The Photovoltaic Primer

D-Lab
Development, Design, Dissemination

Technology Overview

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Solar energy in its purest form can be used for a variety of uses, such as fruit drying, cooking, water heating, and direct transfer to electricity. For the latter technology, the medium is in the form of photovoltaic cells.

Sunshine reaches the earth as radiation, providing 1367 W/m^2 of energy, composed of millions of high energy particles called photons. Roughly 25% of this energy is immediately lost going through the atmosphere, but the rest hits earth as solar radiation, either direct (straight focused rays) or diffused (reflected by the atmosphere). On cloudy days, up to 100% of this radiation is diffused, causing solar panels to lose about 80% of their power. The amount of sunlight actually striking a surface is referred to as *solar irradiance*, which meteorologists measure to determine if a particular area is well-suited for solar electricity. For most of sub-Saharan Africa, this amount is sizable, with anywhere from 3-8 hours a day of prime solar irradiance (over 1000 W/m^2). For example, Uganda averages around 4.5 kwh/m^2 per day, and Botswana averages around 6.1 kwh/m^2 per day.

If this power source could be converted to electricity with no loss, the potential is amazing. In just one meter squared, Uganda could have 108W daily and Botswana 146W. If you factor in the entire earth, in just one hour $1.2*10^{17}$ W of solar power is produced: enough to supply the earth for an entire year. However, photovoltaic systems do have significant losses—most panels operate with an efficiency of less that 15%, and there are further losses in other components of the system. Even so, photovoltaics still are a viable option in areas with sufficient irradiance and have a variety of uses, as shown in Table 1 below:

Installing a PV system in a community center in Petite Anse, Haiti

To learn more about photovoltaics and their application in the developing world, check out ITDG's Tech Briefs: http://www.practicalaction.org/?id=technical_briefs

Table 1: Estimated number of operating PV systems in eastern and southern Africa countries (1994)

Vaccine Refrigeration	>1000
Home Lighting Systems	>50,000
Water Pumping Systems	>200
Schools/Mission Power	>1000
Electric Fencing	>200 km

How Does PV Work?

In 1839, a nineteen year old French scientist, Alexandre-Edmund Becquerel, noticed electrical currents arising from certain materials when exposed to light. He developed his theory: light can cause electricity to be generated. Although he published his knowledge, it took some time until this was refined. In the 1950s, American scientists started to exploit this to a large degree: the first solar cell on a satellite, *Vanguard I*, occurred in 1958. Today, solar cells are manufactured worldwide, with centers in USA, Germany, Spain, Italy, Japan, Brazil and India.

The solar cells most appropriate for use in developing countries are all based on silicon; other semi-conductors are used for applications, such as satellites, where cost is not an issue. When a photon of incident light strikes the silicon, it can transfer its energy to an electron. If a load is connected to this (such as a wire), electrons flow out as a current. The stronger the light, the more electrons will flow and the larger the generated current.

There are three main types of solar cells that are used:

monocrystalline - cells cut from single crystals of silicon. 11-18% efficiency, but most expensive.
polycrystalline - cells cut from many crystals of silicon. 8-11% efficiency, moderately expensive.
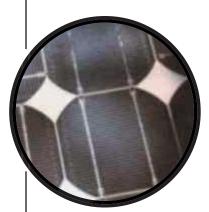*amorphous* - created from silicon not in crystalline form. 3-6% efficiency, least expensive. Shortest lifetime.

Each one of these solar cells generate a potential voltage difference of ~0.5V. Thus to achieve a 12V battery, approximately 24 of them need to be placed in series.
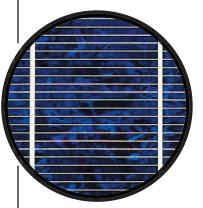
The Battery

Unfortunately, when the sun is shining it is the least likely time for people to be using lights in their house. A medium of energy storage is necessary, which takes the form of

The Three Types of Solar Cells

Monocrystalline cells
(Image: www.pvresources.com)

Polycrystalline cells
(Image: www.plastecs.com/)

Amorphous cells
(Image source: solar.calvin.edu/)

a battery. Although car batteries can be used, it's much better to use a battery especially designed for solar electric systems.

There are two main battery types:

Lead Acid Batteries - Based on the chemical reaction between lead dioxide and negative lead plate, with an electrolyte composed of sulfuric acid and water. When charged, the lead dioxide accumulates on the positive plate and the lead on the negative plate. The relative amount of sulfuric acid in the electrolyte increases, thus leading to an increased voltage difference. When discharged, the sulfuric acid in the battery decreases as the sulphur combines with lead and accumulates on the negative plate.

Nickel-Cadmium (nicad) - Based on the chemical reaction between nickel hydroxide and the (negative) cadmium hydroxide, with similar effects to the lead acid battery.

The nicad batteries are more expensive and have lower efficiency. In addition, they are not as robust and require strict adherence to their recommended charging procedures. Their advantages lie in being lighter and smaller. Furthermore, they can be rapidly discharged without damage to cells, can be left in a low state of charge, require less maintenance, have a longer life, and can be operated over a wider range of temperatures.

In rural Africa, lead acid batteries are much easier to obtain. Among these, there are two different varieties: the deep discharge, or deep cycle, which allows more energy to be taken out, and the shallow discharge, such as those found in automotive applications. Although the former is better as it allows more flexibility, the latter is often used because of its wide availability.

The amount of charge that can be stored in a battery can be approximately determined by multiplying the charge current (I) by the amount of time the current has been applied (t), to get the amount of charge in amp hours (Q). To determine the number of watt hours available in the battery, simply multiply Q by the voltage in the battery (either 12V or 24V).

Batteries should not be charged at a current higher than 1/10 of rated capacity. During the charging phase, 10-30% of the energy is lost as heat.

Charge Controllers and Load Management

We now have the photovoltaic cells and the battery, and now we're ready to connect the battery to the load (lamps, radios, refrigerators, etc.). To ensure that the energy level in the battery remains at optimal levels, there needs to be an inter-mediate device. For this we have charge controllers, to provide central point for connecting the load, modules and battery pack; to manage the system so harvested electricity is used efficiently and protect the components; and to allow users to monitor the system and locate potential system problems.

If nothing else, the charge controller should contain a junction box with fuses to account for large current flow. When the current flows above a certain level, the metal wire inside the fuse will melt, forming an open circuit and stopping current flow. For rural Africa, simple automotive fuses or fuse wires can be used. Most battery shops will stock these. It is also helpful to have a main circuit switch, thus ensuring that forgotten loads will not drain the battery.

Lamps and Appliances

Most lamps and other appliances are built in Africa to run off of the standard 240V AC. If directly plugged into the 12V DC, there will be problems, such as sparks and the destruction of the lamp or the battery will discharge without powering the appliance. There are appliances that are designed to run off 12VDC, or an inverter must be used to convert from direct current to alternating current.

Lamps

incandescent lamps were the first type of the light bulb, designed over a century ago. The bulb is filled with an inert gas, and a thin tungsten wire (the filament) conducts electric. When electric passes over the filament, the resistance causes the wire to heat up to 3000 degrees Celsius, giving off heat and light. These can be designed to run off of 12V. Typically about 90% of the energy is lost as heat, which leads to low lighting efficiency.

The installation of charge controller and circuit breaker box in a PV system

While it is possible to not use a charge controller, extra care must be taken to avoid deep discharge and destroying components.

1. Checking the battery state regularly. Watch for signs: if the lights flicker, the battery is getting low.

2. Calculate how much energy is going into the battery and adjust energy usage.

3. Limit appliances when battery charge is low.

4. Every two months (or more often in cloudy weather), choose battery using alternative means.

fluorescent lamps are typically filled with mercury vapor. As current passes through the lamp, the vapor gives off UV rays, which make contact with a coating of phosphorous on the inside of the lamp, causing light to be emitted. These lamps are 10-20 times more expensive than incandescents, but are about four times as energy efficient and have a much longer life. These must operate between 70-100V AC, and so require an inverter to increase the voltage and change the current from DC to AC (thus losing 10-15% of the electricity in the process).

light emitting diodes (LEDs) are made from layers of silicon and seeded with atoms of phosphorus, or germanium, arsenic and other rare-earth elements. A cheap plastic reflector focuses the light into a beam that can be narrow and very bright, or wide and diffuse. Electricity flowing through the diode is directly converted to light, without heat. Technical advances have greatly improved the quality and reliability of LEDs since they were invented in the 1960s, making them much brighter and more efficient and suitable for home lighting applications.
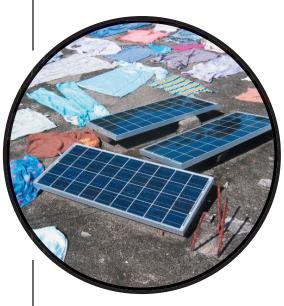
Table 2: Lighting Comparison Table

	Incandescent	Compact Fluorescent	LED
Efficiency (lumens/watt)	5-18	39-70	25-50
Rated life (hours)	1000	6,000-15,000	50,000
Durability	Fragile	Fragile	Robust

Source: Light Up the World Foundation, http://www.lutw/org/Technicalinfo.html

Wirings and Fittings

The amount of current that can flow through a wire is akin to the amount of water that can flow through a pipe: the greater the diameter, the more current that can flow. As 240V AC needs little current due to the high voltage, a 1.0 or 1.5 mm^2 wire is adequate (21 - 23 AWG). For a 12V DC, use at least 2.5 mm^2 (19 AWG) with a separate black wire wrapped around for grounding.

This is what a PV system you might find in a developing country (in this case Haiti) may look like. Without any mounting structure whatsoever, this system is vulnerable to not only theft, but also to wind and rain. Your goals should be set much higher.

Sockets

A low-voltage, high current DC socket is recommended for solar installations, although the standard 240V AC is commonly used. If the latter is used, the energy efficiency is not nearly as high.

Connections

A terminal strip (insulated screw-down wire clamps used to connect wires together) should be used. Strip the insulated ends of the wire 1.5-1 cm from the end. Twist the end, preferably with a crimp tool, and wrap around the clamp before screwing it down. When finished, inspect all connections to ensure that there are no loose wires.

Grounding

To protect against electric shocks and damage to the system from lightning, the system must be grounded to provide an easy path for electricity to travel. Attach a wire leading from metal casings of all valuable appliances or modules to a rod driven into the ground.

Maximum Wire Runs

As the distance from the battery to the appliances increase, the amount of voltage lost through the wire will increase as well. To ensure this doesn't happen, ensure all wires are less than 15 meters and carry no more than 4 amps.

Planning your system

Now that you know all the components you need, it's time to actually plan your system.

1. Determine how much power you need.
2. Electric energy demand will probably grow, so plan for expansion.
3. Consider alternatives carefully.
4. Visit another system before installing your own.
5. Draw a scale diagram of the floor plan.
6. Keep your system as simple as possible.
7. Shop around for different equipment.
8. Estimate load carefully.

Determine daily system energy requirements by listing all of your appliances and multiplying their individual wattage by the number of hours to be used daily. Total this up to determine your daily requirements.

Unfortunately, theft of solar panels can and does occur. To decrease this risk, position the panel as high as possible and use a steel mount. Place it as close to your house as possible so you will be alerted if anyone is near it. Downward facing spikes can be a deterrent.

Maintaining Your System

The Solar Panel - The solar panel is easily maintained, just make sure there is no shade blocking it and rinse it off if dust accumulates. It should last over 20 years.

The Battery - Good batteries will last between two and ten years if properly installed, maintained and managed.
1. Check state of charge to ensure good performance. Keep records.
2. Check electrolyte levels in each cell. Replace water lost during gassing with de-ionized water. Plates should always be below level of electrolyte. Rainwater/ homemade distilled water can be used.
3. Clean top of battery periodically.
4. Clean terminals and contacts. Apply petroleum jelly or grease to terminals to prevent corrosion but be careful not to short the battery terminals.
5. Give battery occasional equalizing charges to mix up electrolyte.

Wiring - Annually, ensure that all wires are still in good working condition, non-frayed and that all connections are attached.

To determine the size of the PV array, calculate the solar energy available by using records from meteorological stations for the area. Check which month has the lowest mean daily irradiance, and pick the module that will meet your energy requirements based on this month. Dividing your total load by the efficiencies of the batteries, charge controllers and inverters will give you the power you need from the array.

Other factors:
1. Can you charge the battery using other methods? Do you need it year-round?
2. Will modules be mounted or tracking (panel moves following the sun)? If tracking, you will get 20% more efficiency.

Table 3: Estimated Energy Consumption of Several Commonly Used Devices

Incandescent lights	60 - 150 W (per bulb)
Fluorescent lights	15 W (per tube)
Laptop computer	20 - 40 W
Desktop computer	150 - 200 W
Stereo system	20 - 50 W
Washing machine	600 - 1,000 W (includes heating the water)
Dryer	4,000 - 6,000 W
Air conditioner	4,000 - 6,000 W
Oven	8,000 - 12,000 W
Microwave	750 - 1200 W
Refrigerator	500 W
Telephone	2 - 5 W
Television	80 - 100 W
VCR	20 - 50 W
Hair dryer	1000 - 1500 W

Assignment Questions

1. Using the values in Table 3 at the right, determine your average daily energy consumption (in kWh). For this assignment, you can take into account only the electricity that you use, though you should be aware that there are additional energy expenditures in terms of transportation, manufacturing processes to make the products that you use, etc.

2. Design a PV system that would provide you with this amount of electricity.

3. Estimate the cost of such a system.

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