Chapter 1
An Overview of Photovoltaics

Contents:

1.1 The Development of Photovoltaics

Photovoltaic systems are solar energy systems that produce electricity directly from sunlight. Photovoltaic (PV) systems produce clean, reliable energy without consuming fossil fuels and can be used in a wide variety of applications. A common application of PV technology is providing power for watches and radios. On a larger scale, many utilities have recently installed large photovoltaic arrays to provide consumers with solar-generated electricity, or as backup systems for critical equipment.

Research into photovoltaic technology began over one hundred years ago. In 1873, British scientist Willoughby Smith noticed that selenium was sensitive to light. Smith concluded that selenium's ability to conduct electricity increased in direct proportion to the degree of its exposure to light. This observation of the photovoltaic effect led many scientists to experiment with this relatively uncommon element with the hope of using the material to create electricity. In 1880, Charles Fritts developed the first selenium-based solar electric cell. The cell produced electricity without consuming any material substance, and without generating heat.

Broader acceptance of photovoltaics as a power source didn't occur until 1905, when Albert Einstein offered his explanation of the photoelectric effect. Einstein's theories led to a greater understanding of the physical process of generating electricity from sunlight. Scientists continued limited research on the selenium solar cell through the 1930's, despite its low efficiency and high production costs.

In the early 1950's, Bell Laboratories began a search for a dependable way to power remote communication systems. Bell scientists discovered that silicon, the second most abundant element on earth, was sensitive to light and, when treated with certain impurities, generated a substantial voltage. By 1954, Bell developed a silicon-based cell that achieved six percent efficiency.

The first non-laboratory use of photovoltaic technology was to power a telephone repeater station in rural Georgia in the late 1950s. National Aeronautics and Space Administration (NASA) scientists, seeking a lightweight, rugged and reliable energy source suitable for outer space, installed a PV system consisting of 108 cells on the United States' first satellite, Vanguard I. By the early 1960s, PV systems were being installed on most satellites and spacecraft.

Today, over 200,000 homes in the United States use some type of photovoltaic technology. Solar modules contribute power to 175,000 villages in over 140 countries worldwide, producing thousands of jobs and creating sustainable economic opportunities. In 2001, worldwide sales of photovoltaic products totaled over 350 megawatts and over $2 billion in the global market. The applications include communications, refrigeration for health care, crop irrigation, water purification, lighting, cathodic protection, environmental monitoring, marine and air navigation, utility power, and other residential and commercial applications. The intense interest generated by current photovoltaic applications provides promise for this rapidly developing technology.

1.2 Current and Emerging Opportunities

Conventional fuel sources have created myriad environmental problems, such as global warming, acid rain, smog, water pollution, rapidly filling waste disposal sites, destruction of habitat from fuel spills, and the loss of natural resources. Photovoltaic systems do not pose these environmental consequences. Today, the majority of PV modules use silicon as their major component. The silicon cells manufactured from one ton of sand can produce as much electricity as burning 500,000 tons of coal.

Photovoltaic technology also creates jobs. Solar industries directly employ nearly 20,000 people and support over 200,000 jobs in areas such as glass and steel manufacturing, electrical and plumbing contracting, architecture and system design, and battery and electrical equipment manufacturing. By some estimates, 3,800 jobs are created for every $100 million in PV sales.

The photovoltaic market grows each year. Economists have predicted that photovoltaics will be the most rapidly growing form of commercial energy after 2030, with sales exceeding $100 billion. In fact, the use of solar and renewable energy is expected to double by the year 2010, which would create more than 350,000 new jobs. It is no surprise that this clean, reliable source of electric power is regarded as the future of energy production.

1.3 Advantages of Photovoltaic Technology

Photovoltaic systems offer substantial advantages over conventional power sources:

- Reliability. Even in harsh conditions, photovoltaic systems have proven their reliability. PV arrays prevent costly power failures in situations where continuous operation is critical.
- Durability. Most PV modules available today show no degradation after ten years of use. It is likely that future modules will produce power for 25 years or more.
- Low Maintenance Cost. Transporting materials and personnel to remote areas for equipment maintenance or service work is expensive. Since PV systems require only periodic inspection and occasional maintenance, these costs are usually less than with conventionally fueled systems.
- No Fuel Cost. Since no fuel source is required, there are no costs associated with purchasing, storing, or transporting fuel.
- Reduced Sound Pollution. Photovoltaic systems operate silently and with minimal movement.
- Photovoltaic Modularity. PV systems are more cost effective than bulky conventional systems. Modules may be added incrementally to a photovoltaic system to increase available power.
- Safety. PV systems do not require the use of combustible fuels and are very safe when properly designed and installed.
- Independence. Many residential PV users cite energy independence from utilities as their primary motivation for adopting the new technology.
- Electrical Grid Decentralization. Small-scale decentralized power stations reduce the possibility of outages on the electric grid.
- High Altitude Performance. Increased insolation at high altitudes makes using photovoltaics advantageous, since power output is optimized. In contrast, a diesel generator at higher altitudes must be de-rated because of losses in efficiency and power output.

1.4 Disadvantages of Photovoltaic Technology

Photovoltaics have some disadvantages when compared to conventional power systems:

- Initial Cost. Each PV installation must be evaluated from an economic perspective and compared to existing alternatives. As the initial cost of PV systems decreases and the cost of conventional fuel sources increases, these systems will become more economically competitive.
- Variability of Available Solar Radiation. Weather can greatly affect the power output of any solar-based energy system. Variations in climate or site conditions require modifications in system design.
- Energy Storage. Some PV systems use batteries for storing energy, increasing the size, cost, and complexity of a system.
- Efficiency Improvements. A cost-effective use of photovoltaics requires a high-efficiency approach to energy consumption. This often dictates replacing inefficient appliances.
- Education. PV systems present a new and unfamiliar technology: Few people understand their value and feasibility. This lack of information slows market and technological growth.

1.5 Environmental, Health, and Safety Issues

Electricity produced from photovoltaics is much safer and more environmentally benign than conventional sources of energy production. However, there are environmental, safety, and health issues associated with manufacturing, using, and disposing of photovoltaic equipment.

The manufacturing of electronic equipment is energy intensive. On the other hand, photovoltaic modules produce more electricity in their lifetimes than it takes to produce them. An energy break-even point is usually achieved after three to six years.

As with any manufacturing process, producing photovoltaic modules often poses environmental and health hazards. Workers may be exposed to toxic and potentially explosive gases, such as phosphine, diborane, hydrogen deselenide, and cadmium compounds. Manufacturers have made steps to minimize environmental and worker hazards by implementing carefully designed industrial processes and monitoring systems.

Safety for installation technicians is also a concern. Only qualified personnel, using equipment that complies with national safety standards, should install photovoltaic systems.

The disposal of photovoltaic system components poses a moderate environmental hazard. Most solar modules have an expected useful life of at least 20 years. Most of the components can be recycled or reused (for example, glass and plastic encasements, and aluminum frames), but semiconductor recycling is extremely limited.

1.6 Photovoltaic System Components

Photovoltaic systems are built from several important components:

- Photovoltaic Cell. Thin squares, discs, or films of semiconductor material that generate voltage and current when exposed to sunlight.
- Module. A configuration of PV cells laminated between a clear superstrate (glazing) and an encapsulating substrate.
- Panel. One or more modules (often used interchangeably with "module").
- Array. One or more panels wired together at a specific voltage.
- Charge Controller. Equipment that regulates battery voltage.
- Battery Storage. A medium that stores direct current (DC) electrical energy.
- Inverter. An electrical device that changes direct current to alternating current (AC).
- DC Loads. Appliances, motors, and equipment powered by direct current.
- AC Loads. Appliances, motors, and equipment powered by alternating current.

1.7 Photovoltaic System Types

Photovoltaic systems can be configured in many ways. For example, many residential systems use battery storage to power appliances during the night. In contrast, water pumping systems often operate only during the day and require no storage device. A large commercial system would likely have an inverter to power AC appliances, whereas a system in a mobile home would likely power only DC appliances and wouldn't need an inverter. Some systems are linked to the utility grid, while others operate independently.

Integrated Photovoltaic Battery-Charging Systems: These systems incorporate all their components, including the application, in a single package. This arrangement may be economical when it compliments or replaces a disposable battery system. Small appliances, complete with a rechargeable battery and integrated PV battery-chargers, are a common example. Solar lanterns and photovoltaic chargers for radio batteries have worldwide market potential. Kits for photovoltaic flashlights, clocks, and radios may eventually replace similar units that use expensive, wasteful, disposable batteries.

Day Use Systems: The simplest and least expensive photovoltaic systems are designed for day use only. These systems consist of modules wired directly to a DC appliance, with no storage device. When the sun shines on the modules, the appliance consumes the electricity they generate. Higher insolation (sunshine) levels result in increased power output and greater load capacity.

Examples of day use systems include:

- Remote water pumping for a storage tank.
- Operation of fans, blowers, or circulators to distribute thermal energy for solar water heating systems or ventilation systems.
- Stand-alone, solar-powered appliances such as calculators and toys.

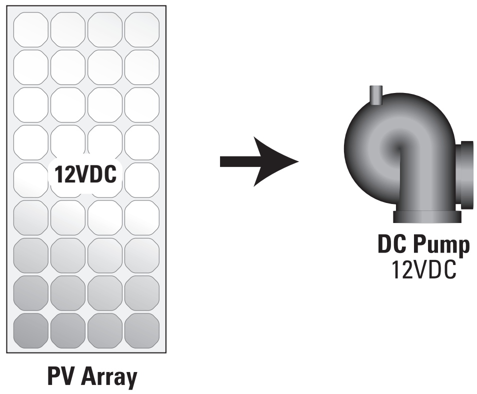

Figure 1-1
DAY USE SYSTEM

Direct Current Systems With Storage Batteries: To operate loads at night or during cloudy weather, PV systems must include a means of storing electrical energy. Batteries are the most common solution. System loads can be powered from the batteries during the day or night, continuously or intermittently, regardless of weather. In addition, a battery bank has the capacity to supply high-surge currents for a brief period, giving the system the ability to start large motors or to perform other difficult tasks. A simple DC system that uses batteries is illustrated in Figure 1-2. This system's basic components include a PV module, charge controller, storage batteries, and appliances (the system's electrical load).

A battery bank can range from small flashlight-size batteries to dozens of heavy-duty industrial batteries. Deep-cycle batteries are designed to withstand being deeply discharged and then fully recharged when the sun shines. (Conventional automobile batteries are not well suited for use in photovoltaic systems and will have short effective lives.) The size and configuration of the battery bank depends on the operating voltage of the system and the amount of nighttime usage. In addition, local weather conditions must be considered in sizing a battery bank. The number of modules must be chosen to adequately recharge the batteries during the day.

Batteries must not be allowed to discharge too deeply or be overcharged—either situation will damage them severely. A charge controller will prevent the battery from overcharging by automatically disconnecting the module from the battery bank when it is fully loaded. Most charge controllers also prevent batteries from reaching dangerously low charge levels by stopping the supply of power to the DC load. Providing charge control is critical to maintaining battery performance in all but the simplest of PV systems.

Direct Current Systems Powering Alternating Current Loads: Photovoltaic modules easily produce DC electrical power, but many common appliances require AC power. Direct current systems that power

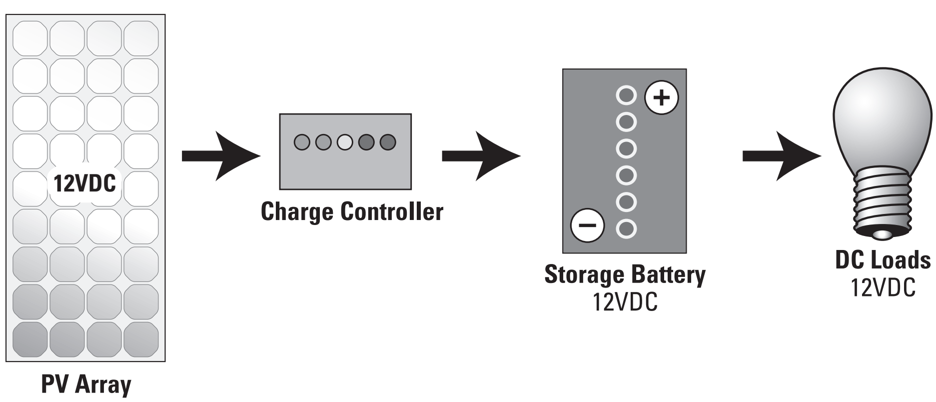

Figure 1-2
DC SYSTEM WITH BATTERIES

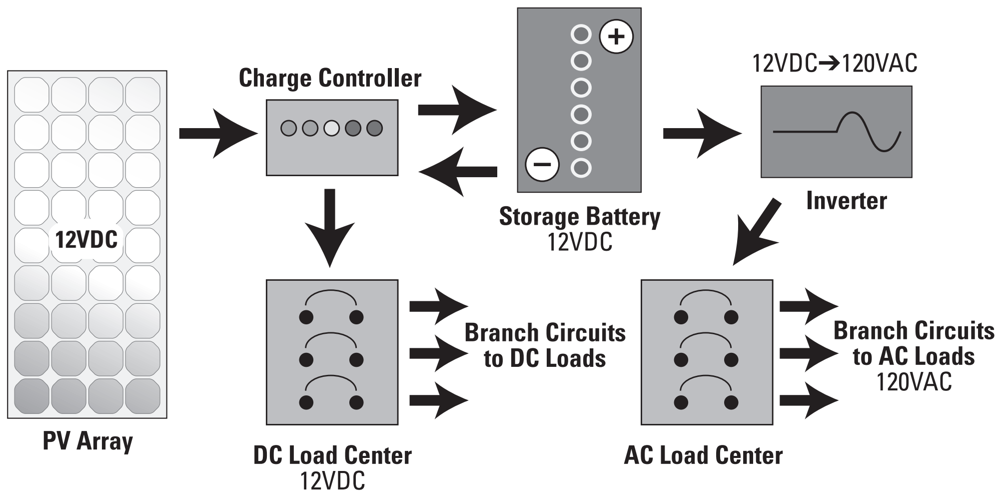

Figure 1-3

SYSTEM WITH DC AND AC LOADS

AC loads must use an inverter to convert DC electricity into AC. Inverters provide convenience and flexibility in a photovoltaic system, but add complexity and cost. Because AC appliances are mass-produced, they are generally offered in a wider selection, at lower cost, and with higher reliability than DC appliances. High quality inverters are commercially available in a wide range of capacities.

Utility Grid Interconnected Systems: Photovoltaic systems that are connected to the utility grid (utility-connected, grid-tie, or line-tie systems) do not need battery storage in their design because the utility grid acts as a power reserve. Instead of storing surplus energy that is not used during the day, the homeowner sells the excess energy to a local utility through a specially designed inverter. When homeowners need more electricity than the photovoltaic system produces, they can draw power from the utility grid. See figure 1-4.

If the utility grid goes down, the inverter automatically shuts off and will not feed solar-generated electricity back into the grid. This ensures the safety of linepersons working on the grid. Because utility-connected systems use the grid for storage these systems will not have power if the utility grid goes down. For that reason, some of these systems are also equipped with battery storage to provide power in the event of power loss from the utility grid.

The Public Utilities Regulatory Policies Act (PURPA) of 1978 requires electric utilities to purchase power from qualified, small power producing system owners. The utilities must pay the small power producers based on their "avoided costs," or costs the utility does not have to pay to generate that power themselves. Additional terms and conditions for these purchases are set by state utility commissions and vary from state to state. While this law allows homeowners in areas with utility power to purchase photovoltaic systems and sell their excess power to an electric utility, people contemplating doing so should remember that this is rarely a profitable venture at the present time.

Some utility companies offer "netmetering" to their customers, where a single meter spins in either direction depending upon whether the utility is providing power to the customer or the customer is producing excess power. The customer or independent power producer pays or collects the net value on the meter. Net metering is very desirable to the independent power producer because he/she can sell power at the same retail rate that the utility charges its customers.

Hybrid Systems: Most people do not run their entire load solely off their PV system. The majority of systems use a hybrid approach by integrating another power source. The most common form of hybrid system incorporates a gas or diesel-powered engine generator, which can greatly reduce the initial cost. Meeting the full load with a PV system means the array and batteries need to support the load

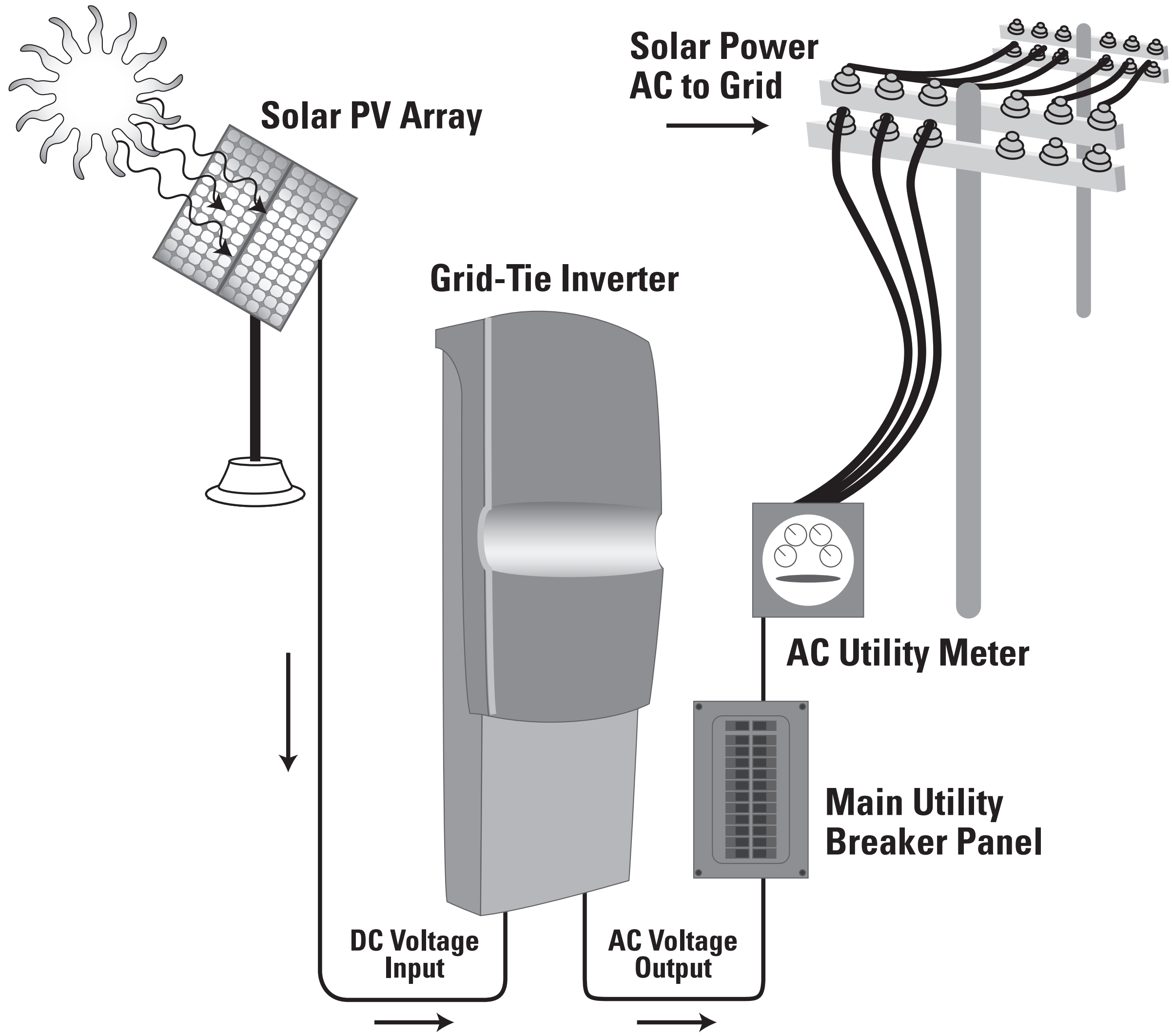

Figure 1-4

UTILITY-INTERACTIVE SYSTEM WITHOUT BATTERIES

under worst-case weather conditions. This also means the battery pack must be large enough to power large loads, such as washing machines, dryers, and large tools. A generator can provide the extra power needed during cloudy weather and during periods of heavier than normal electrical use, and can also be charging the batteries at the same time. A hybrid system provides increased reliability because there are two independent charging systems at work.

Another hybrid approach is a PV system integrated with a wind turbine. Adding a wind turbine makes sense in locations where the wind blows when the sun doesn't shine. In this case, consecutive days of cloudy weather are not a problem, so long as the wind turbine is spinning. For even greater reliability and flexibility, a generator can be included in a PV/Wind system. A PV/Wind/Generator system has all of the advantages of a PV/Generator system, with the added benefit of a third charging source for the batteries.