performance.

A successful PV installation will provide power for more than 20 years with no fuel costs and little maintenance. When compared to diesel generation in particular, PV is a cost-competitive option, especially in the developing world where electricity and diesel prices are often high. Although PV technology is an appropriate choice for many applications in the developing world, high capital costs and poor installation and maintenance practices have been limiting factors in the overall deployment of photovoltaics. The following discussion of photovoltaic systems is meant to convey basic information on PV technology as well as best practices in the design and implementation of such systems, especially in the context of health facilities in the developing world.

THE ROLE OF SOLAR POWER IN HEALTH FACILITY ENERGY SYSTEMS

Solar power offers numerous benefits to health facilities of all types but especially to those with little or no access to grid electricity. Photovoltaics produce no pollutants, require no fuel, and need little maintenance. When economically viable, they are a good option for any health facility energy system. PV systems are of special importance to remote facilities that do not have access to grid power. In such locations, options for power generation are few—usually diesel or PV generation. Often the most economical off-grid solution is a hybrid diesel-PV energy system, which makes the most of either resource at the most appropriate time. Compared to a diesel-only scenario, a diesel-PV hybrid will likely save significant fuel costs over the life of the system. Therefore, PV systems help to ensure the long-term financial sustainability of health clinics by shielding them from fluctuations in fuel supply and cost.

PHOTOVOLTAIC MATERIALS

Photovoltaic materials are able to convert light directly into electricity. This is explained by the photovoltaic effect, which occurs when an electrical current is created in a material upon being exposed to light. Therefore, the type of material used in a PV panel plays a big role in determining the panel's efficiency. Several different types of photovoltaic materials are discussed below, including their relative maturity, efficiency, and cost.

MONOCRYSTALLINE SILICON

Monocrystalline silicon PV cells are the most efficient type of silicon PV cell. The term "monocrystalline" refers to the rigid and uniform arrangement of silicon molecules within the cell. Because the entire cell is formed from a single crystalline structure, electrons are able to flow through the material easily, leading to high efficiencies.

POLYCRYSTALLINE SILICON

Polycrystalline silicon PV cells are the most popular type of PV technology. Such cells are less efficient than monocrystalline cells, but they are also significantly less expensive, resulting in high levels of implementation. As the name suggests, a polycrystalline cell is formed from multiple silicon crystals, rather than a single crystal. Electrons cannot flow through multiple crystals as easily as they would a single crystal, thus the loss in efficiency. The process used to create a polycrystalline cell, however, is easier and less energy intensive than that used in monocrystalline cell production, lowering the cost of the cell.

GALLIUM ARSENIDE

Unlike silicon, gallium arsenide (GaAs) is a compound semiconductor, consisting of two separate materials that have been combined due to their theoretically high solar conversion efficiency. While many different materials can be similarly combined to create a solar cell, GaAs has proven to be the most popular and efficient. GaAs cells are expensive, however, so their use has been restricted to niche applications such as concentrating PV (CPV) installations and satellites.

AMORPHOUS SILICON

Amorphous silicon PV cells do not share the rigid structure of crystalline silicon but consist of a thin layer of silicon, typically coated on plastic or glass. This lack of structure at the molecular level hampers the flow of electrons, so the efficiency of amorphous silicon is less than that of crystalline silicon. Because the material is so thin, however, it can be layered with additional sheets of amorphous silicon or even crystalline silicon to achieve higher efficiencies.

UNITED SOLAR SYSTEMS CORP

CADMIUM TELLURIDE

Cadmium telluride is a thin film PV material that is less costly and more efficient than amorphous silicon.

COPPER INDIUM GALLIUM SELENIDE

Copper indium gallium selenide (CIGS) PV cells show great promise for thin-film technology. The process of producing a CIGS cell, however, is complex and expensive.

OTHER PV TECHNOLOGIES

There are several emerging PV technologies that require further development before becoming commercially viable. These materials show promise in overcoming many of the issues faced by current PV technology, such as cost, efficiency, and building integration:

- Organic photovoltaic, low-cost materials based on organic polymers.
- Dye-sensitized photovoltaic, based on light-absorbing pigments.
- Thermo-photovoltaic, which creates electricity from both light and heat.

PV TERMS

Described below are some important terms used when characterizing PV system performance or the local solar resource. This is not a comprehensive glossary of PV terms but rather a selection of some of the more confusing or practical terms that are used when discussing PV system design.

SOLAR RESOURCE TERMS

DIRECT BEAM RADIATION

Direct beam radiation is light that travels directly from the sun to a solar panel, rather than diffuse light, which is reflected from the sky or ground. Solar concentrator systems rely on direct beam radiation because diffuse light cannot be easily concentrated. For normal, non-concentrator PV systems, direct beam radiation is less important.

PEAK SUN HOURS

Related to solar insolation, this is the number of hours in a day that a given area would receive solar energy if solar irradiance were at a constant 1,000 watts per square meter (W/m_2), or one kilowatt per square meter (kW/m_2), rather than varying throughout the day. This is essentially a location's average solar insolation expressed in terms of hours of peak output. For example, if an area has a solar insolation of five kilowatt-hours per square meter per day ($kWh/m_2/day$), that is equivalent to five peak sun hours per day, because solar panel output is rated at one kW/m_2.

SOLAR INSOLATION

The amount of solar energy that reaches a given area over a given amount of time is commonly expressed as $kWh/m_2/day$. This is the most often cited type of solar resource data because it indicates the amount of useful solar energy available locally for collection through solar PV or solar thermal installations. Solar insolation maps are available for most regions of the world.

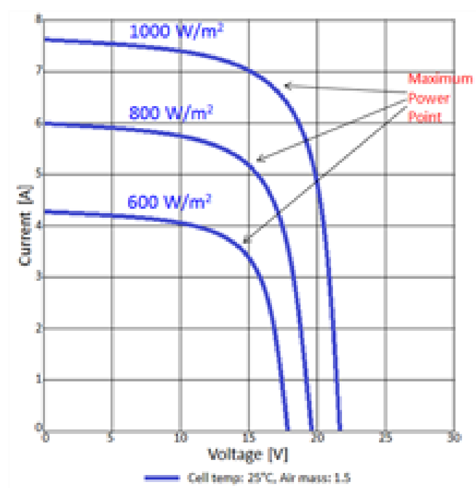
SOLAR IRRADIANCE

Similar to solar insolation, solar irradiance is the intensity at which solar energy reaches a given area and is commonly expressed as W/m_2. While not a direct measure of solar energy potential, local solar irradiance is useful when comparing PV system output to rated output, expressed in watt peak (Wp), which is based on 1,000 W/m_2 (see Standard Test Conditions).

PV PERFORMANCE TERMS

I-V CURVE

The I-V curve of a solar panel is used to show the relationship between the current (I) and voltage (V) of the panel's electrical output under a range of conditions. While a panel's rated performance is determined under Standard Test Conditions (STC), it is also important to understand how the panel will perform when solar irradiance or cell temperature deviate from the standard.



The figure to the right is an example of an I-V curve for a solar panel. In this example, the panel's performance is shown for different levels of irradiation, but I-V curves may also indicate performance at different cell temperatures. This information is useful when estimating a solar system's output under real-world conditions.

Each I-V curve has a Maximum Power Point (MPP), also shown in the example figure, which is the point on the curve where the panel's power output is at a maximum. In electricity, power is the product of current and voltage (power = current x voltage), so the MPP is always at the bend in the I-V curve where current and voltage are both relatively large.

PEAK-WATT (WP)

Peak-Watt is the rated output of a solar module or the amount of power it will generate under standard test conditions. This measure is used to describe the size of a PV system (*e.g.*, 10 kWp PV installation).

STANDARD TEST CONDITIONS (STC)

Standard test conditions are the laboratory conditions under which all PV modules are tested and rated. Specifically, STC are:

- An irradiance of 1,000 W/m2,
- An air mass coefficient of air mass index (AM1) .5 (this determines which parts of the light spectrum reach the panel), and
- A cell temperature of 25°C.

PV SYSTEM IMPLEMENTATION

A PV system represents a major investment in facility energy infrastructure. A successful PV system will last for more than 20 years, providing clean energy without need for fuel or intensive maintenance. In order to achieve that long-term success, a PV system requires upfront planning and investment. Quality equipment must be chosen for all system components. Components must be properly sized according to the system's design load and the local solar resource. Reputable professionals must be found to perform design and installation services. Proper maintenance funds must be put in place to ensure that the system receives necessary preventative and corrective care. The cost of such a system—its installation and the associated professional services—can be quite high. The initial price of a high-quality PV installation, however, is usually justified due to the system's long life span and low operation and maintenance costs. Ensuring a quality installation, then, will lead to a successful implementation. Described below are some important aspects of PV system implementation: common system components, system costs, system sizing, and system maintenance.

COMPONENTS

Photovoltaic systems are made up of much more than just PV solar panels. There are a whole range of other system components, referred to as the balance-of-system (BOS), which are required to properly use the PV panels. A number of components typical to PV systems are explained below. While this list covers most major PV system components, it is not exhaustive, and an installed system will likely involve other minor components. Furthermore, not every component listed is necessarily needed, depending on the type of PV system. The makeup of any PV system will depend on the type of load it powers, and, more importantly, whether it is a grid-connected or an off-grid system.

PV PANELS

Photovoltaic panels, also called PV modules, are the basic building block of any PV system. PV panels are unitary products, manufactured and distributed to consumers as a single piece of equipment. Photovoltaic panels are made up of many smaller PV cells, the most basic unit of PV material. Cells are electrically connected and bound together with a protective polymer to form a sheet of PV material. The connected cells are then sandwiched between a glass cover and a weather-proof backing and framed in aluminum to create a complete solar panel. The back of a panel will also include electrical connections used to wire the panel into a larger system. These connections may be housed in an electrical junction box but more commonly come in the form of multi-contact (MC) connectors, a special type of plug that provides a convenient and stable electrical connection as well as a locking mechanism to prevent theft. While the PV material is the most critical part of the solar panel, it makes up only a small portion of the panel's weight when compared to the glass and frame.

U.S. DEPARTMENT OF ENERGY

Crystalline silicon solar panels are typically rated at between 200 and 350 Wp. In order to produce more power, panels are connected to form an array. Using panels as a building block, a solar array can be sized to produce power for practically any application, from a 1 kW residential installation to a 100 MW grid-scale power plant. Correctly sizing a PV array involves a number of factors, including facility load, geographic location, panel size and rating, cost, space, and grid availability, among other considerations. PV system sizing is more thoroughly discussed in the sizing section.

MOUNTING STRUCTURE

USAID

Mounting structures come in a variety of forms and play several important roles in an overall PV system design. The most common and least expensive type of mounting structure is a stationary structure, where panels are given a fixed orientation optimized for exposure to the sun. Such systems can be mounted on the ground, a pole, or a roof. Sun-tracking mounting systems are also available; these systems are able to automatically rotate the solar array in order to follow the sun's daily path across the sky. Regardless of the type of mounting system, a properly designed structure will provide optimal orientation for the solar panels, space for airflow beneath the panels, structural strength in high winds, easy maintenance access, theft prevention, and aesthetic appeal. The most critical role of the mounting system is to correctly orient the solar panels toward the sun. In order to achieve the highest possible energy output from a solar array, the panels must be exposed to direct sunlight for as much time as possible. To reach this goal, two factors must be considered: orientation and tilt. Orientation refers to the cardinal direction that the system faces. In the northern hemisphere, panels should face true south; in the southern hemisphere, they should face true north. The system's tilt refers to the angle at which the panels are mounted; the optimal tilt angle depends on the geographical latitude of the installation site. Because a PV system is a capital-intensive installation and because the sun is a variable energy resource (it's not constantly shining), proper siting and orientation are absolutely essential to making an investment in PV cost effective.

A PV mounting structure must also provide sufficient airflow to the solar panels in order to keep them from overheating. The temperature of a solar cell can have a dramatic effect on its efficiency; crystalline silicon solar panels can drop 0.3–0.5 percent in efficiency for every 1°C the temperature rises over 25°C. Overheating will also reduce the useful lifetime of the PV material. Allowing for sufficient airflow around the solar panels is important in keeping them cool. This is especially true of roof-mounted installations, where the panels are typically mounted close to the surface of the roof.

Environmental factors must be considered; mounting and other outdoor hardware must be able to withstand extreme weather events, including high winds and corrosion in salty environments. Lightning strikes are also a concern but can be addressed by properly grounding the mounting structure.

Theft prevention techniques include the use of special fasteners or mounting connections that require specific tools to unlock. Fencing and security lighting may also be necessary for ground-mounted arrays.

Maintenance technicians must be able to safely access the underside of panels, and panel faces should be readily accessible for periodic cleaning. The importance of aesthetics will depend on the owner's preferences and the visibility of the installation, but anything lasting 30 years should have at least a uniform appearance.

INVERTERS

Inverters are a type of device able to convert the direct current (DC) electricity produced by PV panels into the alternating current (AC) electricity necessary to run most appliances, lights, and other equipment. Inverters are required for any PV system that will support AC loads; they are therefore an integral component in nearly all PV systems. Note that many inverters may also perform the functions of other system components, such as battery charge controllers or disconnect switches.

The most advanced inverters are designed to interconnect with a utility grid either drawing power from or injecting power back onto the powerline. When utility power goes down, these inverters can revert to an islanding mode where they continue to power the critical loads connected to the PV system. These inverters must comply with IEEE 1547 or UL 1741, standards that outline safe connection and disconnection with the grid.

COMBINER BOX

A combiner box is an electrical housing specifically designed to simplify the wiring of multiple PV panels. The combiner box is usually placed near the solar array, allowing all panels to be connected locally and combined into single feed to the next system component, usually the inverter or charge controller.

WIRING

All electrical systems require wiring; in a PV system, wiring is used to connect the PV panels and all other electrical components to a facility's electrical panel or battery bank. Wiring is available in a variety of sizes defined by the cross-sectional area of the copper wire (not including the wire's insulation) and is usually measured in square millimeters (mm^2) or in the American Wire Gauge (AWG) system in the United States. Wiring must be selected carefully, as undersized wire can be a safety hazard. When choosing the size of wiring used in a PV system, a number of factors come into play: system voltage, rated current, wire length, and efficiency. Higher system voltage, higher rated current, and greater distance between the PV panels and system loads (*e.g.*, electrical panel or battery bank) require larger wiring. Larger wiring also results in lower transmission losses due to resistance in the wire; a 5 percent power loss due to wiring is typical.

DC AND AC DISCONNECT SWITCHES

Disconnect switches are a safety measure that allow owners and technicians to cut the power supply coming from PV panels. A DC and AC disconnect switch must be placed on either side of an inverter, although some inverters and electrical panels are already integrated with disconnect switches. Switches are useful for cutting power during maintenance, but their main purpose is to prevent a condition called "islanding" in grid-connected systems. Islanding occurs when a grid-connected PV system continues to send power to the grid during a power outage. Although the grid is down, the power lines are still electrified by the connected PV system, creating a potential hazard for utility technicians working under the assumption that the lines are not energized.

BATTERIES

Batteries are used to store energy. In off-grid PV systems, they are essential to providing power during periods of low or no sunlight; in grid-tied PV systems, they store both solar and grid energy to provide backup power in the event of an outage, or continuous, clean power to no-contact loads. See the Batteries and Battery Management portion of USAID's Powering Health toolkit for more information.

CHARGE CONTROLLER

PV systems utilizing a battery bank must also include a charge controller. Charge controllers regulate the electrical current being sent to the battery bank to ensure that the batteries are not overcharged. They also prevent the battery bank from discharging current back to the PV system when the panels are not producing power.

TRACKING SYSTEMS

Tracking systems are a type of mounting system in which the orientation, tilt, or both, are consistently adjusted to provide maximum daily exposure to direct sunlight. At a minimum, such systems consist of one or two axes that allow for adjustment of the system's orientation or tilt and a pyrometer, which is used to determine the position of the sun throughout the day. Tracking systems are an essential part of any concentrating solar thermal or concentrating PV system, because only direct sunlight can be concentrated efficiently. Such systems can also be used with normal solar PV panels but are not typically the economical choice.

Tracking systems make solar PV more efficient by increasing the total energy output on a daily basis. This brings about further advantages. First, such a system produces high power for a longer period each day, rather than reaching peak power production at midday, as in stationary mounting systems. This allows the PV system to power loads directly throughout the day, reducing dependence on the system's battery bank or the grid. Second, PV systems utilizing a tracking system require fewer panels than a fixed system to meet the same total load. This can be especially advantageous when space for the system is limited. These advantages must be weighed against the added cost of the tracking equipment (including special design services, added transportation costs, and maintenance needs).

COSTS

The costs associated with a solar PV system are generally put into terms of $/Wp to represent the system's capital cost and $/kWh to represent the cost of energy produced by the system over its life.

Only a portion of cost can be attributed to the PV panels. The remaining costs are for BOS materials (mounting hardware, inverters, batteries, etc.), engineering design, labor, and other materials and services. If the system has no other backup power, a battery bank must be sized appropriately to provide power after several days of overcast weather; therefore, local weather patterns can influence overall system cost. Unusual expenses such as transportation of modules, customs fees, or permitting expenses can increase this cost even further.

While the upfront expenditure is a major hurdle for many potential PV installations, the cost of energy produced by the system is a more appropriate way to compare the value of a PV installation to that of other energy sources such as diesel generators or grid power. PV systems require little maintenance, and their fuel, the sun's energy, is free, so the major cost component to any PV system will be the capital cost. Conversely, a diesel generator has a low upfront cost but will require a constant supply of fuel and multiple overhauls over the life of the equipment. The most cost-effective energy system for any given facility will depend on the facility's electrical load, the availability of grid power, the supply and cost of generator fuel, and the local solar resource. More often than not, the least-cost solution on a net present value basis is a hybrid system, in which solar PV, an on-site generator, and the grid work in tandem.

The HOMER Powering Health Tool for load calculation and system optimization is an easy and effective way to quickly compare energy system designs based on solar PV, diesel generation, grid power, and battery banks. The tool allows users to input facility-specific information, such as the hourly electrical load profile, hours of grid availability, and geographic location, to generate a comparison of energy system options tailored for the facility's needs. Each option's capital cost, net present value, and normalized energy cost are displayed for a simple and meaningful energy system design assessment.

SIZING

Properly sizing a solar PV system requires careful attention to detail and thoughtful planning. Solar system sizing is a step-by-step process that accounts for facility energy needs and the local solar resource in order to determine the necessary size (in kilowatt peak (kWp)) of the solar array. The process outlined here is a guide to estimating the size of a solar installation.

1. DETERMINE LOADS

The first step when considering a solar PV installation, or any other energy system upgrade, is to detail facility electrical loads. This process results in a facility load profile, or a listing of all electricity-consuming equipment at the facility, including the load (power need in Watts) and schedule of operation (how long and at which points throughout the day the equipment runs) for each individual piece of equipment. Understanding facility load requirements is essential to correctly sizing a PV system and is a matter of good facility energy management in its own right.

See the Health Facility Load Calculation Examples in USAID's Powering Health toolkit for sample load profiles, and use the Energy Audit tool to create a facility load profile.

2. OPTIMIZE/PREDICT LOADS

Once a current facility load profile has been established, it is a good opportunity to consider ways to reduce that load, or conversely, to predict future increases in load. Solar panels, batteries, inverters, and other BOS equipment are costly and must be sized according to the loads they are meant to power. By reducing facility loads before PV system installation, a smaller, less expensive system may be possible. Ways to reduce loads include energy efficiency retrofits or a reduction in operating hours for electrically powered equipment. While energy efficiency retrofits also have an upfront cost, the capital costs saved by installing a smaller PV system may make the measures worthwhile.

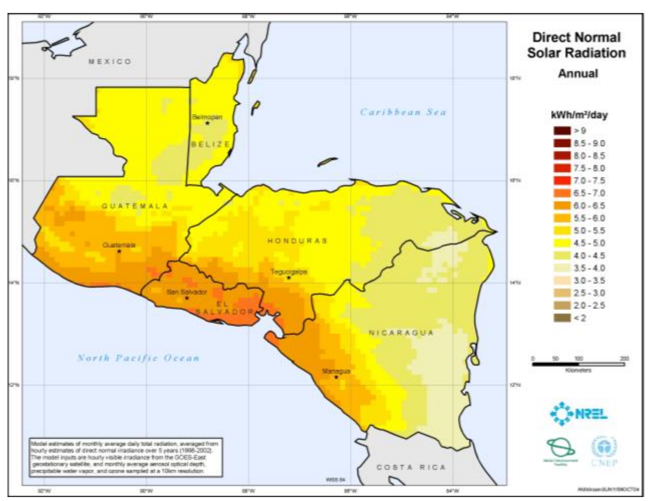
Potential increases in facility load should also be considered. When additional electrical loads are placed on a PV system, there is a risk of overloading the system and damaging the battery bank. Before sizing a PV system and battery bank, any foreseeable additions to the system's electrical load should be accounted for. When procuring new equipment, energy-efficient models should be selected to minimize their effect on the facility's energy system.

3. SIZE BATTERY BANK

In off-grid situations, or locations that do not allow grid interconnection, battery banks are a necessary part of any PV system. Like the PV array, the battery bank must be sized according to the loads it is meant to support. Another important factor that affects the size of both the PV array and battery bank is autonomy. Autonomy is the number of days that the PV system and battery bank can provide power without sunlight. Energy stored in the battery bank will be used for periods of inadequate sunlight, so greater autonomy requires a larger battery bank. Determining how much autonomy is needed depends on the local climate, specifically the maximum number of days with cloudy weather. The availability of other power sources may also influence the amount of autonomy needed for the PV system. For example, a diesel generator can be used during periods of low sunlight in order to offset the need for a large battery bank. For more information on battery banks, see the Batteries and Battery Management portion of USAID's Powering Health toolkit.

4. DETERMINE SOLAR RESOURCE

The local solar resource is the amount of solar energy that reaches the PV installation site. See the PV Terms section for an explanation of the different ways to describe a solar resource. The solar resource for any given location is mainly based on geographic location and climate, so solar resource data is available for every region of the world (for example see https://globalsolaratlas.info/map). Knowing the local solar resource is essential to sizing a PV system because it indicates the amount of solar energy available to meet the load requirements.



NREL

5. SIZE ARRAY

With the targeted loads and local solar availability well understood, determining the size of the PV array is relatively easy. Essentially, the array must be sized in order to generate enough electrical power for the targeted loads, accounting for the overall system efficiency (panels, inverters, batteries, wiring, *etc.*), using only the available solar energy. In practice, many other factors must also be taken into consideration, including PV performance under low light conditions, the battery bank's days of autonomy, and the DC voltage of the battery bank. For this reason, PV system design should be done by a trained engineer.

Use the HOMER Powering Health Tool to estimate and compare PV systems based on a facility's load profile and geographic location.

MAINTENANCE

Solar PV panels are low-maintenance equipment, but a regular and organized maintenance program is still absolutely essential to system longevity. Unfortunately, installation programs do not always include a sufficient service component. Health-care facilities with solar panels must have a vigorous training program for local users and an established maintenance protocol.

The most frequent maintenance need of solar panels will be the cleaning of the panel faces. Dirt or other debris on the panel faces block sunlight and reduce PV electrical production. For systems incorporating battery banks, regular maintenance of batteries is essential; they should be checked every week, with the electrolyte level replenished as needed. If properly maintained, they should last several years before needing replacement. See the Batteries and Battery Management portion of USAID's Powering Health toolkit for more information on battery maintenance.

While training local health-care facility staff in system maintenance is essential for routine maintenance, a professional technician should also perform a semi-annual maintenance check, examining wiring connections, mounting bolts, and inverter operation and be on call to fix the system if it does not work. Maintenance funds should be established upfront and be dedicated only to solar system repair. Mixing maintenance funds with general operating budgets has proven to be an ineffective model.