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Emergency Power Systems with Photovoltaics

Presented at the Governor's Hurricane Conference 2000

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Emergency Power Systems with Photovoltaics

Photo by: Robin Flynn

Presented at the Governor's Hurricane Conference 2000

Course Manual

An emergency power training program for emergency management, disaster relief organizations, and industry on the appropriate use and implementation of applicable photovoltaic systems in disaster response, recovery and mitigation.

FLORIDA SOLAR ENERGY CENTER
A Research Institute of the University of Central Florida

PV DISASTER TRAINING WORKSHOP MANUAL

TRAINING DOCUMENT DEFINITION

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Abstract:

The manual has been developed for three main audiences: disaster relief and emergency management organizations, the photovoltaic industry and the general public. Disaster relief and emergency management organizations will gain an understanding of how to appropriately apply photovoltaic systems to help meet their energy needs. The photovoltaic industry will find this manual a valuable tool in their efforts to design and supply photovoltaic systems that are appropriate for this specialized application. The general public will also learn how photovoltaics can supply their needs for electrical power in disaster situations.

Keywords
Disaster relief, emergency management, emergency power, photovoltaics, solar power, energy.

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PV DISASTER TRAINING WORKSHOP MANUAL

Florida Solar Energy Center

1.0 INTRODUCTION

Natural disasters such as hurricanes, floods, tornados, and earthquakes are violent and uncontrollable, often destroying homes, businesses, and natural surroundings. A case in point, on August 24, 1992, Hurricane Andrew devastated South Florida, leaving several hundred-thousand people homeless. Many people were without electrical service, water and sewage systems, communications, and medical services for days, even weeks, in the aftermath of the storm. Emergency management teams, the military, and countless public and private organizations staged a massive relief effort. FSEC and Sandia National Laboratories were two such organizations, responding with photovoltaic-powered equipment that provided electricity for communications, lighting, refrigeration and other vital needs.

Following a disaster, emergency response organizations provide food, shelter, and other life supporting resources, most often by relying on gasoline or diesel generators to supply electricity when utility power is down. Although the utility works aggressively to restore power, being without electricity for even a day can seem interminable. We don’t realize how important electrical power is until we no longer have it.

The sun shining on the earth each day provides vast amounts of solar energy, which can be converted to thermal or photovoltaic (solar electric) energy to power a variety of equipment. This is an attractive alternative to the traditional generators because photovoltaic (PV) cells generate quiet, safe, pollution-free electrical power. A PV system can generate electricity anywhere the sun shines, mounted on a trailer for mobility or set up as a stationary unit. It can be used in remote areas unconnected to the grid or as back-up power, as in the case of Hurricane Andrew, when the grid is down.

In recent years, solar energy has been used for disaster relief, but only sporadically. Disaster relief organizations knew very little about photovoltaic power, and so, it was not included as an option. Likewise, the photovoltaic industry had not been directly involved with disaster relief efforts and did not aggressively pursue that market. However, photovoltaics have supplied emergency power for Hurricanes Hugo and Andrew, and the earthquake at Northridge in Southern California. And word is spreading – many of the energy needs of emergency management organizations, relief workers, and the general public can be satisfied with photovoltaic power systems.

This workshop manual is divided into 18 sections, which are listed on the following page. The manual has been developed for three main audiences: disaster relief and emergency management organizations, the photovoltaic industry and the general public. Disaster relief and emergency management organizations will gain an understanding of how to appropriately apply photovoltaic systems to help meet their energy needs. The photovoltaic industry will find this manual a valuable tool in their efforts to design and supply photovoltaic systems that are appropriate for this specialized application. The general public will also learn how photovoltaics can supply their needs for electrical power in disaster situations.

The purpose of this manual is to provide information on the use of photovoltaic systems to disaster response, recovery and mitigation. The goal of the manual is to train disaster relief organizations and other interested groups in the proper use of PV-powered equipment and to help them integrate PV systems into their operations. Attendees will gain extensive knowledge on procuring, maintaining, and deploying PV-powered equipment for use during disaster situations and in post-disaster recovery and mitigation.

The Florida Solar Energy Center is funded through the Florida Energy Office of the Department of Community Affairs to produce this manual and other training materials and to conduct workshops on the application of photovoltaics to disasters relief, recovery and mitigation.

1.0 INTRODUCTION

This section introduces the concept of using photovoltaics in disaster response and provides an overview of the workshop manual.

2.0 EMERGENCY MANAGEMENT OPERATIONS

Section 2 describes emergency management; disaster relief plans, operations and activities; and the organizations involved in disaster response, recovery and mitigation.

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This section, based on studies that have been conducted with emergency management and disaster relief organizations, identifies the electrical power needs those organizations have defined.

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2.0 EMERGENCY MANAGEMENT OPERATIONS

The burden of disaster management, and the resources for it, require a close working partnership among all levels of government (federal, regional, state, county, and local) and the private sector (business, industry, voluntary organizations, and the general public). The federal government provides guidance and assistance to state and local governments in preparing for and coordinating recovery from a disaster. State governments provide comprehensive plans and systems to assist local governments with preparedness and recovery activities along with support from various governmental agencies. Local governments are responsible for providing the primary resources for public protection from all types of hazards and for management of the disaster. Local governments provide and maintain police and fire protection, highway resources, facilities, supplies, and personnel capabilities to resolve problems. When local governments are without sufficient resources, they can ask the state or federal governments for assistance. Two of the greatest resources that the state and federal governments provide are the National Guard and the military.

Disasters can occur any time, night or day, any season of the year. Each disaster has a life cycle that calls into play a series of management phases. These phases include strategies to mitigate hazards, prepare for and respond to emergencies, and recover from the disaster's effects. Local and state governments prepare and maintain an Emergency Operations Plan (EOP) that describes how citizens and property will be protected in a disaster. The EOP describes actions that may be required in response to any natural or man-made hazard, including tasks for specific organizations, administrations, and authorities. The plan may also include a definition of responsibilities, standard operating procedures, logistics activities and a list of available resources. The EOP resource list provides both personnel and equipment requirements, including responsibility level and where personnel and equipment are located. This resource list should contain renewable as well as conventional energy resources.

Emergency management personnel from public agencies and utilities are organized into teams to resolve emergency situations created by a major disaster or incident. Both short-term immediate response and long-term relief effort teams respond to a disaster, each with its designated function. Immediate response teams are deployed within the first 24 to 72 hours following a disaster or incident. As immediate needs and problems are resolved, response teams are dismantled either because they are no longer needed or because they are replaced with relief teams, which take over for long-term restoration efforts.

2.1 Emergency Support Functions

Some emergency management personnel from government agencies, voluntary organizations, industry and utilities are organized into teams to resolve specific emergency situations within a disaster or incident. The teams are organized into service areas or disaster relief activities called Emergency Support Functions (ESF). There are 17 ESFs, which manage and coordinate specific categories of assistance common to all disasters, defined as follows:

ESF1 - Transportation	Coordinate busses, transport of evacuees
ESF2 - Communications	Provide communications where needed
ESF3 - Public Works	Debris removal, floodwater control
ESF4 - Fire Rescue	Fires and immediate rescue
ESF5 - Information & Planning	Message control, resource allocation
ESF6 - Red Cross	Mass care, institutional responsibility
ESF7 - Purchasing	Expedite procurement of resources
ESF8 - Public Health	Assess contamination dangers
ESF9 - Search & Rescue	Finding lost persons
ESF10 - Hazardous Materials	Neutralizing spills and toxic gases
ESF11 - Food & Water	Feeding and potable water
ESF12 - Energy	Provision of electrical energy and fuel
ESF13- Military Support	Coordinates with military for security
ESF14 - Public Information	Interfaces with public media for information
ESF15 - Volunteers & Donations	Coordinates walk-in volunteers and donations
ESF16 - Law Enforcement	Wide area & road block
ESF17 - Animal Issues	Pet shelter resources

Each ESF is headed by a lead organization responsible for coordinating the delivery of goods and services to the disaster area, and is supported by numerous other organizations. In a disaster, the lead team for each support function calls on the various organizations committed to supporting that function. They also solicit support from other organizations outside the system as needed.

2.2 Disaster Relief Organizations and Their Roles

Many organizations that respond to various disasters or hazardous incidents do so through an "all-hazards" management approach to protect property and save lives. All levels of government — federal, state and local— and the private sector — industry, voluntary organizations and associations — work closely together to mitigate the effects of disasters.

Local and state governments prepare and maintain a Comprehensive Emergency Management Plan (CEMP) that specifies how citizens and property will be protected in a potential disaster. The CEMP describes actions that may be required in response to any natural or technological hazard, including tasks to be carried out by specified organizations, administrations, and authorities. The plan may also include definitions of responsibilities, standard operating procedures, logistics activities, and a list of available resources. The CEMP resource list provides both personnel and equipment requirements, including responsibility level and where these resources are located.

Mutual Aid Agreements and Memoranda of Understanding provide vehicles for local and state governments to request disaster response and recovery assistance from other local and state governments and organizations. These agreements are also used by utilities, industry and voluntary organizations. The most widely used agreement is between the local, state and federal governments and the American Red Cross to provide and maintain shelters and other services.

To effectively and safely respond to a disaster, trained, experienced individuals and organizations are called on by the local emergency management agency affected by the disaster. Only when needed, does the local emergency management call for or accept outside personnel or resources. Untrained personnel and inappropriate resources can hinder disaster recovery efforts and reduce the safety of operations.

2.2.1 Federal Government

The federal government provides guidance and assistance to state and local governments when state and local resources are insufficient. Most federal assistance is in the form of financial loans and grants to individuals, businesses and communities, which become available after a disaster has passed. The Federal Response Plan (FRP) provides the system for the overall delivery of federal assistance. When a disaster is overwhelming to state and local governments, the federal government can be mobilized and provide support through 27 federal departments and agencies. The FRP defines the policies and procedures for federal assistance in providing necessary personnel, technical expertise, equipment and other resources. Federal disaster recovery programs and mitigation assistance are implemented under the FRP as directed by the President under the Robert T. Stafford Disaster Relief and Emergency Assistance Act, Public Law 93-288.

The Federal Emergency Management Agency (FEMA) is the lead organization at the federal level involved in mitigation, preparedness, response, and recovery activities. It provides training programs and research information on the latest mitigation measures, and reviews and coordinates state emergency plans. FEMA also provides financial assistance, coordinates federal services for disaster response and recovery activities, provides flood insurance and coordinates other programs.

Other federal departments, agencies, and national laboratories involved in disaster relief are as follows:

- Department of Energy
- General Services Administration
- Office of Foreign Disaster Assistance
- Department of Health and Human Services
- Department of Housing and Urban Development
- Department of the Interior
- Department of Agriculture
- National Communications System
- Department of Transportation
- Sandia National Laboratories
- Environmental Protection Agency
- National Oceanic and Atmospheric Administration
- Caribbean Disaster Emergency Response Agency
- Idaho National Engineering and Environmental Laboratory
- Center for Natural Disaster Response, Recovery and Mitigation: DOE
- National Renewable Energy Laboratory

- Oakridge National Laboratory
- Lawrence Livermore National Laboratory
- National Weather Service
- National Hurricane Center
- U.S. Army Corps of Engineers
- National Center for Appropriate Technology
- Center for Renewable Energy and Sustainable Technology

2.2.2 State Government

State governments provide a comprehensive emergency management plan, programs and resources to assist local governments with preparedness and recovery activities. Each state carries out statewide emergency management activities, helps coordinate emergency management activities involving more than one community, and coordinates support from the various state agencies. The state is the pivotal point between policy guidance and resources available at the federal level and the implementation of comprehensive emergency management programs at the local level.

Some typical state government agencies involved are as follows:

- Emergency Management Agency
- Department of Transportation
- Energy Office
- National Guard
- General Services
- Department of Community Affairs

2.2.3 Local Government

Local governments manage all types of hazards and disasters, with responsibility for making plans and providing the primary resources for public protection. Local governments provide and maintain police and fire protection, highway resources, municipal equipment and facilities, sanitation services, schools, supplies, and personnel capabilities to resolve prevailing problems. They must provide the initial response and assistance in a disaster.

Local governments provide protection through the following activities:

- Identify hazards and assess their potential risks to the community.
- Determine the community's ability to prepare for, respond to, mitigate the effects of and recover from major emergencies.
- Identify and employ methods to improve a community's capability through the efficient use of resources, improved coordination, and cooperation with other communities and with the state and federal governments.
- Establish mitigation measures such as building codes, zoning ordinances, and land-use management programs.

- Develop and coordinate preparedness plans.
- Establish warning systems.
- Stock emergency supplies and equipment.
- Educate the public and train emergency personnel.
- Activate response plans and rescue operations.
- Ensure that shelter and medical assistance is provided.
- Assess damage caused by the emergency.

Locally, there are various government agencies and community organizations that provide valuable resources as follows:

- Community Emergency Management Agency
- Governor, Mayor, or Community Administrator
- Local Emergency Planning Committee
- Fire Department
- Police Department
- Emergency Medical Services
- Department of Transportation
- General Services
- Department of Community Affairs
- Public Works Department
- Telephone Companies
- Electric Utilities

When local governments are without sufficient resources, they can request assistance from the state or federal government. Two of the greatest response resources that the state and federal governments provide are the National Guard and the military.

2.2.4 Industry

Industry manufactures equipment and supplies, and provides services to be used before, during and after disasters. All sorts of equipment is needed from cots to radios, portable toilets to food. Some equipment is obtained before a disaster and is stored or used for other things, while other equipment is obtained after a disaster to restore buildings or help people survive. In many cases, the equipment is purchased or, in some cases, rented, usually by prior agreement. Also, there are service companies that assist in planning for future and managing present disasters.

2.2.5 Voluntary Organizations

Voluntary organizations supply most of the personnel needed in a recovery effort. They maintain vast supplies and equipment for relief efforts and administer donations programs. Feeding stations, clothing, mass or individual shelters, cleaning and comfort kits, first aid, blood, supplementary medical care, child care and other resources and social services are available from these organizations. Some of the organizations also support the many emotional and spiritual needs of the survivors, their relatives and neighbors.

Many of the organizations are members of the National Voluntary Organizations Active in Disaster (NVOAD). Members maintain a memorandum of understanding with emergency management agencies and cooperate among fellow member organizations during disasters.

Some NVOAD member organizations include:

- Adventist Community Services
- Catholic Charities
- International Relief Friendship Foundation
- National Organizations for Victim Assistance
- Volunteers of America

A description of the NVOAD is presented in Appendix A. A complete directory with links to expanded descriptions of each member organization can be found on the world wide web at the following address: http://www.vita.org/nvoad/.

Other organizations (some local) can offer specialized expertise, which can prove particularly useful in disaster relief efforts. The following list includes a sample of these:

- University of Miami Field Epidemiology Survey Team
- International Disaster Preparedness and Response Team
- Habitat for Humanity
- K-9 Search and Rescue
- United Way

2.2.6 Associations and Other Organizations

Several professional associations provide professional development, education, outreach and other services for personnel working in this field. The associations are as follows:

- National Coordinating Council of Emergency Management
- National Emergency Management Association
- Florida Emergency Medicine Foundation
- National Building Protection Council
- Medical Examiner Association
- Insurance Institute for Property Loss Reduction
- Insurance Information Institute
- Southern Building Code Congress
- National Committee on Property Insurance
- Wind Engineering Research Council
- Electric Power Research Institute
- National Association of State Energy Officials
- Association of Contingency Planners

- Florida Emergency Preparedness Association
- Emergency Management Planners
- Central United States Earthquake Consortium
- Institute of Emergency Administration and Fire Science
- Solar Energy Industries Association

A few research institutes have been established with a specific area of study. Some examples are as follows:

- Disaster Research Center/Delaware - Research in sociology and social psychology, including scientific studies of the reactions of groups and organizations in community-wide emergencies, particularly disasters, and how resulting problems are solved by affected persons and communities; response planning and mitigation policy development.

- Center for Disaster Management/New York- Promotes the development and use of information science and technology for decision making and management, especially the development of effective and usable management information systems to assist New York state officials in improving emergency plans and procedures for a variety of disaster contingencies.

Some people working in emergency management or for disaster relief organizations are required to complete training for their position. Some colleges provide training and degree programs for managers, planners and others on various aspects of emergency management and disaster relief.

Some of the nationally recognized Florida institutions that provide such programs are as follows:

- Florida College of Emergency Physicians
- Lewis and Clark Community College
- Emergency Management Institute
- St. Petersburg Junior College

3.0 Energy Needs During Disasters

Disasters, whether man-made or natural, destroy homes and businesses, along with a community's infrastructure. For days and often weeks in the aftermath of a disaster, many people experience disruptions in electrical service, water and sewage system operation, communications, and other services. Vital resources, such as food, water, and medical supplies, may be urgently needed. Clinics, hospitals, fire stations, and police stations may have no utility service or their facilities may be damaged beyond use. The destruction can be so overwhelming that it takes months to restore an area to its pre-disaster condition.

Though extensive areas may be without electricity, many organizations' disaster response activities require electric power. As an example, the American Red Cross provides shelters that require electrical power for lights, radios, air conditioning, refrigerators, computers and various other equipment.

Emergency Operation Centers require large amounts of electrical energy and typically have generators of 25 kW or larger. These centers usually have 20 or more personnel directing recovery efforts. Radios, telephones, fax and copy machines, lights, air conditioning, computers, and other equipment are constantly in use, as shown in Figure 1.

Figure 3.1 Emergency Operation Center.

Feeding stations usually depend on natural gas and propane for cooking; their main electrical power demand is for refrigerators, lighting and fans. Resource Distribution Centers are medium power users and usually need only lights and radios for communications. Sometimes they use electric fork lifts or other power equipment to move supplies.

Electrical power needs for transportation are very different than those for facility operations. Power is needed for traffic lights, street lights, changeable message signs, arrow boards, highway radio advisory systems and many other individual traffic devices.

Over time, each disaster relief organization has gained experience and has developed procedures defining its operation and needs. Each has obtained equipment to support its operations, usually relying on generators or utility power to satisfy equipment needs for electric power. Organizations maintain resource lists that provide size and quantity information on their electric power equipment, including fuel consumption information. Equipment is even prioritized to identify the most critical items and energy needs. The real need for electric power is not defined by energy units consumed, but by a resource, defined and stored for a typical task or operation.

The following table provides typical power requirements for each type of device for each ESF. These power requirements take into consideration differences in manufacturer and sizes used by the various organizations.

Table 3.1. Power Requirements

Device	Power Requirement
ESF 1.Transportation	
Portable highway changeable message signs	500 W
Portable highway advisory radio	160 W
Street lights	120 W
Portable arrow board signs	80 W
Flashing barricade lights	1.5 W
Portable information services radio	160 W
ESF 2. Communications	
Portable Cellular phones	20 W
Call boxes	20 W
Operational base station radios	150 W
Hand-held portable radios	5 W
Radio relay stations	250 W
ESF 3. Public Works	
Portable sump pumps	600 W
Small portable DC power tools	100 W
ESF 4. Fire Fighting	
Portable pumping stations	600 W
ESF 5. Information and Planning	
Cellular phone and battery charger	5 W
Facility power	1000 W
Portable AM/FM radios and TV	10 W
ESF 6. Mass Care	
Flash lights	1.5 W
Portable AM/FM radios	1.5 W
Small battery charger	5 W
Outside security lighting	120 W
Inside lighting	500 W
Portable refrigerators	500 W
Water purification	500 W
ESF 7. Resource Support	
Communications equipment	250 W
Portable PV generator	600 W

Device	Power Requirement
ESF 8. Health and Medical	
Flash lights	1.5 W
Small battery chargers	5 W
Facility power	600 W
Outside security light	120 W
Inside lights	500 W
Medical equipment PV generator	500 W
Portable refrigerators	500 W
Water purifications	240 W
Water heater	1000 W
Communications equipment	240 W
ESF 9. Search and Rescue	
Flash light	5 W
Small battery charger	5 W
Sensing equipment	260 W
Communication equipment	240 W
ESF 10. Environmental Protection and Hazardous Material	
Sensing equipment	260 W
Outside security light	120 W
Communications equipment	240 W
ESF 11. Food and Water	
Portable refrigerators	500 W
Outside security lights	120 W
Inside lighting	300 W
ESF 12. Energy	
Mobile PV generators for AC	1000 W
ESF 13. Military Support	
Mobile PV generator	1000 W
ESF 14. Public Information	
Cellular phone and battery charger	5 W
Facility power	1000 W
Portable AM/FM radios and TV	10 W
ESF 15. Volunteer and Donations	
Outside security lights	120 W
Inside lighting	300 W
ESF 16. Law Enforcement	
Outside security lights	120 W
Inside lighting	300 W
Communications equipment	600 W
ESF 17. Animal Issues	
Outside security lights	120 W
Inside lighting	300 W
Water purifications	240 W

Of the various types of disasters, hurricanes and floods are the most common. In response to these disasters, the longest time most people are without conventional electricity is generally over 6 weeks, with most of the disaster victims being without electricity for between 2 and 6 weeks. About half of the population are without conventional electricity for over 3 days after the disaster.

The loss of electric power quickly makes us realize how dependent our society is on electricity. Medical, fire and police services are needed immediately after a disaster and during the period of reconstruction. Communication is very important to emergency personnel who need to request assistance, supplies and information. It would be a difficult task to rebuild businesses and homes without the usual services of water, sewer and electricity. Emergency Management Teams, the military, and countless public and private organizations providing recovery efforts require varying amounts of electrical power.

The Emergency Support Functions performed by the many emergency management organizations cover a wide spectrum of relief and recovery efforts. Many of the resources needed to perform these support functions require stand-alone electrical power. Fast and deliberate deployment of equipment is needed in response to a disaster; therefore, ready-to-use systems designed for individual applications are most effective.

In large-scale disasters, power can be out for long periods of time and survivor support is difficult to provide due to the extensive area affected. Massive infrastructure damage makes roads impassable and resources are difficult to transport. Pumping stations for water and sewer are often inoperable. Power distribution lines are difficult to fix because of impassable roads, which hinder the transport of personnel and materials for reconstruction.

Sometimes, makeshift shelters and temporary medical clinics are set up in buildings that received little damage and are safe to occupy. They need electrical power to provide medical services to injured people. Personnel may need to deal with issues such as disease control, producing a need for vaccine refrigerators. They may also need electricity to provide hot water, to sterilize instruments and to power equipment for laboratory work.

Recovery efforts are hampered by the loss of local business and services, both when buildings are destroyed and when an area simply loses electrical power. In turn, if these are long-term losses, they can damage the local economy, as people lose jobs.

This scenario serves to show how well-suited photovoltaics are to disaster relief work. Portable, quiet, and non-polluting, photovoltaic equipment can power medical clinics, radios, highway signs, and a myriad of other machinery essential to relief and recovery efforts.

4.0 RESTORING UTILITY POWER

Natural and man-made disasters are taking an ever increasing economic and personal toll. Each year, about 10,000 violent thunderstorms, 5,000 floods and 1,000 tornadoes strike the United States. Natural disasters have cost an average of at least 8 billion dollars per year over the last 30 years, with Hurricane Andrew alone resulting in losses of 30 billion dollars. These and other costly disasters have caused utilities to lose business and commercial customers.

As a result, utilities have developed their own disaster recover plans and are working with various organizations such as EPRI to reduce the economic and personal effect of disasters. A new project called Disaster Recovery Business Alliance has been formed within EPRI to establish processes and tools to mitigate the effects of disasters. Its purpose is to build public-private partnerships to mitigate disasters and relieve disaster losses. The various organizations involved have stepped up their efforts to deploy mitigation technologies and techniques and business recovery support. Part of the program deals with identifying technologies that can help utilities and their customers to train, warn, mitigate, respond to and recover from a disaster, and also to support communities with post disaster recovery efforts.

Each disaster plan addresses the type of utility and services performed, along with the types of disasters that utility experiences. The plan establishes main headquarters for the emergency operation center and usually an alternative headquarters. Lines of communication and responsibility are clearly defined to ensure effective coordination of efforts. Redundant communications and access to systems drawings and data must be prepared for use at selected emergency headquarters. Drills need to be planned and conducted periodically, along with tests of various entities.

Mutual aid partners need to be established for efficient and effective response. For example, an important resource is having spare parts to replace components damaged in a disaster, which can be tens of thousands of pieces. Many utilities regularly exchange data on distribution parts and materials that can be made available to neighboring companies on short notice. The Edison Electric Institute created and maintains the Mutual Assistance Plan, which compiles and updates a list of transmission and distribution equipment that its member utilities can make available to their neighbors. The North American Electric Reliability Council keeps a comprehensive database listing the available equipment on major power transformers from virtually every utility in the country.

Crews and repair equipment are shared to reduce restoration times and relieve crews of the affected utility. Logistics is a critical function, which includes providing lodging for crews and preparing meals for emergency workers.

After the disaster, evaluation teams are deployed to survey the damage so repair schedules can be made. Two and three person crews generally work from the end of the feeder in towards the substation, with one crew erecting poles, followed by crews hanging pole hardware and transformers, and then by crews stringing conductors. The prime intent is to restore basic service as quickly as possible, and complete standard installations later. Customers not in a position to accept service, either because they have no house or because the service entrances are too badly damaged to re-power the house are left to the future. Reconnecting damaged buildings without proper building inspection would invite fires, so house-to-house site inspections are done before feeders are energized. Power can be restored to those houses ready for occupancy.

Utilities implement their service restoration plan after a major storm or disaster. This plan emphasizes safety and efficiency while restoring service as quickly as possible. Most plans have two basic priorities. The first priority is to restore power for essential services. Immediately after a disaster, a thorough damage assessment is made. Then repair crews initially restore service to those customers who provide health, safety and other essential services to the community. These groups include:

- Communications stations such as emergency radio systems, telephones and television
- Hospitals
- Public services such as Red Cross facilities
- Designated sewage pump and disposal plants and water supply utilities
- Transportation providers such as airports, electrically operated bridges and rapid transit systems

The second priority is to repair power lines that restore power in the shortest period of time to the largest number of customers. This occurs before repair crews begin the more time consuming task of restoring service to individual homes and businesses.

If the storm or disaster is major, the utility knows which areas are the most heavily damaged. Customers living is those areas do not have to report that service is out because the assessment teams have already identified them. It is important that downed power lines that are sparking or obviously unsafe equipment be reported and that these areas be avoided.

Portable generators can be a problem and a safety issue for electric utilities when used improperly by their customers. The following operating practices apply to portable generators:

- Do not connect a power generator directly to a home's main fuse box or circuit panel.
- Use heavy duty, properly grounded extension cords to connect an appliance to a generator.
- Make sure that extensions cords are not frayed or worn.

Customer perception of the restoration operation is important. Customer service representatives and media liaisons need to get the message out fast enough to the customer so he feels that the utility knows what it's doing and that the customers are not helpless. Most utilities have web pages, hotlines or brochures that provide information on what to do during and after a disaster.

5.0 Portable Generator Power

In America, we take electrical power for granted. We experience small interruptions in power when, for example, a car knocks down a supply pole or an electrical storm damages a transformer. In these cases, power is interrupted for a few minutes or hours or maybe for a day. Such inconveniences force most home and business owners to slow down until power is restored. Few people turn to alternative power sources such as generators to operate lights and other non-critical systems. However this scenario changes dramatically when major natural disasters cut off the supply of power for days, even weeks. The typical duration without conventional electricity following a disaster is from two to six weeks.

Figure 5.1 Military generator used in hurricane Andrew.

In 1992, Hurricane Andrew left three million homes and businesses in Dade County without electrical power. The Dade County Emergency Operations Center (EOC) has two large generators to power the facility during outages or disasters. The county's Emergency Management Plan calls for the deployment of generators to critical facilities and shelters where needed. During this disaster, it was estimated that about 8,000 portable generators were used. There are accounts of some people becoming so desperate for electricity that they were paying $2,000 for a $500 generator. Often generators are provided by insurers under the Additional Living Expense portion of a typical homeowners policy. About 85-90% of those insured are eligible for generators under homeowners' policies.

Many local governments have support contracts with generator suppliers to provide generators on demand during a disaster. About 95% of these generators are powered by gasoline, with the rest using propane, diesel, or natural gas. Portable generators can provide varying amounts of power up to 100 kW or more. They can be configured as hybrid systems interfacing with photovoltaics, wind, or another electrical power source.

Generator power is not provided without a price; current high fuels costs and, more importantly, safety problems are issues to consider. Small generators account for post-disaster burns, fuel explosions, and asphyxiation, particularly with the homeowner user. In addition, many new users do not select the best generators for their purpose, which leads to cost overruns and power shortages. Medical and communications workers also complain that the noise from generators is annoying and adds to the trauma of victims.

Fossil fuel generators, however, will probably remain the mainstay of emergency power for a long time to come. Their small physical size to power output ratio, portability, and large power outputs make them a valued resource in a disaster. Their benefits and limitations need to be understood for safe and proper deployment.

5.1 How Generators Work

The whole thing started in 1821 when people first learned to take a coil of wire and pass it through a magnetic field to produce electricity. Conversely, applying a magnetic field to a coil can create a force. These simple theories have become the crux of modern electrical motors, dynamos, and alternators. This section describes the basic parts of a generator and can serve as an aid for their repair and efficient use in the field. Most generators that will be used in the field as self contained power supplies are composed of three basic parts: a generator (dynamo), a fossil fuel locomotion source, and a power conditioning system.

The dynamo converts the locomotion provided by an external source into current by turning a coil of wire through a magnetic field. The speed at which the coil is spun dictates the frequency of the output power. There are two types of dynamos: those that produce AC and those that produce DC current. The mechanics are basically the same. Although the dynamo is the most reliable part of a generator, some of its components can fail. For the output of electricity to be clean and at a stable frequency (say 60hz), the locomotion must turn the dynamo at a steady rate. A dynamo is a mechanical device and therefore suffers from wear. There are many points of physical contact within the dynamo, most notably the contact between the brushes and the commutator (the spinning coil of wire). If these contacts melt or become pitted, the generator will operate inefficiently or even overheat.

The fossil fuel engine, which supplies the locomotion to turn the dynamo, is probably the least reliable and most often replaced part of a generator. The many different types of engines on the market range from small, single-cylinder air-cooled engines to multi-cylinder liquid-cooled engines. If the total run time of the generator is about 50 hours yearly, a single-cylinder air-cooled engine can work nicely. However if the run time is 200 or more hours yearly, a much larger multi-cylinder unit is a better choice. A big consideration of running a generator is keeping it at a steady cool temperature. The larger liquid-cooled engines have an advantage over their smaller counterparts because a liquid-cooled engine stays cooler and maintains a steady temperature much better than an air-cooled engine. Another advantage is that liquid-cooled engines are often much quieter. This is especially helpful if the generator will be housed near people.

The third basic part, the power conditioning system, conditions the output to conform to the needed voltage range and the 60hz specification. In addition, the speed at which the engine needs to run is often controlled by the power conditioner's logic circuits. If there is a heavy load on the generator, the speed will increase to meet the demand.

5.2 Generator Applications

The question of how to apply a generator in an outage covers a host of issues . Where are you going to put the generator? It must be sheltered from the rain and the danger of flooding. How are you going to keep the generator cool? What type of fuel is available and how are you going to keep it fueled? Will you need an auxiliary fuel pump and, if so, where are you going to get the power to run it? Can someone run the generator at least once a month, and how are you going to put a load on it? How do you isolate it from the power grid? Are you going to have automatic starting or manual starting when the power goes out? Will the generator be readily accessible before and during the storm? Don't forget that the fuel lines and fuel tank must be storm proof as well. What size will meet your needs? Who will get to use the electricity?

Using city water to keep large generators cool may pose a problem. When trees blow over, their roots pull up water mains and you lose the water supply. Air cooling may not be a good idea; it isn't easy to ventilate a room properly under hurricane conditions – either too much water gets in or the room gets too hot. A hot generator is no better than a wet generator. Generators are noisy and air-cooled generators are the noisiest. Now the trend is for a self-contained cooling system. It has its own radiator and fan (just like a car); only the radiator needs to be filled with coolant periodically.

If the application is an emergency shelter, you are going to use the generator full time for several days. so you probably want a "continuous" duty cycle. "Duty cycle" is a term that refers to how long you can run a generator at full power. If the application is your home, you may turn the generator off at night because of the noise.

5.2.1 Critical Facilities

There are certain facilities in a community that are critically needed during and after a disaster. Emergency workers – fire, police, emergency managers, doctors, and other personnel – must be able to occupy and use the fire departments, police stations, emergency operations centers, hospitals, shelters, and various other facilities. Restoring the operation of these critical facilities is very important. If the utility power is out, work virtually stops and the safety of the community is at risk. Having backup generator power is critical so that these facilities can operate continuously. In a recent survey, EOC professionals were asked to put critical facilities and resources in order of priority. Their responses, from most important to least important need, were communication devices, lighting, refrigeration, medical equipment, traffic control devices, water and sewer, and battery charging.

Emergency Operation Centers are usually considered the most important for maintaining or restoring power. Emergency services cannot be effectively deployed if the EOC is without power. EOC typically use very large generators in the range of 50 to 100kW and may have two units at the facility. Other emergency facilities, such as fire stations and hospitals, also use large generators and may have more than one source of backup power. For those operating a hospice or other medical shelter for patients with special requirements, the cost may not be important as the need.

5.2.2 Businesses

Typically, banks have been the only businesses that have used back-up power for security reasons. Since Hurricane Andrew, insurance companies, hardware stores, and gasoline stations have installed generators for backup power. Without these services, the recovery effort is crippled and economic losses are great. Clean up and construction crews also need power to operate their tools and machinery. Businesses typically use medium-size generators in the range of 5 to 15kW to power lights, cash registers, computers, and tools.

5.2.3 Homes

In the wake of a disaster, homeowners use the most generators. They buy anything that makes electricity from 500 watt to 5000 watt generators that use whatever fuel is available. These users are the most dangerous and account for most of post-disaster burns, fuel explosions, and asphyxiation. Utility workers repairing downed power lines watch for generators connected to a home's power panel that can feed back onto the grid and endanger workers.

For minor outages backup power may not be needed, as the utility usually restores power shortly. In a disaster, homeowners may leave the area and not need power until they return to repair damage. If the home was designed with an emergency power panel a generator or other backup power supply could be safely connected to the home to provide electricity for necessities.

5.3 Which Generator is Right For You?

Since there is a wide variety of generators on the market in many configurations, the task of picking the right generator in a disaster situation can be daunting. There are three critical areas to consider when making this decision: size, fuel, and environment.

5.3.1 Size

Size is determined by the users' electrical needs (for example, emergency manager at the EOC). Everything electrical adds to the load, which adds to the cost. You would need lights, ventilation, air conditioning, refrigeration, computers, and perhaps other things. How many of each item? You may not include "luxuries," such as air conditioning or refrigeration, as the load and cost go up. Once you decide what your electrical needs are, an electrician can add up your power requirements. Remember that refrigerators or air conditioners have motors and require a power reserve for starting loads. A good rule of thumb is to figure out how much power you need and double it. Doubling ensures that the generator can deliver the power you require without straining or browning out the loads with low voltage.

Generators come in various voltages from 120 single-phase to 240-volt 3-phase to as large as 440/460 VAC at 200,000 kilowatts. When you specify a generator, you need to decide about KVAs, and kilowatts, voltages and phases, duty cycles and starting systems, "Y" connections and Delta connections. The power factor of the load and generator needs to be considered, as this will reduce the amount of power generated. It is also important to note that the rating on the generator is always the maximum amount of power. It is more fuel efficient to run a generator at no more than 75% of its maximum rated loading. Running the generator at its full load rating will not only be less efficient but will radically shorten the engine's lifetime. Many generators are rated using resistive electrical loads. If you run reactive loads like battery chargers and electrical motors, the poor power factor of these loads actually increases the loading on the generator. Since most of the loads you need to power are reactive loads, consider derating the generator by 25%. This derating should give you ample room to prepare for the added load.

5.3.2 Fuel

There are four different fuels used in generators: gasoline, natural gas, propane, and diesel, with gasoline being used about 95% of the time. A fifth fuel, bio-diesel, is relatively new to the market and is both renewable and cleaner burning. With each fuel, storage, shelf life, availability, transportation, cost, performance, safety, and environmental impact need to be considered. None of these fuels (except bio-diesel) is renewable. Fuel choice should be based on two main factors: the number of hours you plan to put on the generator and fuel availability. If you are merely backing up systems with small loads or using it for infrequent outages, a gasoline generator is probably the best choice because of its relatively small initial cost. If you have ready access to natural gas or propane and have a heavy load to place on the generator, a natural gas- or propane-fueled generator is the way to go. Although the initial cost is much higher, these choices offer higher efficiency and cleaner exhaust.

Gasoline: As a liquid, gasoline is fairly easy to store and transport by several means. In addition, since many support vehicles use gasoline as a fuel source; they can be a ready source and safe storage for emergency fuel. While not too expensive, most of it is imported and may not always be readily available or affordable. Safety is a problem, too. Seventy percent of all generator fires involve gasoline-powered generators. Gasoline requires special safety precautions. It evaporates very easily and its vapors are explosive. If you opt for gasoline, you will need battery-operated ventilation fans running before you start the generator. Emissions from gasoline are hazardous and add to the effect of greenhouse gasses.

Natural Gas/Propane: Both natural gas and propane fuels are easy to store and to transport. Each is economical, and doesn't require a fuel pump. Since it is delivered to the engine as a gas, gas leaks are a possibility. Instruments are available that can monitor for leaks and for the safety of ventilation systems. Even with the possibility of a gas leak, both of these fuels are safer than gasoline.

Diesel/Bio-Diesel: Like gasoline, diesel is a liquid and is fairly easy to store and transport by several means. It is the most efficient way to run a generator. Diesel fuel does not readily evaporate into an explosive mixture and now comes in a renewable form known as bio-diesel. Diesel engines are more expensive, though, and require more frequent fuel filter changes. This raises the overall maintenance cost, but diesel is still a sound choice.

5.3.3 Noise & Maintenance

Engine noise is a large concern for many. In fact, it is the second largest problem, next to fueling, reported by workers in the field. All generators produce noise as well as electricity, but there are a few simple things you can do to reduce this byproduct. When selecting a generator for purchase, start the unit in the store if possible and gauge its output. Usually, the cheaper the generator, the more noisy it is. There are a wide variety of models in the same output/size range that produce drastically different amounts of noise. Pick one with a good muffler and, if possible, with water cooling. The best solution is to house the generator in a separate, nearby structure that has good ventilation and sound proofing.

Most generators require many hours of care. They have a wide variety of mechanical parts, which wear over time, so preventive maintenance is very important. One of the easiest and most common preventive measures is changing the oil. On average, most generators have an oil change cycle of about 25 hours of use. The more expensive the generator, the longer the oil change interval. Some larger units have an interval of 100 hours of use. While noise is a large problem, people often use devices or configurations that lessen the noise but that also stifle the engine and release more fumes into an area. Be sure that when you are combating noise, you don't lose efficiency or unintentionally load down the generator. One good solution is to house the generator in a separate shelter with protection from the elements and sound insulation.

6.0 OTHER SOURCES OF POWER

There are several energy sources available for use in disasters with each having its own limitation and benefits.

The following is a list of energy sources beyond gasoline and diesel generators and utility grid system.

Photovoltaic systems
Solar Thermal system
Fuel cell generators
Hydro-generators
Wind-generators
Bio-mass

7.0 Solar Energy

7.1 Basic Concepts

The following ideas are fundamental to the photovoltaic process.

7.1.1 Energy and Power

Energy is the capacity for doing work. Power is the rate of doing work or expending energy.

Energy

- Capacity for doing work
- Symbol: E
- Units: kWh

Power

- Rate of doing work
- Symbol: P
- Units: kW, or watts

$$\text{Power} = \frac{\text{Energy}}{\text{Time}}$$

Light drives the photovoltaic process and provides the energy that is converted into electricity. The total amount of solar power striking the earth's surface at any given time is about 1.2×10^{17} watts.

7.1.2 Irradiance

The amount of solar power available per unit area is known as irradiance.

Irradiance, or radiant-flux density:

- Radiant power per unit area
- Symbol: H
- Units: kW/m^2, or watts/m^2, or mW/cm^2
- Measuring device: Pyranometer (e.g., Eppley PSP)
- Reference (solar) cells
- Peak value (used in rating): 1 kW/m^2 (1000 watts/m^2, 100 mW/cm^2)
- Nominal value: 0.8 kW/m^2 (800 watts/m^2, 80 mW/cm^2)

Irradiance fluctuates according to the weather and the sun's location in the sky. This location constantly changes throughout the day due to changes in both the sun's altitude (or elevation) angle and its azimuth (or compass) angle. Figure 7.1 shows the two angles (the sun's altitude or elevation angle and the sun's azimuth or compass angle) used to specify the sun's location in the sky.

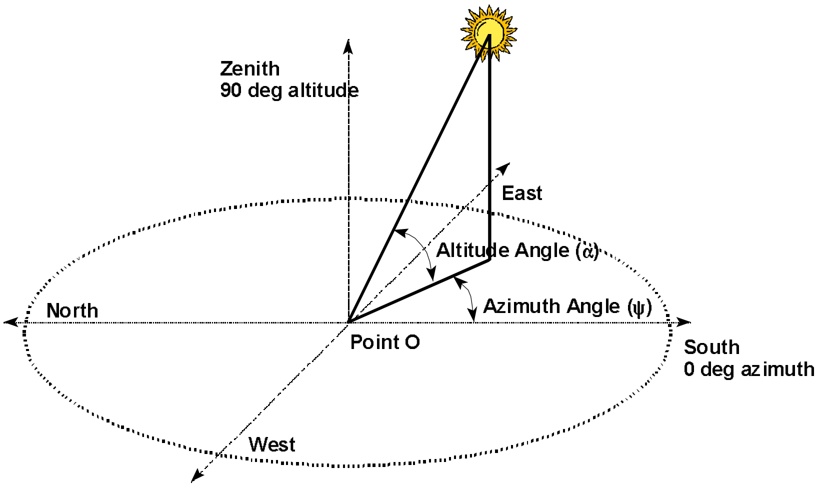


Figure 7.1 Sun's position in the sky.

7.1.3 Solar Constant

Although photovoltaic devices can be powered by artificial light, their value lies in their ability to use free and renewable sunlight. A photovoltaic device that is outside the earth's atmosphere and that maintains normal incidence to the sun's rays receives a nearly constant rate of energy. This amount, called the solar constant, is approximately 1.36 kW/m^2. The solar constant and the associated solar spectrum immediately outside the earth's atmosphere are determined solely by the nature of the radiating source (i.e., the sun) and the distance between the earth and the sun.

$$\text{Solar constant} = 1.36 \text{ kW/m}^2$$

Whereas the solar constant is a measurement of solar power density outside of the earth's atmosphere, terrestrial applications of photovoltaic (or any solar) devices are complicated by, and must take into consideration, two variables: 1) geometric effects, including the earth's rotation about its tilted axis and its orbital revolution about the sun, and 2) atmospheric effects.

7.2 Geometric Effects

7.2.1 Hourly and Seasonal Variations

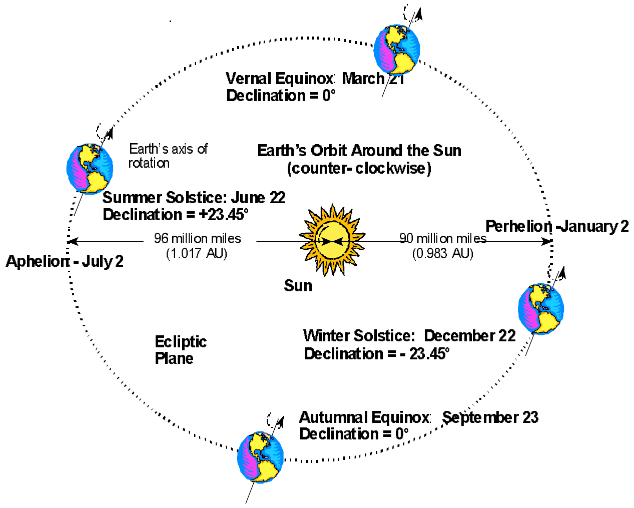


Figure 7.2 Earth's orbit and seasons of the year.

The earth's rotation about its axis produces hourly variations in power intensities at a given location on the ground during the daytime and results in complete shading during the nighttime. In addition, a device located in the northern hemisphere receives more energy during the summer than in winter, thus giving rise to seasonal variations in power intensities. Figure 7.2 illustrates the earth's orbit and seasons of the year.

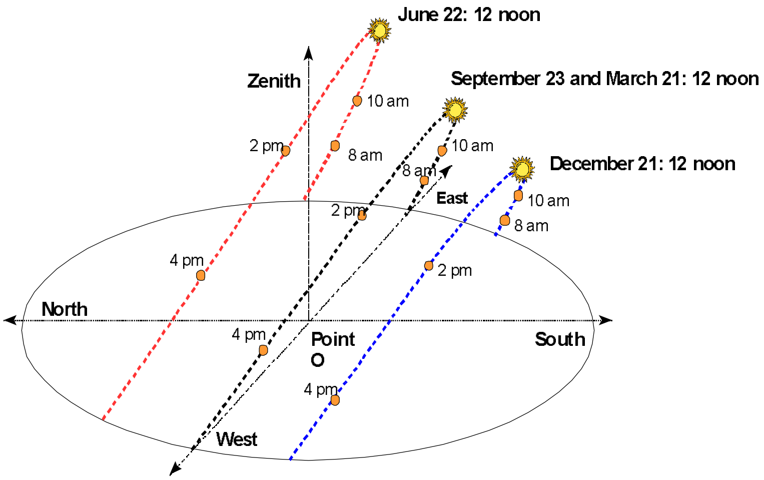


Figure 7.3 Sun paths for 30° N latitude.

Figure 7.3 illustrates the seasonal changes in the sun's path for a given location. This example, for 30° North latitude, shows that in winter the sun rises in the Southeast, sets in the Southwest, has a relatively short path and rises to a shallow angle above the horizon at noon. In summer, the sun rises in the Northeast, sets in the Northwest, has a longer path and rises to a much higher angle above the horizon at noon.

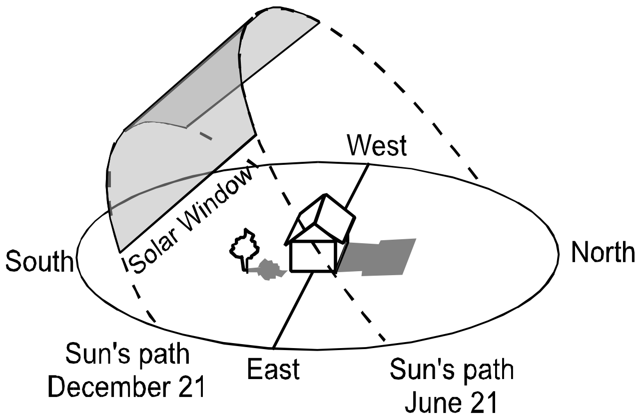


Figure 7.4 The solar window.

7.2.2 Solar Window

The solar window represents the effective area through which useful levels of sunlight pass throughout the year for a specific location. The solar window is used to determine potential shading problems when designing a photovoltaic system as illustrated in Figure 7.4.

7.2.3 Receiver Orientation and Relationship to Application

Specifying the receiver orientation is an important step in the design process and depends not only upon location, but also the type of system (e.g., stand-alone or utility-interactive) and the application.

If the demand for electricity is relatively constant throughout the year, receiver orientation for a stand-alone system is usually based on a worst month or worst season level of insolation. If electric demand varies significantly, the receiver should be tilted to maximize the solar energy collected when it is most needed. Figure 7.5 shows that the optimum array tilt during the summer months is nearly horizontal, whereas the optimum array tilt in the winter is much steeper.

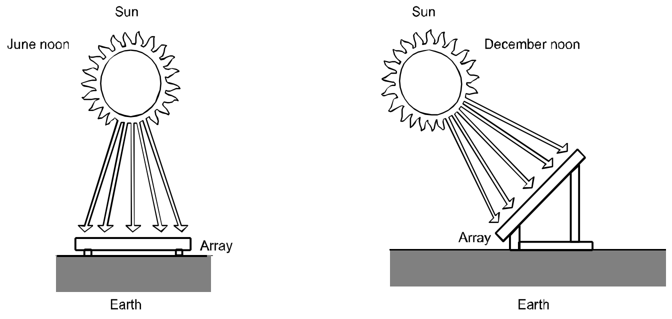
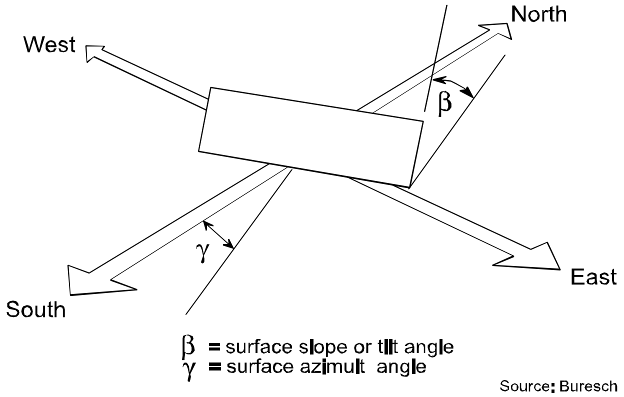


Figure 7.5 Optimum array tilt for June and December.

The receiver for utility-interactive systems should be tilted to maximize annual energy production. For fixed orientation systems, this tilt angle (between the collector surface and the horizontal) is approximately equal to 90% of the local latitude. Receivers in the northern hemisphere should be south facing, while those in the southern hemisphere should be north facing. Figure 7.6 shows the two angles, B and γ, that must be given to specify the orientation of a flat-plate array surface. For a sun-tracking device, one or both of these angles will vary with time.



Source: Buresch

Figure 7.6 Orientation of array surface.

7.3 Atmospheric Effects

The presence of the atmosphere and associated climatic effects both attenuate and change the nature of the solar energy resource. The combination of reflection, absorption (filtering), refraction and scattering result in highly dynamic radiation levels at any given location on the earth's surface. Because of cloud cover and scattering of sunlight, the radiation received at a point is both direct (or beam) and diffuse (or scattered). Figure 7.7 illustrates the atmospheric effects on solar energy reaching the earth.

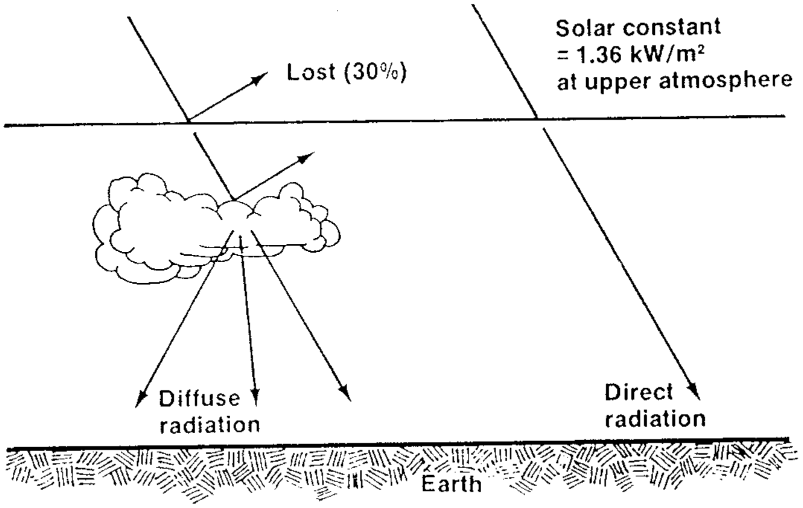


Figure 7.7 Atmospheric effects.

Air mass, defined as 1/cos q (where q is the angle between the sun and directly overhead), is a useful quantity in dealing with atmospheric effects. Air mass indicates the relative distance that light must travel through the atmosphere to a given location.

Because there are no effects due to air attenuation immediately outside the earth's atmosphere, this condition is referred to as air mass zero (AMO). Air mass one (AM1) corresponds to the sun being directly overhead. Air mass 1.5 (AM1.5), however, is considered more representative of average terrestrial conditions and is commonly used as a reference condition in rating photovoltaic modules and arrays. Figure 7.8 shows the relative distance through the earth's atmosphere that the sun's rays must pass at two times during the day.

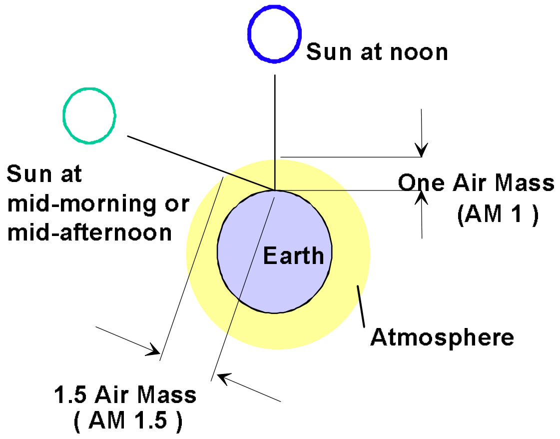
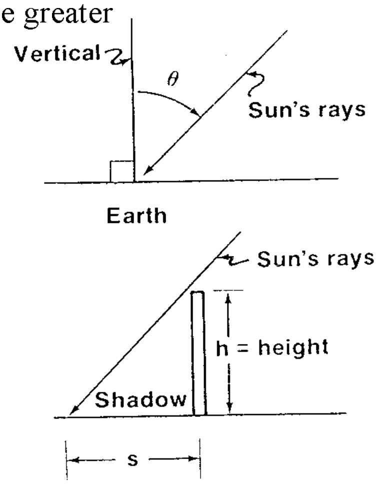


Figure 7.8 Sun's angle of incidence versus distance through atmosphere.

The value of air mass at any given time and location can be easily computed using the relations shown in Figure 7.9. The higher the value of air mass, the greater the attenuating effect of the atmosphere.

$$\text{Air mass} = \frac{1}{\cos\theta}$$



$$\text{Air mass} = \sqrt{1 + \left(\frac{s}{h}\right)^2}$$

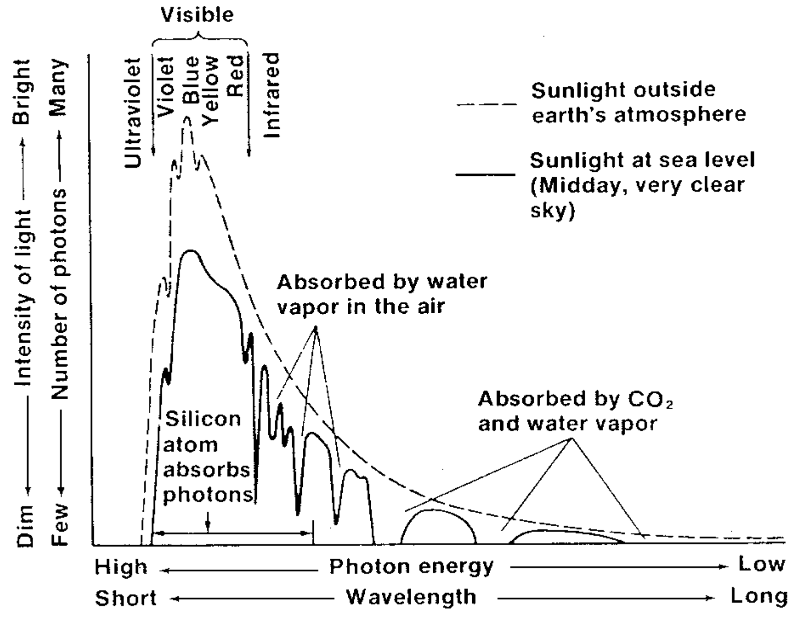
Figure 7.9 Air mass formulas.

7.4 Solar Spectrum

The sun radiates power over a continuous band, or spectrum, of electromagnetic wavelengths. Power levels for the various wavelengths in the solar spectrum are not the same.

7.4.1 Ultraviolet, Visible and Infrared Radiation

The sun's total energy is composed of 7% ultraviolet radiation, 47% visible radiation and 46% infrared (heat) radiation. Ultraviolet (UV) radiation causes many materials to degrade and is significantly filtered out by the layer of ozone in the upper atmosphere. Photovoltaic cells primarily use visible radiation. The distribution of colors within light is important because a photovoltaic cell will produce different amounts of current depending on the various colors shining on it. Figure 7.10 illustrates the relative amounts of power in the various wavelengths of the solar spectrum.



Source: Maycock

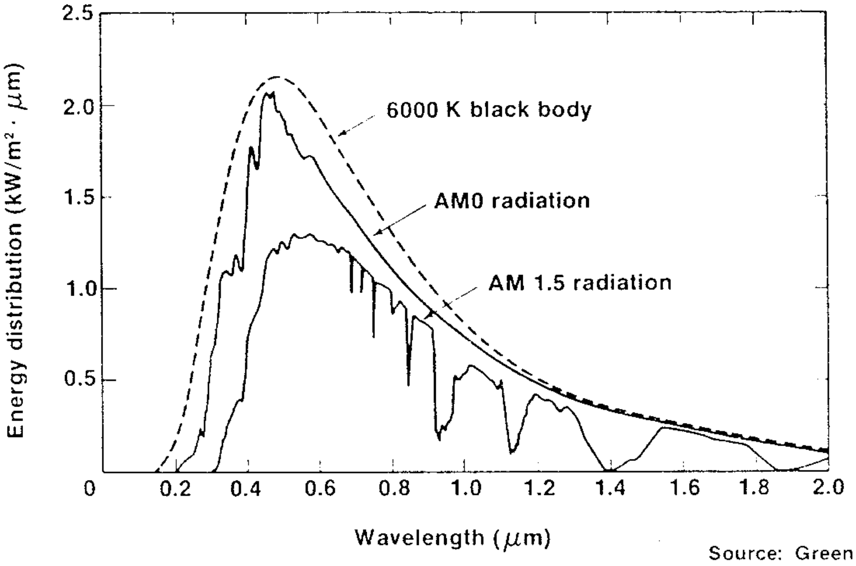
Figure 7.10 The solar spectrum.

Infrared radiation contributes to the production of electricity from crystalline silicon and some other materials. In most cases, however, infrared radiation is not as important as the visible portion of the solar spectrum.

7.4.2 Effect of the Atmosphere on Spectral Energy Distribution

The atmosphere absorbs certain wavelengths of light more than others. The exact spectral distribution of light reaching the earth's surface depends on how much atmosphere the light passes through, as well as the makeup of the atmosphere. In the morning and evening, the sun is low in the sky and lightwaves pass through more atmosphere than at noon. The same is true for winter versus summer.

Different latitudes on the earth have different average thicknesses of atmosphere that sunlight must penetrate. An average value of 1.5 air masses (or AM1.5) has been chosen as a standard atmosphere, which in turn determines a certain spectral distribution to be used for specifying module output. The spectral distribution of sunlight can be plotted for various air mass values, thus providing a useful indcation of atmospheric attenuation effects. Figure 7.11 shows the spectral distribution for AM1.5 in relation to AM0 and a radiating black body at the same temperature as the surface of the sun.



Source: Green

Figure 7.11 Power distribution in sunlight.

7.4.3 Sensitivity of Photovoltaic Materials to Various Wavelengths

The spectral distribution of power is important because different photovoltaic cell materials are stimulated by different portions of the solar spectrum. For example, crystalline silicon responds fairly evenly to most of the visible wavelengths and the near infrared wavelengths up to about 1.1 microns, whereas thin-film silicon favors the blue end of the visible spectrum. (See figures 7.10 and 7.11.) Photovoltaic cell research involves developing materials or combinations of materials which better utilize the power within the solar spectrum.

7.5 Solar Insolation

The results of the earth's motion and atmospheric effects at various locations have led to essentially two types of solar insolation data: average daily and hourly.

Unlike irradiance, which is power per unit area, solar insolation is radiant energy per unit area. Solar insolation is determined by summing solar irradiance over time and it is usually expressed in units of kWh/m^2 per day.

7.6 Average Daily Solar Radiation Data for Each of the 12 Months

To provide long-term average daily solar radiation data, daily solar radiation for each month is averaged over past years (typically 30 years). These data are useful both in predicting long-term performance and in analyzing the economics of solar energy systems. The actual average daily solar radiation for a given month may vary significantly from the long-term average for that month.

Average daily solar radiation can be obtained from various sources, one of which is the Solar Energy Research Institute's Insolation Data Manual. Data from one source may differ somewhat from another.

7.6.1 Peak Sun Hours

The number of peak sun hours per day at a given location is the equivalent time (in hours) at peak sun condition (i.e., at 1 kW/m^2) that yields the same total insolation. Figure 7.13 shows how peak sun hours are determined by constructing a graph having the same area as that for the actual irradiance versus time.

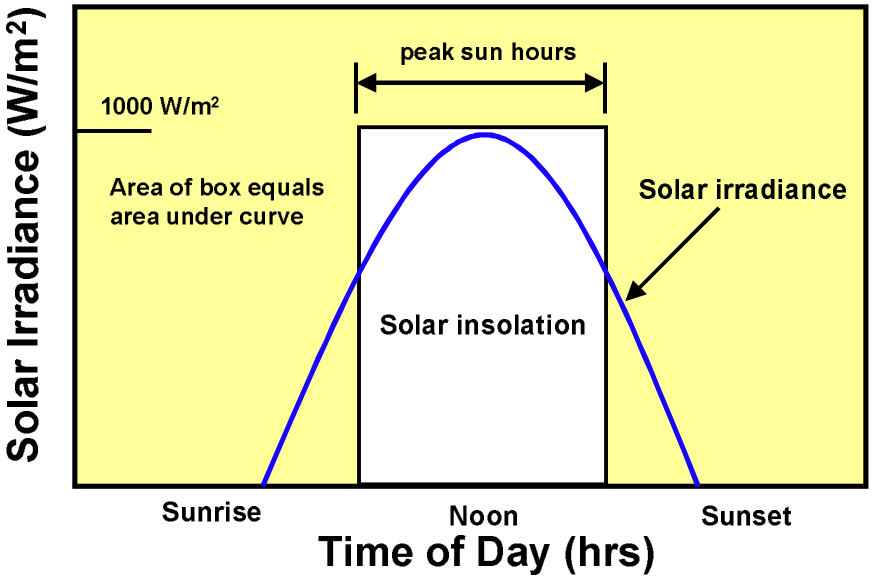


Figure 7.13 Peak sun hours.

7.6.2 Hourly Solar Radiation Data for Each of the 12 Months for a Typical Year

Typical meteorological year (TMY) data are the result of statistical analysis of SOLMET (i.e., solar and meteorological) rehabilitated weather data for past years. The TMY consists of 12 months, with each month selected so that it best represents the average of that particular month over past years. Therefore, the typical meteorological year is a composite year with representative months selected from different years.

To select a representative month such as January, each month of January for past years is compared with the average January of all the years. The one closest to the average is used. The selection is weighted 50% on solar radiation and 25% each on ambient temperature and wind speed. TMY data are good for photovoltaic system analysis.

TMY data are available for 26 cities from the National Climatic Data Center in Asheville, NC. Less reliable ERSATZ-TMY data (constructed data) are available for an additional 209 U.S. cities.

References:

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2. p. M-54.

3. Khattar, Mukesh, *Solar Radiation Data,* **Fundamentals and Applications of Photovoltaics,** Cape Canaveral, FL: Florida Solar Energy Center, 1983, pp. 2-9 through 2-10.

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8.0 PHOTOVOLTAIC SYSTEMS

8.1 Photovoltaic Cell Response

Photovoltaic cells are devices that convert light into electricity. Because the source of light (or radiation) is usually the sun, they are often referred to as solar cells. The word photovoltaic comes from photo, meaning light, and voltaic, for voltage. The output of a photovoltaic cell (or a connected array of cells) is direct-current (dc) electricity.

8.2 Photovoltaic Effect

A typical photovoltaic cell is a thin rectangular or circular wafer of phosphorous-doped silicon adjacent to a second wafer of boron-doped silicon. The region in which these two layers are in contact, called the p-n (i.e., positive-negative) junction, sets up a permanent electric field. It is this electric field that gives direction to the light-stimulated electrons and allows direct-current electricity to flow.

Light can be thought of as small bullets of pure energy called photons. These photons actually penetrate into the cell, knocking loose electrons that were bound to atoms. When bound electrons are hit by photons and dislodged from their crystal atoms, they gain potential energy and are in a position to move and do useful work before they settle back into a bound state again.

The positions vacated by the electrons, called holes, act in a similar manner to the electrons, but with an associated positive charge. The electric field of the p-n junction acts as a broom, sweeping the free electrons with potential energy in one direction, and the holes in the other. This flow of charge is electric current and the potential energy is called voltage. Common mechanical analogies to these electric quantities are:

- voltage = electrical pressure = force = push
- current = electrical flow = motion + volume = volume rate of flow
- power = rate of doing work = rate of energy gain or loss
- energy = work = (power x time) added up

8.2.1 The Current-Voltage (I-V) Characteristic

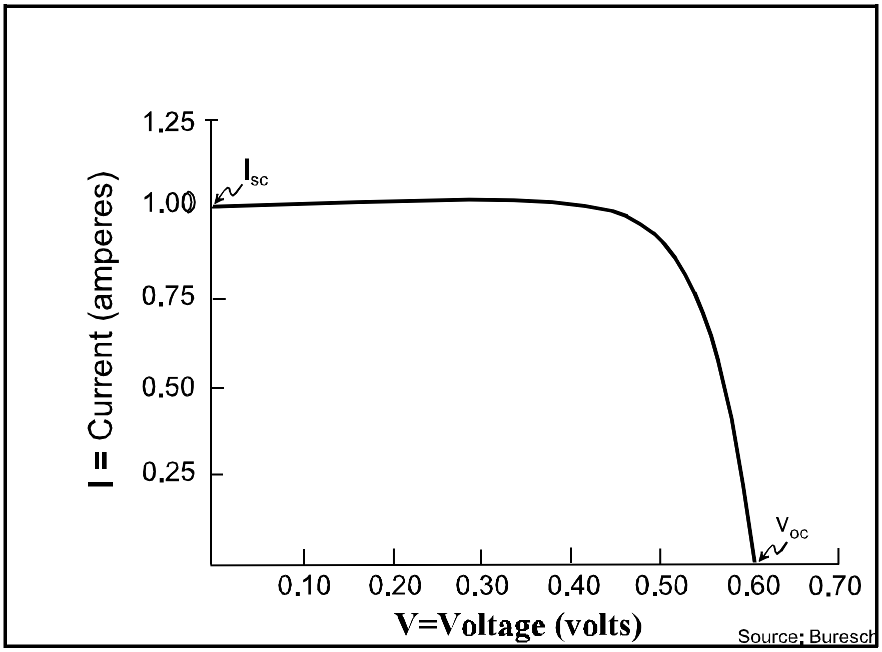
The most important performance descriptor for a photovoltaic device (cell, module or array) is its current-voltage, or I-V, characteristic. (I represents current and V represents voltage.) For a given irradiance, temperature and area, the operating voltage and current vary with the load. By varying the load (say, for example, with a variable resistance) one can measure the corresponding values of current and voltage and thus generate an I-V curve to illustrate the photovoltaic device's performance.

Current will vary from zero (corresponding to infinite resistance or open circuit) to a maximum, called short-circuit current, or Isc (corresponding to zero resistance).

The maximum, or open-circuit, voltage, Voc, corresponds to the infinite resistance condition. Voltage is zero at the short-circuit condition. Thus, Isc and Voc are two limiting parameters that are used to characterize a photovoltaic cell, module or array for a given irradiance, operating temperature and area. In Figure 8.1 each point on the I-V curve represents a possible operating point for a given irradiance, cell temperature and cell area. The actual operating point is determined by the battery voltage, the load or the voltage control electronics package to which the array is connected.

Isc = Short-circuit current
Zero load
Maximum current
Zero voltage

Voc = Open-circuit voltage
Infinite load
zero current
maximum voltage



Source: Buresch

Figure 8.1 Current -voltage (I-V) characteristic for a PV cell

For each point on an I-V curve, the product of the current and voltage represents the power output for that operating condition. By calculating power (current x voltage) for a sufficient number of points, power can be plotted versus voltage (or current, if desired). The voltage at which maximum power is extracted is the desired operating voltage (or maximum power voltage) for a photovoltaic cell, module or array. The photovoltaic cell must be operated at this point to attain maximum efficiency. Figure 8.2 shows that of all the possible operating points for a photovoltaic cell, there is only one voltage (and corresponding current) for which maximum power can be extracted. Note that no power is extracted at open-circuit and short-circuit conditions since the current and voltage are zero, respectively.

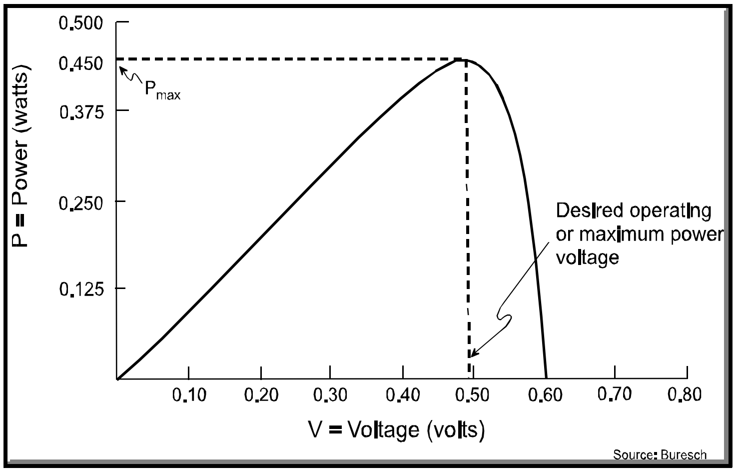


Figure 8.2 Power versus voltage for a PV cell.

The current corresponding to the maximum power voltage, Vmp, is called the maximum power current, Imp. The maximum power point (Pmax) is the point on the I-V curve for which maximum power is extracted. The quantities, Pmax, Imp and Vmp, together with Isc and Voc, are the five parameters that manufacturers use to specify their product's power output under given conditions of irradiance, operating temperature and air mass. Figure 8.3 shows an overlay of the power versus voltage curve and the I-V curve.

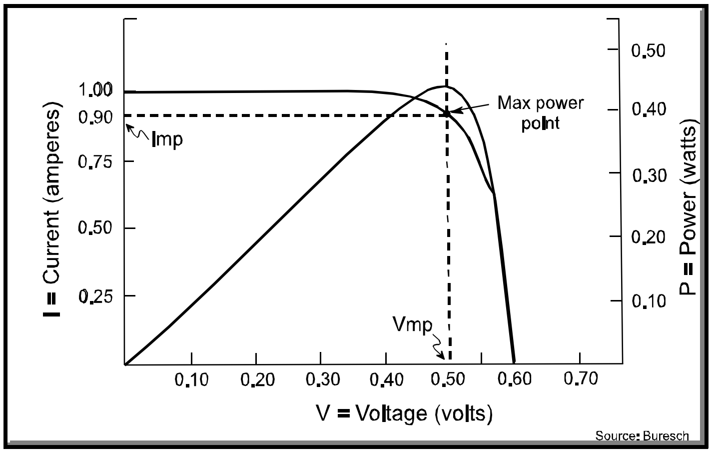
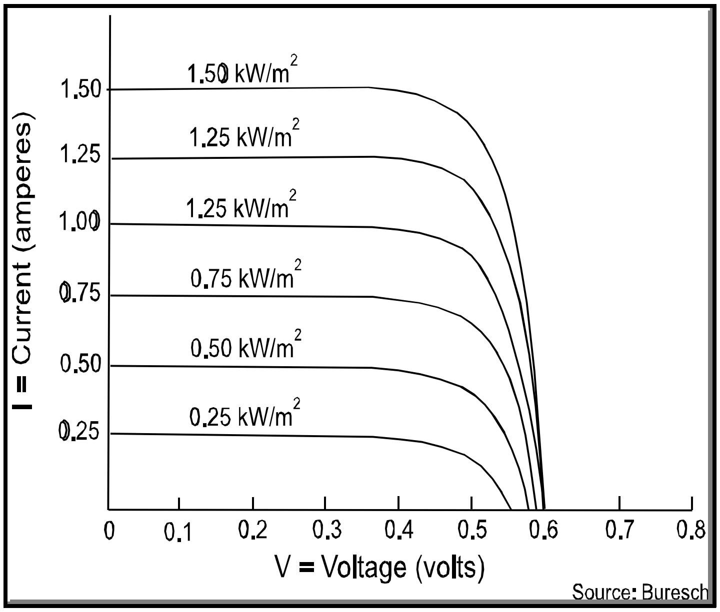


Figure 8.3 Maximum power parameters.

8.2.2 Response to Irradiance

Changes in irradiance level significantly affect output current, but have a much smaller effect on voltage. Figure 8.4 shows the significant effect of the sunlight level on current and the rather small effect on voltage. It is this latter phenomenon that makes photovoltaic devices especially attractive for charging batteries.



Source: Buresch

Figure 8.4 Effect of irradiance on cell response.

8.2.3 Response to Temperature

The operating temperatures of solar cells are important in that higher operating temperatures typically result in lower power outputs and efficiencies; they also decrease cell lifetime. As temperature increases, current increases slightly. Voltage, however, decreases significantly with increases in cell temperature, resulting in a net reduction in power.

8.2.3.1 Nominal Operating Cell Temperature

The nominal operating cell temperature (NOCT) is the temperature at which a cell operates under conditions of 0.8 kW/m^2 irradiance, 20°C ambient temperature, 1.0 m/sec wind speed and array open-circuit conditions.

8.2.3.2 Temperature Correction Factor

Current output, voltage output and consequent power output vary with temperature. If power output for other than a given temperature is desired, a correction factor must be used. The typical correction factor for maximum power is (-0.004/C) for crystalline silicon cells.

8.3 Connecting Photovoltaic Devices

The output of one PV cell is not enough to power most devices. Therefore, cells are connected in series and parallel combinations to increase power production.

8.3.1 Connecting Photovoltaic Devices in Series

Connecting photovoltaic devices in series means the positive terminal of one device is connected to the negative terminal of another device. When similar or matched devices (i.e., identical cells, modules, panels) are connected in series (see Figure 8.5) the voltages add and the current is unaffected.

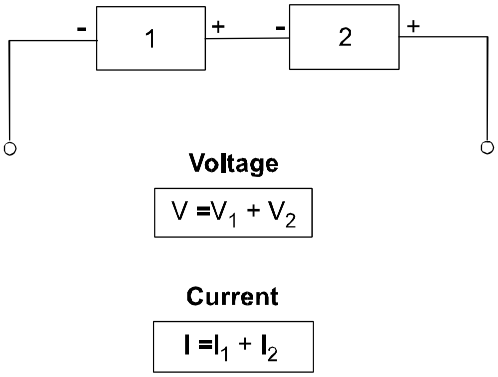


Figure 8.5 Two similar series-connected PV devices.

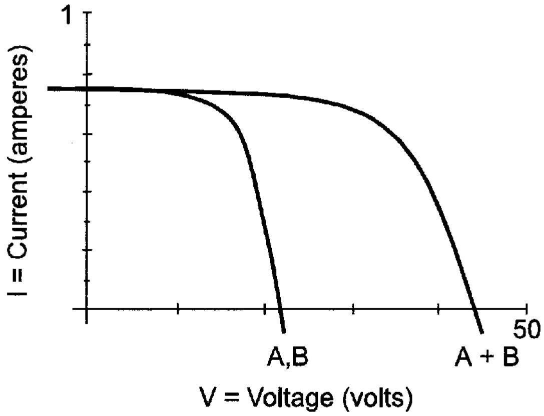


Figure 8.5a I-V curves for two similar series-connected PV devices.

The I-V curves in Figure 8.5a illustrates the effect of connecting similar devices in series.

8.3.2 Connecting Photovoltaic Devices in Parallel

Connecting photovoltaic devices in parallel means the positive terminal of one device is connected to the positive terminal of another device (and the negative terminal of one device is connected to the negative terminal of another device).

Paralleling similar photovoltaic devices causes the individual currents to add while the voltage stays the same, as shown in Figure 8.6.

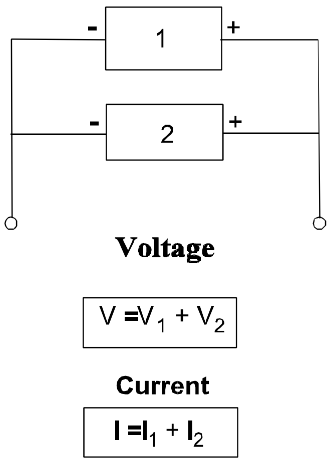


Figure 8.6 Two similar parallel-connected PV devices.

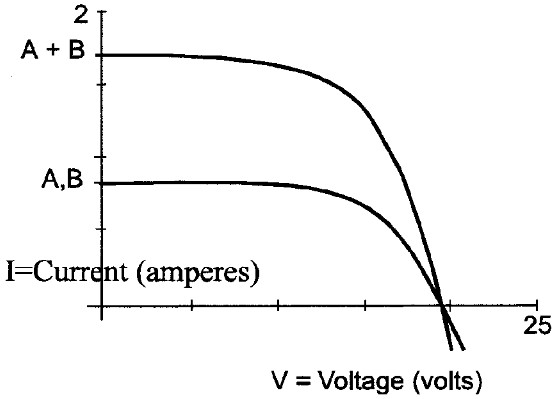


Figure 8.6a curves for two similar parallel-connected photovoltaic devices.

Figure 8.6a illustrates the additive effect of currents on an I-V curve for similar devices connected in parallel.

8.3.3 Dissimilar or Unmatched Devices

When dissimilar or unmatched devices are connected in series voltages still add, but current through the circuit is limited by the weakest device in the series. If there is one module in a string with a lower current output than the others, the current through the string will be approximately equal to that of the module with the least current.

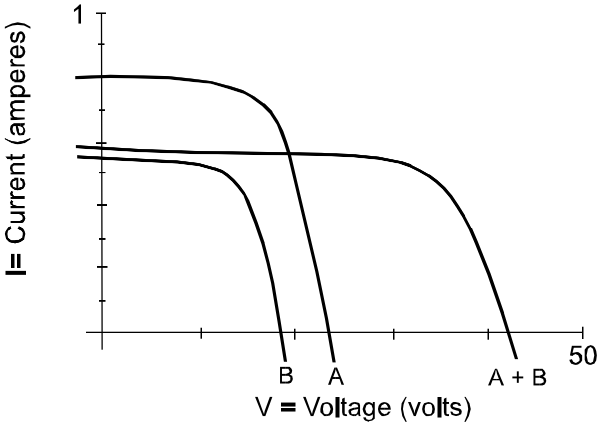


Figure 8.7 I-V curves for two dissimilar PV devices connected in series.

Figure 8.7 shows I-V curves for two dissimilar photovoltaic devices connected in series. In this illustration, device A has a higher current and voltage than device B. When connected in series the total voltage is equal to the voltage of A plus the voltage of B. However, the resulting current is only slightly higher than the current of device B.

Figure 8.8 shows the I-V curves for two dissimilar photovoltaic devices connected in parallel. The two devices, A and B, have different I-V characteristics. When connected in parallel the current of device A and device B are added together to get the total current. The open-circuit voltage is approximately equal to the average of the open-circuit voltages of the two devices.

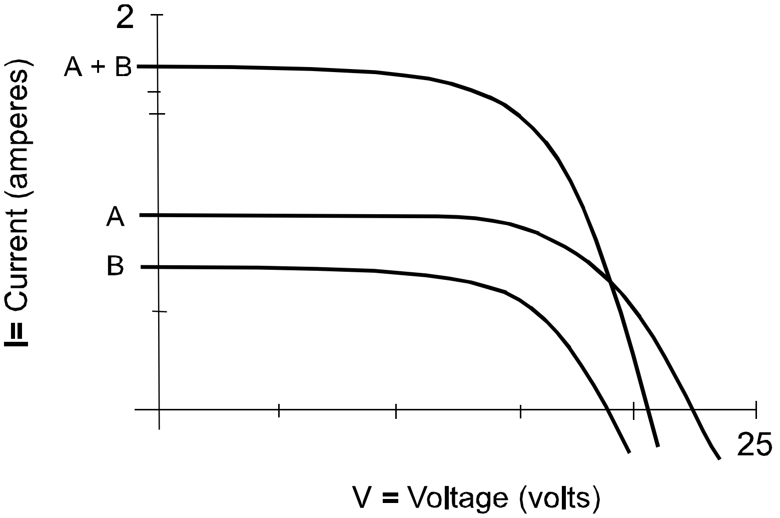


Figure 10.8 curves for two dissimilar parallel-connected PV devices

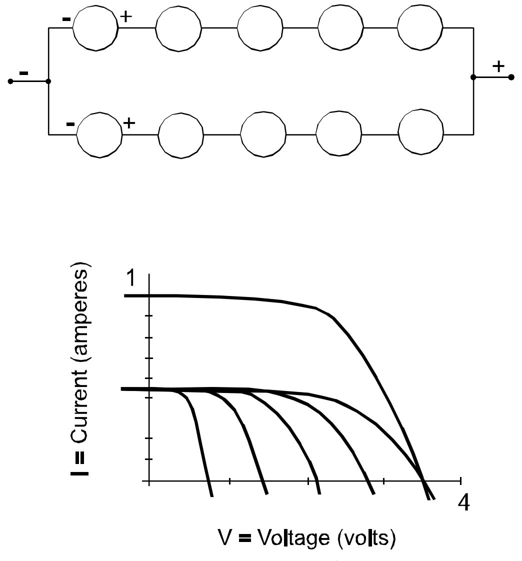


Figure 8.9 series block, five cells per substring.

8.4 Building a Photovoltaic Array

Photovoltaic arrays are designed to meet an electrical need. By connecting modules in series and in parallel, a desired voltage and current output can be obtained.

The cell is the basic building block of a photovoltaic module. Groups of cells connected in series are called strings. Figure 8.9 shows two strings (each string contains five cells) connected in parallel and their associated I-V curves. The two parallel strings are connected to form a series block.

8.4.1 Selecting Arrays

The size of the photovoltaic array is determined by:

- electrical loads
- available solar insolation
- tilt of the array
- characteristics of the individual photovoltaic modules in the array.

8.4.2 Protection Diodes

Diodes, semiconductors that allow current to flow in only one direction, are key components in the wiring of an array. Diodes are used in two ways in a photovoltaic array: as blocking diodes and as bypass diodes. Both of these functions are of fundamental importance in minimizing system power loss.

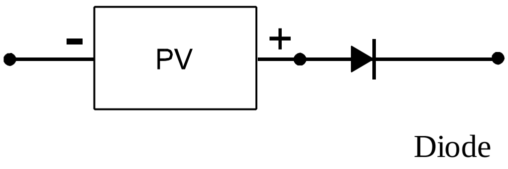


Figure 8.10 Blocking diode

8.4.2.1 Blocking Diodes

Blocking diodes (also known as series or isolation diodes) are placed in series with a module, or string of series-wired modules, to prevent current from flowing backwards through the modules. Figure 8.24 illustrates a blocking diode.

Blocking diodes conduct current during normal system operation and, for stand-alone systems, prevent discharge of batteries at night.

8.4.2.2 Bypass Diodes

In a string of cells in series, if one cell is bad or is shaded from the sun, an open circuit can exist and result in no current flow. Bypass (or shunt) diodes are used to shunt current around rather than through a group of cells or modules when necessary. Bypass diodes bridge the gap so the other cells and modules continue to produce power in the photovoltaic array.

8.5.0 Array Mounting Systems

There are two major array mounting concepts: Ground and building roof.

8.5.1 Roof-Mounted Arrays

There are four generic roof-mounting schemes: standoff, rack, integral and direct. All array mounting designs should provide for ready access in case maintenance or repair is required.

8.5.1.2 Standoff Mounting

Standoff arrays are mounted above and parallel to the roof surface as illustrated in Figure 8.11.

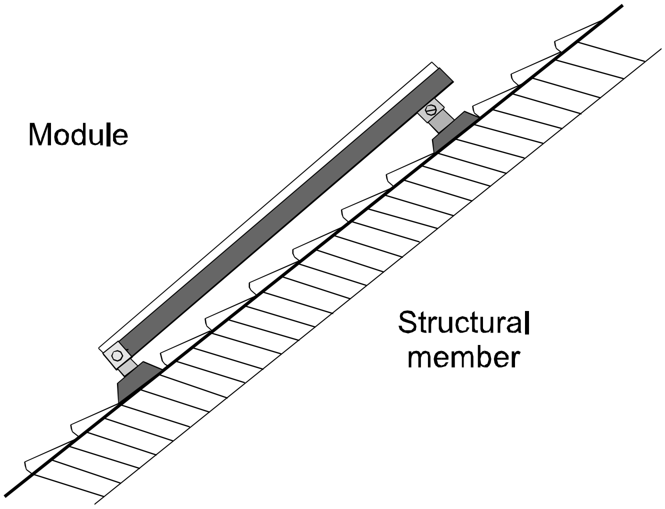


Figure 8.11 Standoff mount.

Standoff mounts work well in both new and retrofit applications for buildings with sloping roofs. When installing a standoff mounted array, affix panels or subarrays to the roof using point connections (usually at the corners of panels or subarrays). Keep the number of point connections and roof penetrations to a minimum. Maintain at least three inches between the roof and the bottom of the module frame.

Design considerations for standoff mounting are:

- Designs that allow for both lateral and vertical airflow can be expected to lower operating temperatures.
- Designs that induce pressure differences between air inlet and exit regions can be expected to lower operating temperatures due to increased airflow.
- Arrays with a higher ratio of lateral to vertical dimension may operate at lower temperatures than those with lower aspect ratios.

Standoff mounts can significantly reduce heat gain in attics.

8..5.1.3 Rack Mounting

Rack-mounted arrays are above and tilted at a non-zero angle to the roof, as illustrated in Figure 8.12. Rack mounts are recommended for flat roofs and roofs with a slope of 2 in 12 or less. Rack mounts are usually subjected to higher structural loads, incur higher costs for mounting hardware, and are less attractive than standoff mounts. However, for the same array area, the total energy output is often somewhat higher because of optimized orientation and lower average operating temperatures.

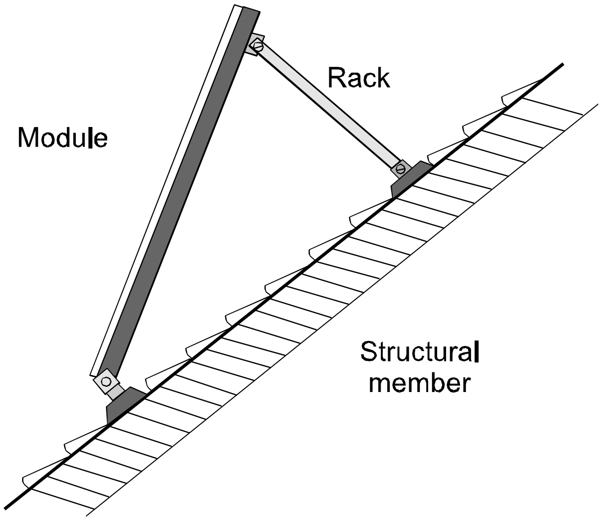


Figure 8.12 Rack mount.

Rack arrays typically run relatively cool compared with other mounts and can reduce heat gain through roofs. Because the primary mechanism of rack array cooling is convection from the front and back of the module surfaces, cooling can possibly be enhanced by locating the rack to take advantage of natural air channels and reducing obstructions to air flow, such as screens, grates, and walls.

8.5.1.4 Integral Mounting

For integral arrays, the array replaces conventional roofing material, as illustrated in Figure 8.13. Integral mounting often increases the array installation labor costs and is difficult to weather seal. Only experienced installers should consider this method.

Because integral-mounted arrays replace conventional roofing material, they become a significant architectural feature of a building and can be aesthetically very pleasing. It is recommended that only thoroughly tested and proven designs be used because of possible serious water leakage.

Modules in integral mounts are often individually framed in a structural support, usually on all four sides. For a given total array area, the larger the size of the individual modules used, the smaller the total linear dimension of framing required. Structural framing of the modules should be designed to allow for thermal expansion and contraction of array materials.

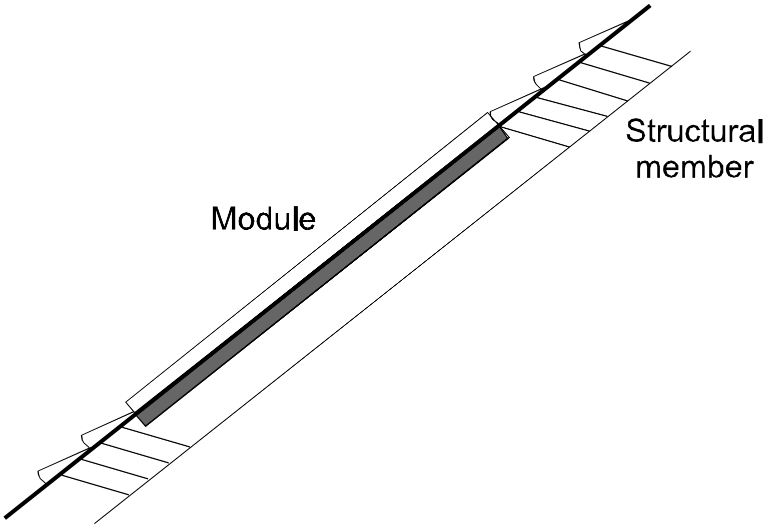


Figure 8.13 Integral mount.

8.5.1.5 Direct Mounting

In direct mounting, the array is affixed directly to the roofing material, with little air space between the module and roof. Figure 8.14 illustrates a direct-mounted array.

Experimental results with direct mounts to date have been discouraging. Array operating temperatures have been much higher than for other mounting techniques, resulting in poorer performance and severe degradation of the modules. The use of direct mounting may prove desirable for new thin-film modules that are not as sensitive to operating temperature, but it is not recommended for conventional crystalline silicon modules.

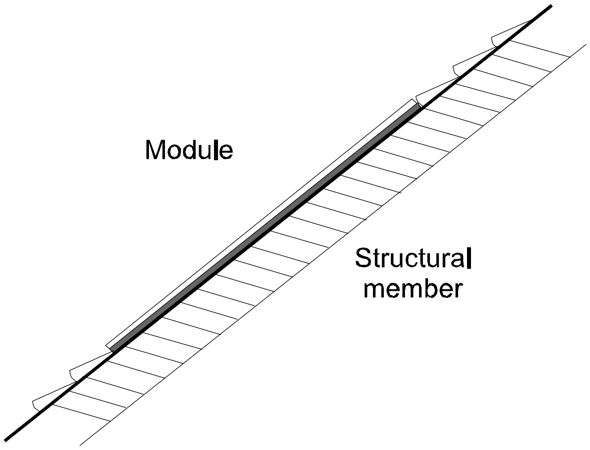


Figure 8.14 Direct mount.

8.5.2.0 Ground-Mounted Arrays

Ground-mounted arrays are supported by racks, poles, or tracking stands. These arrays must be strongly secured to the ground to resist uplifting caused by wind loads. All ground-mounted arrays run relatively cool because good airflow is possible over both the front and back surfaces of the modules. This cooling can be enhanced by minimizing obstructions to air flow, such as shrubbery and fences.

8.5.2.1 Rack Mounting

Rack mounting is commonly used for mounting arrays on the ground. It uses simple structural hardware, such as angles and channels, and it is adaptable for both small and large PV arrays. Most PV module manufacturers and PV equipment suppliers offer hardware for rack mounting. Figure 8.15 is an example of a low cost rack-mounted array design developed by Battelle Columbus Laboratories.

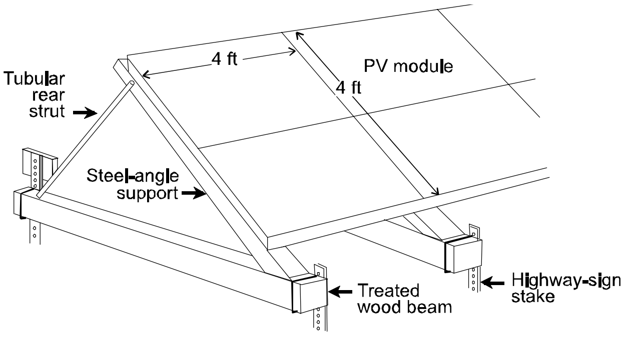


Figure 8.15 Battelle Columbus Laboratories rack mounting design.

8.5.2.2 Pole Mounting

If the array is made up of only a few modules, it can be mounted on a pole as shown in Figure 8.16. Depending on the number of modules and their height above the ground, the pole may need to be set in concrete to prevent overturning during windy conditions. Outdoor lighting is a good application for pole-mounted arrays.

8.5.2.3 Tracker Stand Mounting

Because tracking arrays have the ability to receive more sunlight over the day than stationary arrays, their modules produce more energy. The value of a tracking array depends on whether the additional energy produced offsets its added cost and complexity. There are two types of trackers: active and passive. Active trackers use electric motors and gear drives to direct the array at the sun, and they may track in either one or two axes. The tracking direction is determined by a computer calculating the sun's position, or with sun-seeking sensors.

Passive trackers normally track in only one axis and use a fluid such as freon that vaporizes and expands when it is heated by the sun. The expanding fluid causes the tracker to pivot towards the sun as the weight of the freon shifts from one side of the tracker to the other. An alternative design uses freon to operate a hydraulic cylinder and linkage arrangement. For both designs, sun shades help regulate the heating of the freon by the sun and, hence, help control tracker direction. A passive tracker is shown in Figure 8.17 Compared with a fixed-tilt array, these trackers show the greatest energy enhancement in the summer when the days are long. Trackers are less beneficial in winter when days are shorter. Typical applications are water pumping because water demand is usually higher in summer than in winter.

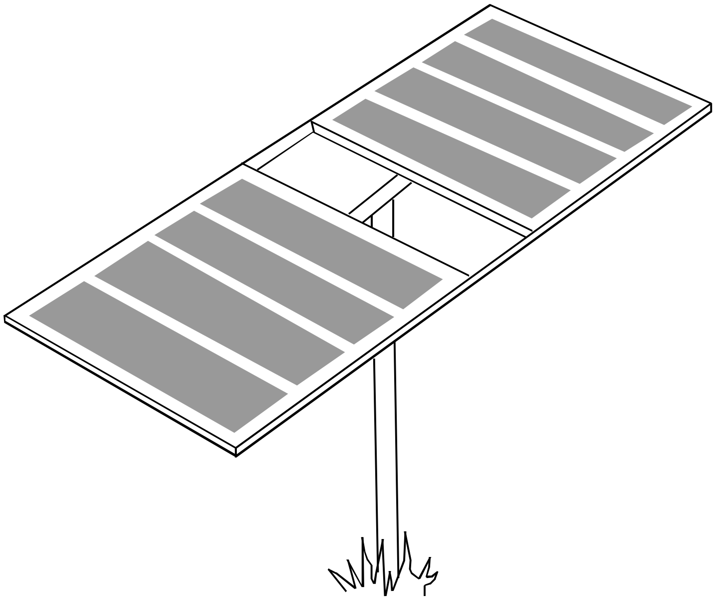


Figure 8.17 Passive tracker.

8.6 Manufacturers' Performance Data

Manufacturers' specification sheets usually provide data on module output under standard test conditions. Output under other conditions of irradiance and temperature is sometimes (but not always) provided. Commercially available silicon cells have efficiencies as high as 15%. Laboratory efficiencies of about 20% have been achieved. Considerable research is in progress to improve efficiency, lower production costs and increase durability.

8.6.1 Manufacturing Processes

A variety of semiconductor materials are used in fabricating photovoltaic cells and modules. These include single-crystal silicon, polycrystalline silicon, hydrogenated thin-film amorphous silicon and a large number of advanced technology materials, including cadmium telluride, copper indium diselenide and gallium arsenide.

Single-crystal and most polycrystalline silicon cells are referred to as thick cells. They come in a range of thicknesses from about four to seventeen mils and, in general, are in a more advanced state of development than their thin-film counterparts. Thin-film materials are typically less than five microns thick and are, therefore, orders of magnitude less material intensive.

8.6.1.2 Czochralski Process

The standard method of growing single-crystal silicon from a molten bath is called the Czochralski process. A relatively small amount of polysilicon is placed in a crucible in a vacuum furnace to produce a silicon melt. A solid, single-crystal silicon seed is lowered into the bath, rotated slowly and pulled upward. The molten silicon adheres to the seed and solidifies as it is drawn out, forming a cylindrical ingot. The crystalline structure of the grown ingot conforms to that of the single-crystal seed material.

Pure silicon ingots are typically 10 to 15 cm in diameter and 75 to 100 cm in length. The ingots are sliced into very thin wafers, losing about half of the valuable silicon in the process.

8.6.1.3 Edge-Defined Film-Fed Growth (EFG) Technique

This process, developed by Mobil Solar Energy Corporation, uses the growth of silicon ribbons to make cells. A die is partially immersed in molten silicon and capillary action causes the silicon to rise and meet a solid ribbon in the die. The molten silicon solidifies as it is withdrawn from the dye.

In order to increase production rates, manufacturers have developed a machine that produces nine ribbons simultaneously. The resultant product is called a nonagon because its cross-section is a nine-sided polygon. Ribbons have the advantage of not wasting material in the slicing process. They also enable a more dense packing of the rectangular module than circular cells.

8.6.1.4 Dendritic Web Process

Specific manufacturers have developed relatively high efficiency silicon cells (i.e., 16% and higher) using a ribbon process that uses surface tension properties rather than capillarity. Two-edge dendrites are formed in the molten silicon and, as they are withdrawn, a superior ribbon material with controllable thickness and uniformity is produced.

8.6.1.5 Cast Ingot Methods

The heat-exchange method (HEM) uses a casting process that produces a crystalline silicon ingot with a square cross section. The ingot is mostly single crystal except near the edges. The ingot is sliced into square wafers that allow for densely packed modules. Average cell efficiencies of about 11% have been produced, with some cells reaching efficiencies as high as 15%.

Larger ingots possessing more than 90% single-crystal material must be produced in the fuure in order to lower costs. Solarex Corporation has developed an ingot casting process, known as Semix, which uses a different cooling rate than the HEM process and produces a high quality polycrystalline cell with an efficiency comparable to single-crystal cells.

8.6.1.6 Thin-Film Devices

Considerable research is in progress with many different materials to develop low cost photovoltaic devices. The most common of these is hydrogenated thin-film amorphous silicon. Unlike crystalline silicon, in which the molecular alignment is ordered, the molecular alignment in amorphous silicon is random. The efficiency of thin-film materials is relatively low and is subject to degradation. However, efficiencies can be improved by using multiple layers of compatible materials, and progress in minimizing the effects of degradation is being made. Flat-plate module efficiencies are typically 2% to 5% for single junction devices, and can exceed 6% for multiple junction devices. Improvements in manufacturing processes may yield thin-film module efficiencies comparable to those for thick cell devices.

Most thin-film manufacturing processes involve some type of vapor deposition in an electric field environment. The most common is referred to as the glow-discharge process.

8.6.2 Module Performance Specifications

Module output parameters (e.g.,Voc, Isc,Vmp, Imp, Pmax) only have meaning when the rating conditions for these outputs are specified.

8.6.2.1 Rating Conditions

Standard Test Conditions (STC)

- Irradiance = 1000 watts/m^2

- Cell temperature = 25°C
- Air mass = 1.5

Standard Operating Conditions (SOC)

- Irradiance = 1000 watts/m^2
- Cell temperature = NOCT
- Air mass = 1.5

Nominal Operating Conditions (NOC)

- Irradiance = 800 watts/m^2
- Cell temperature = NOCT
- Air mass = 1.5

Nominal Operating Cell Temperature (NOCT) is measured under the following conditions:

- Irradiance on surface of array = 800 watts/m^2
- Ambient air temperature = 20°C
- Photovoltaic array electrically open-circuit
- Wind speed = 1.0 m/sec

8.6.3 World Module Shipments

The photovoltaics industry is international. Table 8.2 presents 1999 world module shipments by module type.

Table 8.2 1999 WorldCell/Module Production By Cell Technology (MW)

Technology	U.S.	Japan	Europe	R.O.W.	Total	%
Single Crystal Flat Plate	36.6	9.5	11.6	15.5	73.2	36.3
Polycrystal SI	16.0	51.6	19.6	1.2	88.4	43.9
Single and Polycrystal Total:					**161.6**	**80.2**
Amorphus Silicon	5.3	9.6	5.2	3.8	23.9	11.9
Amorphous Silicon Indoor Use					(8.6)	
Crystal Silicon Concentrators	0.5	--	--	--	0.5	0.25
Ribbon (Silicon)	4.20	--	--	--	4.20	2.1
Cadmium Telluride*	0.0	1.20	--	--	1.20	0.6
SI on Low-Cost-Sub	2.0	--	--	--	2.0	1.0
A-SI on Cz Slice		8.1	--	--	8.1	4.0
Total:	**64.6**	**80.0**	**36.4**	**20.5**	**201.5**	**100.0**

* 1.2 MW of CdTe is for indoor use

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9.0 PHOTOVOLTAIC SYSTEM COMPONENTS

9.1 Introduction

Although a photovoltaic array produces electricity directly from sunlight, this energy must be properly controlled, stored, converted and distributed in order to be useful. Several components are required in addition to the PV array to perform these functions. The material in this section provides an overview of the common types and classifications of PV systems, considerations of electrical loads, and describes the design and performance characteristics of common components such as batteries, battery charge controllers, inverters and other balance of system (BOS) components.

9.1.1 Types of PV Systems

Photovoltaic systems are generally divided into two major categories: stand-alone systems and utility-interactive, or grid-connected, systems.

Stand-Alone Systems: As the name implies, this type of PV system operates autonomously, or independent of the electric utility grid. Due to their practical and cost-effective application for a variety of remote power needs, stand-alone PV systems are a large part of the PV market. The few common types of stand-alone PV systems are defined as follows.

> ***Direct-Coupled Systems:*** Direct-coupled systems are the simplest type of stand-alone PV system and are configured with a dc load directly connected to the positive and negative terminals of a PV module or array. Direct-coupled systems have no electrical storage, and can only be used where the load requirements and the power produced by the PV array coincide. Common direct-coupled applications include water pumping/circulation and ventilation fans. Even dc-powered refrigerators may be operated directly coupled to PV arrays if sufficient thermal storage is available to maintain required temperatures at night and during period of below average insolation. A critical factor in direct-coupled PV system design is the matching of the load with the maximum power output of the PV array. Figure 9.1 diagrams a direct-coupled PV system.

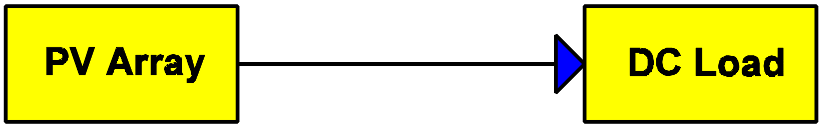

Figure 9.1 Direct-Coupled Stand-Alone PV System.

Battery Storage Systems: Since the power produced by a PV array cannot always be used when it is produced, energy storage in the form of batteries is generally required in stand-alone PV systems. Some types of systems do not use battery charge control, and are typically employed where the load profile is well defined and where the battery is oversized with respect to the PV array, resulting in low charge rates. PV-powered navigational aids designed by the U.S. Coast Guard are typically of this type [ref]. Figure 9.2 illustrates a stand-alone PV system with battery storage.

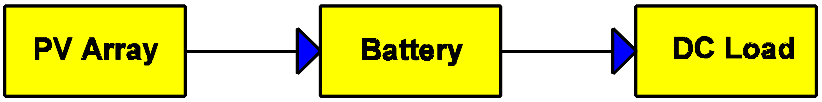

Figure 9.2 Stand-Alone PV System with Battery Storage.

Battery Storage with Charge Control: Where the load is variable or not well defined, and the battery is marginally or optimally sized with respect to the PV array and load, a battery charge controller is generally required to protect the battery from overcharge and overdischarge. The types and characteristics of battery charge controllers are discussed in detail later in this section. Figure 9.3 illustrates a stand-alone PV system with battery storage and charge control.

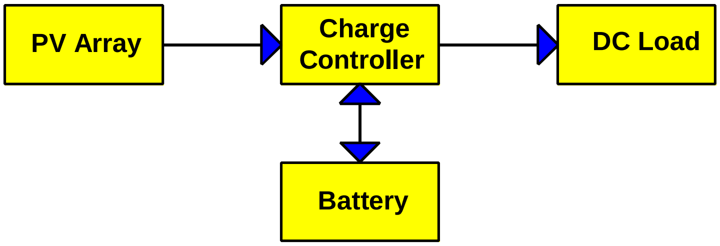

Figure 9.3 Stand-Alone PV System with Battery Storage and Charge Control.

Battery Storage With AC and DC Loads: In some cases, it is required to power both ac and dc electrical loads in stand-alone PV systems. In these cases, an inverter is needed to convert the dc battery energy to ac energy. Figure 9.4 illustrates a stand-alone PV system with battery storage, charge control and ac and dc electrical loads.

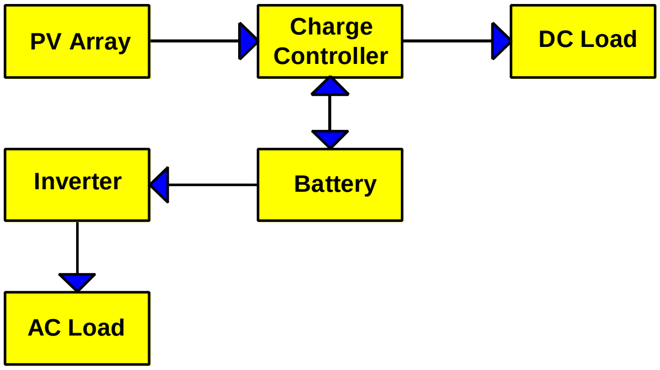

Figure 9.4 Stand-Alone PV Systems with DC and AC Loads.

Hybrid Systems: Hybrid systems are a type of stand-alone PV system that has one or more energy sources in addition to the PV array that may be used for battery charging. Common energy sources used in PV hybrid systems include wind turbine generators and diesel, gas or petrol-fueled engine generator sets. Figure 9.5 shows a typical hybrid system diagram.

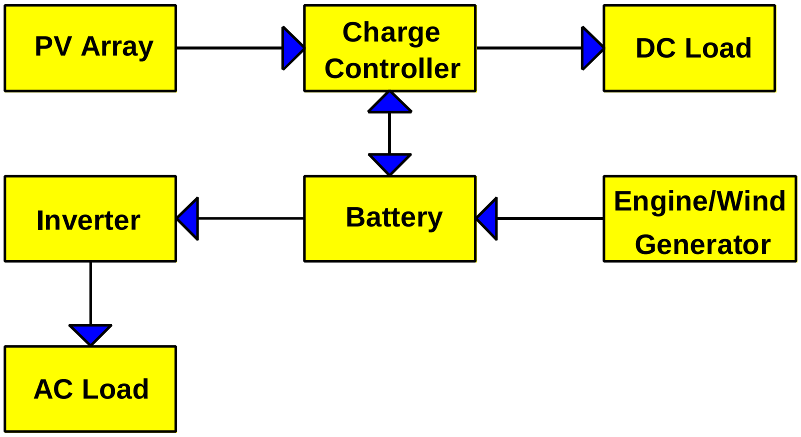

Figure 9.5 Stand-alone Hybrid PV System with DC and AC Loads.

Utility-Interactive Systems: Sometimes referred to as grid-connected systems, these systems require an interface with the utility grid to operate. These systems generally do not have backup or energy storage, and the power produced by the PV system is delivered first to the system loads with the balance being delivered to the utility grid. When the loads exceed the power produced by the PV system, such as at night and during low insolation periods, the balance of required power is taken from the utility grid. As a result these systems involve a bi-directional flow of energy between the PV system and utility grid. A primary component of grid-connected PV systems is the power conditioner, or inverter, which converts the dc energy produced by the PV array to ac energy at the appropriate voltage, phase and frequency. Often these power conditioners are referred to as synchronous inverters, as they match, or synchronize their output power phase and frequency with that of the utility grid. Utility-interactive inverters are different from stand-alone inverters in that they cannot operate without connection to an energized utility grid.

Due to their high life cycle energy costs compared with common utility energy rates, grid-connected PV systems have had limited application. Figure 9.6 shows a basic diagram of a utility-interactive PV system.

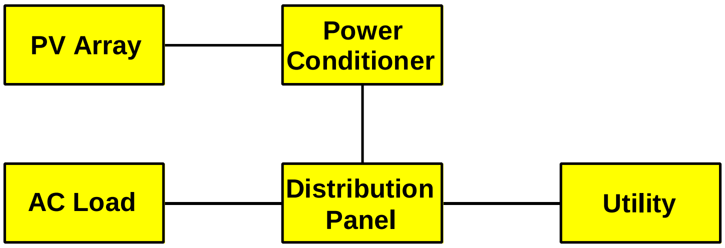

Figure 9.6 Utility-Interactive PV System.

9.1.2 BOS Components

BOS, or balance of system a term used to classify equipment, materials and hardware other than the PV array. Primary BOS components include batteries, battery charge controllers and inverters. Electrical BOS hardware includes disconnect and overcurrent protection devices, diodes, surge suppressors and grounding equipment. Mechanical BOS hardware includes such items as the array support structure, enclosures, ventilation, etc.

9.2 Electrical Loads

Electrical loads are defined as the end-use appliances, devices or equipment that require electricity to operate. In stand-alone PV systems, electrical loads may include lights, water pumps, refrigerators, fans, telecommunications equipment, common household appliances or any other electrically-operated devices. Any type of electrical load can be operated by PV systems; however it is important that designers have a good understanding of electrical loads and their voltage, current and power requirements. This knowledge is essential in the design of the PV electrical system and in the specification of power conditioning equipment, if required.

Quantifying the electrical loads, or developing the *system load profile* is the first critical step in sizing stand-alone PV systems. The *magnitude* and *duration* of the electrical load determines the type, size and performance requirements of a PV system. Considerable variations exist in the energy consumption and efficiency of electrical loads, making the load selection an important part of the design process. Because the electrical load dictates the overall size and cost of the PV system required, loads to be operated by a PV system should be as energy efficient as possible.

Many electrical loads require *alternating current* (ac) electricity rather than the *direct current* (dc) available from the photovoltaic array and battery subsystem. Alternating current loads include most common household appliances, power tools, office equipment and any other devices or equipment that operates from utility-supplied power. Where possible, dc-powered electrical loads should be used in stand-alone PV systems, thereby eliminating the need for an inverter and usually resulting in a more energy-efficient and simplified system design. For cases in which ac and dc loads are required, the designer must carefully consider which loads are best served by using dc versus ac power, as this affects the size and selection of the inverter needed. In many cases, dc-powered appliances may be substituted for ac-powered ones.

9.2.1 Common Types and Characteristics of Electrical Loads

Several types of electrical loads exist, but they can generally be divided into a few categories. In some cases, the same end-use or task may be performed with different types of electrical loads, for example with heating and lighting. The following paragraphs describe the common types of electrical loads and their characteristics.

Resistive Loads: Resistive loads are those electrical loads that utilize the flow of current through a filament, wire, coil or other resistive element to produce heat or light. Common examples of resistive loads include incandescent lamps, electric water and space heaters, clothes dryers, electric blankets, toasters and electric ranges. Resistive loads are flexible in that they can be operated on either direct or alternating current at their rated voltage. In general, resistive loads are simple, low cost, and widely available; however they are inefficient and expensive to operate when compared with competing alternatives. For example, fluorescent and high intensity discharge lamps are several times more efficient than resistive incandescent, and propane and natural gas are less expensive than electricity to operate those devices producing heat, such as cooking and space heating appliances. For domestic water heating, solar water heating is generally an economical alternative over electric or gas-fired heaters.

Motor Loads: Electrical motors are those devices which convert electrical energy into rotational mechanical energy. Generators are essentially motors driven by a rotational force which produce electrical energy. A motor operates by passing a current through a wire loop, or armature in a magnetic field, causing the armature to rotate. Depending on their design, electric motors can be operated with either dc or ac power, or both as in a universal type motor.

Electric motors are used to power pumps, compressors, fans, kitchen appliances, power tools and many commercial and industrial processes. The characteristics of the electrical load created by the motor depend to a certain extent on the mechanical load it is powering. This can be seen when operating centrifugal and positive displacement pumps, which impose different loading on the motor. The size and performance of electric motors vary widely, depending on the mechanical load, or horsepower to be delivered, the torque and speed. The common types of electric motors are discussed below:

DC Motors: In a dc motor, the direction of the current in the armature is switched each half rotation by means of a split-ring commutator and brushes in order to maintain the same direction armature rotation. Permanent magnets are used for the magnetic field in small dc motors, while electromagnets are used in larger designs. Series and shunt are two types of dc motors, the series type being more common as it performs better over a greater speed range than a shunt motor. DC motors are often directly coupled to PV arrays in water pumping systems using water storage. In these cases, the matching of the pump/motor load with the PV array maximum power point is an important part of an effective system design.

AC Motors: In an ac motor, current fed into the armature windings causes it to rotate in the magnetic field, thus turning the shaft. Since the ac current switches every half cycle, there is no need for a split-ring commutator as in the dc motor. One disadvantage of ac motors is that speed control is difficult, and must be done by varying the frequency of the input power. Synchronous motors are designed to rotate one revolution every cycle of the alternating current supply. For 60 Hz ac power, this results in 60 revolutions per second, or 3600 revolutions per minute. Synchronous motors are used where maintaining exact speed is critical, more often they are used for generators. *Induction* motors constitute most of the motors in use today, as they are simple to build, inexpensive and robust.

9.3 Storage Batteries

In stand-alone photovoltaic systems, the electrical energy produced by the PV array cannot always be used when it is produced. Because the demand for energy does not always coincide with its production, electrical storage batteries are commonly used in PV systems. The primary functions of a storage battery in a PV system are:

1. to store electrical energy when it is produced by the *PV array* and to supply energy to *electrical loads* as needed.

2. to supply power to *electrical loads* at stable voltages, by suppressing or 'smoothing out' *transient* voltages that may occur in PV systems.

3. to supply surge or high peak operating currents to *electrical loads* or appliances.

A storage battery is an electrochemical *cell* which stores energy in *chemical bonds*. When a battery is connected in a circuit to an electrical load, such as an incandescent light or resistor, the chemical energy within a battery is converted to electrical energy, and there is a flow of current through the circuit. An understanding of storage battery design and performance characteristics is essential in the performance of stand-alone PV systems.

9.3.1 Battery Design and Manufacturing

Battery manufacturing is an intensive, heavy industrial process involving the use of hazardous and toxic materials. Batteries are generally mass produced, combining several sequential and parallel processes to construct a complete battery unit. After production, initial charge and discharge cycles are conducted on batteries before they are shipped to distributors and consumers.

Cell: The basic electrochemical unit in a battery, consisting of a set of positive and negative plates divided by separators, immersed in an electrolyte solution and enclosed in a case. In a typical lead-acid battery, each cell has a nominal voltage of about 2.1 volts, so there are 6 series cells in a nominal 12 volt battery. Figure 9.7 shows a diagram of a basic battery cell.

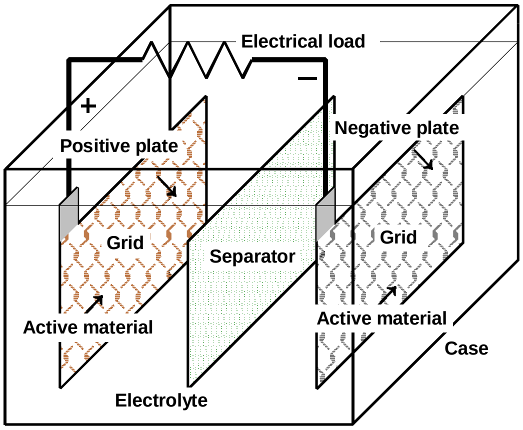

Figure 9.7 Battery Cell Composition.

Active Material: The raw composition materials that form the positive and negative plates, and are reactants in the electrochemical cell. The amount of active material in a battery is proportional to the capacity a battery can deliver. During charging, the directions of the reactions are reversed.

9.3.2 Battery Performance Characteristics

Ampere-Hour (Ah): The common unit of measure for a battery's electrical storage capacity, obtained by integrating the discharge current in amperes over a specific time period. An ampere-hour is equal to the transfer of one ampere over one hour, equal to 3600 coulombs of charge. For example, a battery which delivers 5 amps for 20 hours is said to have delivered 100 ampere-hours.

Capacity: A measure of a battery's ability to store or deliver electrical energy, commonly expressed in units of ampere-hours. Capacity is generally specified at a specific discharge rate, or over a certain time period. The capacity of a battery depends on several design factors, including the quantity of active material, the number, design and physical dimensions of the plates, and the electrolyte specific gravity. Operational factors affecting capacity include the discharge rate, depth of discharge, cut off voltage, temperature, age and cycle history of the battery. Sometimes a battery's energy storage capacity is expressed in kilowatt-hours (kWh), which can be approximated by multiplying the rated capacity in ampere-hours by the nominal battery voltage and dividing the product by 1000. For example, a nominal 12 volt, 100 ampere-hour battery has an energy storage capacity of (12 x 100)/1000 = 1.2 kilowatt-hours.

Cut Off Voltage: The lowest voltage which a battery system is allowed to reach in operation, defining the battery *capacity* at a specific *discharge rate*. Manufacturers often rate capacity to a specific cut off, or *end of discharge voltage* at a defined discharge rate. If the same cut off voltage is specified for different rates, the capacity will generally be higher at the lower discharge rate.

Cycle: In battery terminology, a cycle refers to a *discharge* to a given *depth of discharge* followed by a complete *recharge*. A 100 percent *depth of discharge cycle* provides a measure of the total battery *capacity*.

Discharge: The process when a battery delivers current, quantified by the *discharge current* or *rate*. Discharge of a lead acid battery involves the conversion of *lead*, *lead dioxide* and *sulfuric acid* to *lead sulfate* and *water*.

Charge: The process when a battery receives or accepts current, quantified by the *charge current* or *rate*. Charging of a lead acid battery involves the conversion of *lead sulfate* and *water* to *lead*, *lead dioxide* and *sulfuric acid*.

Rate of Charge/Discharge: The rate of charge or discharge of a battery is expressed as a ratio of the nominal battery *capacity* to the *charge* or *discharge* time period in hours. For example, a 4 amp discharge for a nominal 100 ampere-hour battery would be considered a C/20 discharge rate.

Negative (-): Referring to the lower *potential* point in a dc electrical circuit, the negative battery terminal is the point from which *electrons* or the *current* flows during *discharge*.

Positive (+): Referring to the higher *potential* point in a dc electrical circuit, the positive battery terminal is the point from which *electrons* or the *current* flows during *charging*.

Open Circuit Voltage: Pertaining to batteries, the voltage when a battery is at *rest* or steady-state, not during *charge* or *discharge*. Depending on the battery design, *specific gravity* concentration and *temperature*, the open circuit voltage of a fully charged lead-acid battery is typically about 2.1 volts.
Battery Charging: Manufacturers often refer to three recommended modes of battery charging:

normal or bulk charge, finishing or float charge and equalizing charge.

> ***Bulk or Normal Charge:*** Bulk or normal charging is an unregulated charge, usually at higher charge rates, which occurs between zero and about 80 % state of charge.
>
> ***Float or Finishing Charge:*** Above 80 % SOC most of the active material in the battery has been replenished, and voltage and current regulation are generally employed to limit the amount over overcharge supplied to the battery.
>
> ***Equalizing Charge:*** For many lead-acid battery types, an equalizing or refreshening charge is required periodically to attain full-rated battery capacity. An equalizing charge generally consists of a current-limited charge to higher voltage limits than set for the finishing or float charge. The equalizing charge provides overcharge to the battery, and in lead-acid designs is used to reverse the effects of sulfation, or prolonged operation at partial states of charge. Equalization is also used to reestablish consistency among cells in a series string that have become unequal in terms of capacity.

Short-Circuit: An extreme low resistance current path allowing high current flows. Common lead acid batteries can deliver over 1000 amps short-circuit, and require special precaution when handling. Internal to a battery, a short-circuit between cell plates may discharge the cell.

Specific Gravity (sg): The ratio of the density of a solution to the density of water, typically measured with a hydrometer. By definition, water has a specific gravity of one. In a battery, specific gravity is related to the state of charge, depending on the electrolyte concentration and temperature. Typical ranges of specific gravity for flooded lead-acid batteries ranges from 1.28 for a fully charged battery, to 1.00 for a fully discharged battery. In very cold climates, the concentration of the sulfuric acid solutions in lead-acid batteries is often increased above a specific gravity of 1.28 to increase the reaction rate. Similarly, in tropical or very warm climates, the electrolyte is often diluted below 1.28 sg to extend battery life. Although not an accurate measure of battery capacity in itself, low specific gravity readings may indicate sulfation, stratification, or lack of equalization between cells. Table 9.1 shows the typical relationship between specific gravity and freezing point in a lead acid battery.

Table 9.1. Properties of Sulfuric Acid Solutions

Specific Gravity	H_2SO_4 (Wt%)	H_2SO_4 (Vol%)	Freezing Point (°C)
1.000	0.0	0.0	0
1.050	7.3	4.2	-3.3
1.100	14.3	8.5	-7.8
1.150	20.9	13.0	-15
1.200	27.2	17.1	-27
1.250	33.4	22.6	-52
1.300	39.1	27.6	-71

Depth of Discharge (DOD): The depth of discharge of a battery is defined as the percentage of capacity that has been withdrawn from a battery compared with the total fully charged capacity. By definition, the depth of discharge and state of charge of a battery add to 100 %. The two common qualifiers for depth of discharge are the allowable or maximum DOD and the average daily DOD and are described as follows:

Allowable DOD: The maximum percentage of full-rated capacity that can be withdrawn from a battery is known as its allowable depth of discharge. The allowable DOD is the maximum discharge limit for a battery, generally dictated by the cut off voltage and discharge rate. In stand-alone PV systems, the low voltage load disconnect (LVD) set point of the battery charge controller dictates the allowable DOD limit at a given discharge rate. Furthermore, the allowable DOD is generally a seasonal deficit, resulting from low insolation, low temperatures and/or excessive load usage. Depending on the type of battery used in a PV system, the design allowable depth of discharge may be as high as 80 % for deep cycle, motive power batteries, to as low as 15-25% if SLI batteries are used. The allowable DOD is related to the *autonomy*, in terms of the *capacity* required to operate the system loads for a given number of days without energy from the PV array. A system design with a lower allowable DOD will result in a shorter autonomy period.

Average Daily DOD: The average daily depth of discharge is the percentage of the full-rated *capacity* that is withdrawn from a battery with the average daily load profile. If the load varies seasonally, for example in a PV lighting system, the average daily DOD will be greater in the winter months due to the longer nightly load operation period. For PV systems with a constant daily load, the average daily DOD is generally greater in winter due to lower battery temperature and lower rated capacity. Depending on the rated capacity and the average daily load energy, the average daily DOD may vary from only a few percent in systems designed with a lot of autonomy to as high as 50 % for marginally sized battery systems. The average daily DOD is inversely related to autonomy, meaning that systems designed for longer autonomy periods have a lower average daily DOD.

State of Charge (SOC): The amount of energy in a battery, expressed as a percentage of the energy stored in a fully charged battery. Discharging a battery results in a decrease in state of charge, while charging results in an increase in state of charge.

A battery that has had three quarters of its capacity removed, or been discharged 75 %, is said to be at 25 % state of charge. Figure 9.8 shows the seasonal variation in battery state of charge and depth of discharge or a typical PV system.

Autonomy: Generally expressed as the days of storage in a stand-alone PV system, autonomy refers to the time a fully charged battery can supply energy to the systems loads when there is no energy supplied by the PV array. For common, less critical PV applications, autonomy periods are typically between two and six days. For critical applications involving essential load or public safety, or where weather patterns dictate, autonomy periods may be greater than ten days.

Longer autonomy periods generally result in a lower average daily DOD, and lower the probability that the allowable DOD, or minimum load voltage is reached.

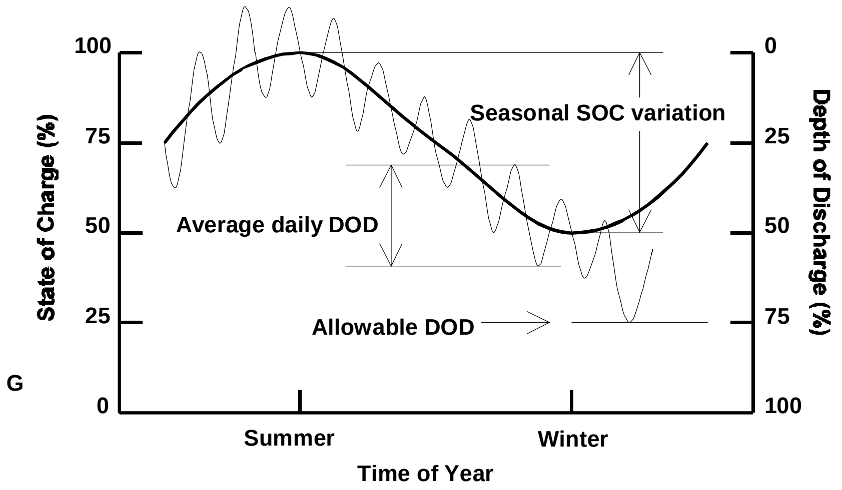

Figure 9.8 Seasonal Battery Depth of Discharge.

Self Discharge Rate: In open-circuit mode without any load or charging, a battery undergoes a reduction in state of charge, due to internal mechanisms and losses within a battery. Different battery types have different self discharge rates, the most significant factor being the active materials and grid alloying elements used in the design. Higher temperatures result in higher discharge rates, particularly for lead-antimony designs.

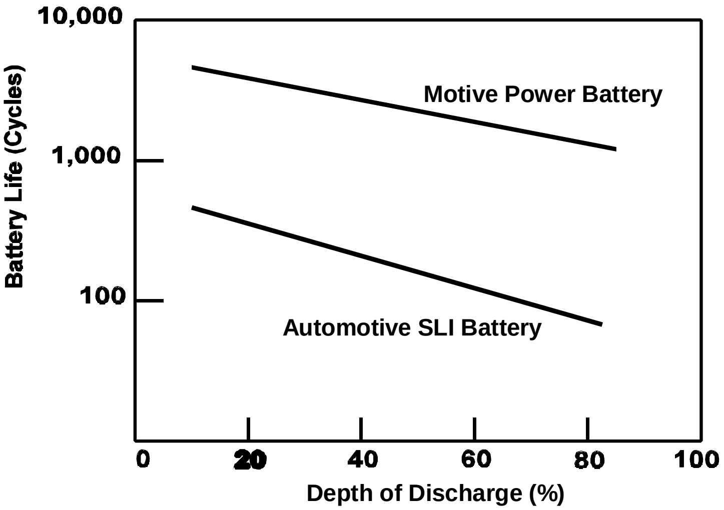

Figure 9.9 Effects of Depth of Discharge on Lead-Acid Battery Cycle Life.

Battery Lifetime: Battery lifetime is dependent upon a number of design and operational factors, including the components and materials of battery construction, temperature, frequency and depth of discharges, average state of charge and charging methods. As long as a battery is not overcharged, overdischarged or operated at excessive temperatures, the lifetime of a battery is proportional to its average state of charge. A typical flooded lead-acid battery that is maintained above 90 % state of charge will provide two to three times more full charge/discharge cycles than a battery allowed to reach 50 % state of charge before recharging. This suggests limiting the allowable and average daily DOD to prolong battery life.

Lifetime can be expressed in terms of cycles or years, depending on the particular type of battery and its intended application. Exact quantification of battery life is difficult due to the number of variables involved, and generally requires battery test results under similar operating conditions. Often, battery manufacturers do not rate battery performance under the conditions of charge and discharge experienced in PV systems. In general however, a reasonable estimate of battery life can be determined with knowledge of the PV system operational characteristics and battery performance data.

Temperature Effects: an electrochemical cell such as a battery, temperature has important effects on the battery performance. In general, as the temperature increases by 10^{o} C, the rate of an electrochemical reaction doubles, resulting in the recommendations from battery manufacturers that battery life decreases by a factor of two for every 10^{o} C increase in average operating temperature. Higher operating temperatures accelerate corrosion of the positive plate grids, result in greater gassing and electrolyte loss. Lower operating temperatures generally increase battery life, however the capacity is reduced significantly, particularly for lead-acid batteries. Where severe temperature variations from room temperatures exist, battery are located in an insulated or other temperature regulating enclosure to minimize battery temperature swings.

Effects of Discharge Rates: The higher the discharge rate or current, the lower the capacity that can be withdrawn from a battery to a specific allowable DOD or cut off voltage. Higher discharge rates also result in the voltage under load to be lower than with lower discharge rates, sometimes affecting the selection of the low voltage load disconnect set point. At the same battery voltage, the lower discharge rates, the lower the battery state of charge compared to higher discharge rates.

Overcharge: A process in a battery that occurs when essentially all of the active material in a battery has been converted to its fully charged composition, generally resulting is gassing and loss of electrolyte. While a certain amount of overcharge is needed to fully charge batteries, excessive overcharge results in considerable water loss and corrosion of the positive plate grids.

9.3.3 Battery Types and Classifications

Many types and classifications of batteries are manufactured today, with specific design and performance characteristics suited for particular applications. In PV systems, lead-acid batteries are most common due to their wide availability, low cost and known performance characteristics. In a few critical applications nickel-cadmium cells are used, but their high initial cost limits their use in most PV systems. Table 9.2 lists common battery types and their characteristics. Following are descriptions of basic battery types and classifications which are of importance to PV system designers.

Table 9.2 Secondary Battery Types and Characteristics

Battery Type	Cost	Deep Cycle Performance	Maintenance
Flooded Lead-Acid			
Lead-Antimony	low	good	high
Lead-Calcium Open Vent	low	poor	medium
Lead-Calcium Sealed Vent	low	poor	low
Lead-Antimony/Calcium Hybrid	medium	good	medium
Captive Electrolyte Lead-Acid			
Gelled	medium	fair	low
Absorbed Glass Mat	medium	fair	low
Nickel-Cadmium			
Sintered Plate	high	good	none
Pocket-Plate	high	good	medium

Primary Battery: A battery that can store and deliver electrical energy, but cannot be recharged. Typical carbon-zinc and lithium batteries commonly used in consumer electronic devices are primary batteries. Primary batteries are ***not*** used in PV systems.

Secondary Battery: A battery that can store and deliver electrical energy, and can also be recharged by passing a current through it in an opposite direction to the discharge current. Common nickel-cadmium and lead-acid batteries used in automobiles and PV systems are secondary batteries. Table 9.2 lists common secondary battery types and their characteristics.

9.3.3.1 Lead-Acid Batteries

Many types of lead acid batteries are used in PV systems, however traction or motive power types are most suitable for use in PV systems due to their deep cycle capability and long life.

SLI Batteries: Starting, lighting and ignition (SLI) batteries are a type of lead-acid battery designed primarily for shallow cycle service, most often used to power automobile starters. These batteries have a number of thin positive and negative plates per cell, designed increase the total plate active area and current density to deliver high discharge currents for short periods. While they are not designed for long life under deep cycle service, SLI batteries are sometimes used for PV systems in developing countries where they are the only type of battery locally manufactured. Although not recommended for PV applications, SLI batteries may provide up to two years of useful service in PV systems where the average daily depth of discharge is limited to 10-20 %, and the maximum allowable depth of discharge is limited to 40-60 %.

Motive Power or Traction Batteries: Motive power or traction batteries are a type of lead acid battery designed for deep discharge cycle service, typically used in electrically operated vehicles and equipment such as golf carts, fork lifts and floor sweepers. These batteries have a fewer number of plates per cell than SLI batteries, however the plates are much thicker and of generally more robust construction. High content lead-antimony grids are primarily used in motive power batteries to give good deep cycle performance.

Stationary Batteries: Stationary batteries are commonly used in uninterruptible power supplies (UPS) to provide backup power to computers, telephone equipment and other critical loads or equipment. Stationary batteries may have characteristics similar to both SLI and motive power batteries but are generally designed for occasional deep discharge, limited cycle service. Lead-calcium battery designs are used for most stationary battery applications.

9.3.3.1.1 Lead-Acid Battery Types

Lead-Antimony Batteries: Lead-antimony batteries are a type of lead-acid battery which use antimony (Sb) as the primary alloying element with lead in the plate grids. The use of lead-antimony alloys in the grids has both advantages and disadvantages. Advantages include providing greater mechanical strength than pure lead grids, and excellent deep discharge and high discharge rate performance. Lead-antimony grids also limit the shedding of active material. These batteries also last longer than lead-calcium batteries when operated at higher temperatures. Disadvantages of lead-antimony batteries are a high self-discharge rate and, as the result of necessary overcharge, the need for frequent water additions, depending on the temperature and amount of overcharge.

Most lead-antimony batteries are flooded, open vent types with removable caps for water additions. They are well suited to application in PV systems due to their deep cycle capability and ability to take abuse. However they do require periodic water additions. Water additions can be minimized by the use of catalytic recombination caps. The health of flooded, open vent lead-autonomy batteries can be checked easily by measuring the specific gravity of the electrolyte with a hydrometer.

Lead-Calcium Batteries: Lead-calcium batteries are a type of lead-acid battery which uses calcium (Ca) as the primary alloying element with lead in the plate grids. Like lead-antimony, the use of lead-calcium alloys in the grids has both advantages and disadvantages. Advantages include providing greater mechanical strength than pure lead grids, a low self-discharge rate, and reduced gassing, resulting in lower water loss and lower maintenance requirements than for lead-antimony batteries. Disadvantages of lead-calcium batteries include *poor charge acceptance* after deep discharges and shortened battery life at higher operating temperatures and if allowed to reach 25 % depth of discharge repeatedly.

Flooded Lead-Calcium, Open Vent: Often classified as stationary batteries, these batteries are typically supplied as individual 2 volt cells in capacity ranges up to and over 1000 ampere-hours. Flooded lead-calcium batteries have the advantages of low self discharge and low water loss, and may last as long as 20 years in stand-by service. In PV applications, these batteries usually experience short lifetimes due to sulfation and stratification of the electrolyte unless they are charged properly.

Flooded Lead-Calcium, Sealed Vent: Primarily developed as 'maintenance free' automotive starting batteries, the capacity for these batteries is typically in the range of 50 to 120 ampere-hours, in a nominal 12 volt unit. Like all lead-calcium designs, they are intolerant of overcharging, high operating temperatures and deep discharge cycles. These batteries are employed in small stand-alone PV systems, but must be carefully charged to achieve maximum performance.

Lead-Antimony/Lead-Calcium Hybrid: These are typically flooded batteries, with capacity ratings of over 200 ampere-hours. A common design for this battery type uses lead-calcium tubular positive electrodes and pasted lead-antimony negative plates. This design combines the advantages of both lead-calcium and lead-antimony design, including good deep cycle performance, low water loss and long life. Stratification and sulfation can be problems with these batteries, and must be treated accordingly. These batteries are sometimes used in PV systems with larger capacity requirements.

9.3.3.2 Captive Electrolyte Batteries

Captive electrolyte batteries are another type of lead-acid battery, and as the name implies, the electrolyte is *immobilized* in some manner and the battery is sealed under normal operating conditions. Under excessive overcharge, the normally sealed *vents* open under gas pressure. Often captive electrolyte batteries are referred to as valve regulated lead acid (VRLA) batteries, noting the pressure regulating mechanisms on the cell vents. Electrolyte cannot be replenished in these battery designs; therefore they are not tolerant of overcharge.

Captive electrolyte batteries are popular for PV applications because they are spill proof, easily transported, and require no water additions, making them ideal for remote applications were maintenance is unavailable. However, a common failure mode for these batteries in PV systems is excessive overcharge and loss of electrolyte, which is accelerated in warm climates. For this reason, it is essential that the *battery charge controller* regulation set points are adjusted properly to prevent overcharging. A benefit of captive or immobilized electrolyte designs is that they are less susceptible to freezing than flooded batteries. Typically, lead-calcium grids are used in captive electrolyte batteries to minimize gassing; however some designs use lead-antimony/calcium hybrid grids to gain some of the favorable advantages of lead-antimony batteries.

In the U.S., about half of the PV systems being installed use captive electrolyte, or sealed batteries [4]. The two most common captive electrolyte batteries are the gelled electrolyte and absorbed glass mat designs.

> ***Gelled Batteries:*** Initially designed for electronic instruments and consumer electronics, gelled lead-acid batteries typically use lead-calcium grids. The electrolyte is 'gelled' by the addition of

silicon dioxide to the electrolyte, which is then added to the battery in a warm liquid form, which gels as it cools. This battery technology is very sensitive to charging methods, regulation voltage and temperature extremes. Optimal charge regulation voltages for this type of battery vary between designs, so it is necessary to follow manufacturers' recommendations. The recommended charging algorithm for gelled batteries is constant-voltage, with temperature compensation of the regulation voltage required to prevent overcharge. Some gelled batteries have a small amount of phosphoric acid in the electrolyte to improve deep cycle discharge performance. The phosphoric acid is similar to the common commercial corrosion inhibitors and metal preservers, and minimizes grid oxidation at low states of charge. Gelled batteries represent over 90 % of the captive electrolyte batteries used in small PV systems in the U.S. [4].

Absorbed Glass Mat (AGM) Batteries: Another sealed, or valve regulated, lead-acid battery, theAGM battery has electrolyte absorbed in glass mats, which are sandwiched between the plates. Similar in other respects to gelled batteries, AGM batteries are also intolerant of overcharge and high operating temperatures. Recommended charge regulation methods stated above for gelled batteries also apply to AGMs. Unfavorable performance of AGM batteries in early PV applications has limited their use to less than 10 % of the captive electrolyte batteries currently used in small PV systems [4].

9.3.3.3 Nickel-Cadmium Batteries

Nickel-cadmium (Ni-Cad) batteries are secondary, or rechargeable, batteries and have several advantages over lead-acid batteries that make them attractive for use in stand-alone PV systems. These advantages include long life, low maintenance, survivability from excessive discharges, excellent low temperature capacity retention, and non-critical voltage regulation requirements. The main disadvantages of nickel-cadmium batteries are their high cost and limited availability compared with lead-acid designs.

A typical nickel-cadmium cell consists of electrodes made from nickel-hydroxide and cadmium, immersed in a potassium hydroxide electrolyte solution. The nominal voltage for a nickel-cadmium cell is 1.2 volts, compared with 2.1 volts for a lead-acid cell, requiring more cells configured in series to achieve the nominal system voltage. The voltage of a nickel-cadmium cell remains relatively stable until the cell is almost completely discharged, where the voltage drops off dramatically. Nickel-cadmium batteries can accept charge rates as high as C/1, and are tolerant of continuous overcharge up to a C/15 rate. Nickel-cadmium batteries are commonly subdivided in two types: sintered plate and pocket plate.

Sintered Plate Ni-Cads: Sintered plate nickel cadmium batteries are commonly used in electrical test equipment and consumer electronic devices. The batteries are designed by heat processing the active materials and rolling them into a metallic case. The electrolyte in sintered plate nickel-cadmium batteries is immobilized, preventing leakage, allowing any orientation for installation. The main disadvantage of sintered plate designs is the so called 'memory effect,' in which a battery that is repeatedly discharged to only a percentage of its rated capacity will eventually 'memorize' this cycle pattern, and will limit further discharge resulting in a loss of capacity. In some cases, the 'memory effect' can be erased by conducting special charge and discharge cycles, regaining some of its initial rated capacity.

Pocket Plate Ni-Cads: These nickel-cadmium batteries use a flooded, or liquid, electrolyte, and are sometimes used in critical PV applications for military and telecommunications applications. Similar to flooded lead-acid design, these batteries require periodic water additions. These batteries can withstand extreme discharges and temperature extremes much better than lead-acid batteries, and they do not experience the 'memory effect' associated with sintered plate designs. The main disadvantage of pocket plate nickel cadmium batteries is their high initial cost; however their long lifetimes can result in the lowest life cycle battery cost option.

9.3.4 Battery System Design and Selection Criteria

Battery system design and selection criteria involve many decisions and tradeoffs. Choosing the right battery for a PV application depends on many factors. While no specific battery is appropriate for all PV applications, common sense and a careful review of the battery literature with respect to the particular application needs will help the designer narrow the choice. Some decisions on battery selection may be easy to arrive at, such as physical properties, while other decisions are much more difficult and may involve making tradeoffs between desirable and undesirable battery features. With the proper application of this knowledge, designers should be able to differentiate among battery types and gain some application experience. Table 9.3 summarizes the main considerations in battery selection and design.

Table 9.3 Battery Design and Selection Criteria

- Type of system and mode of operation
- Charging characteristics; internal resistance
- Required days of storage (autonomy)
- Amount and variability of discharge current
- Maximum allowable depth of discharge
- Daily depth of discharge requirements
- Accessibility of location
- Temperature and environmental conditions
- Cyclic life and/or calendar life in years
- Maintenance requirements
- Sealed or unsealed
- Self-discharge rate
- Maximum cell capacity
- Energy storage density
- Size and weight
- Gassing characteristics
- Susceptibility to freezing
- Susceptibility to sulfation
- Electrolyte concentration
- Availability of auxiliary hardware
- Terminal configuration
- Reputation of manufacturer
- Cost and warranty.

9.3.4.1 Battery Selection

The selection of proper battery design is as important as the proper charge control strategy in improving the longevity of batteries in PV systems. A few of the important battery design characteristics necessary for deep-cycle, long-life performance are listed as follows.

- Low-antimony, thick plates for reducing water loss and providing adequate mechanical strength for long cycle life.

- Separator envelopes around the positive plates, and appropriate plate edge protection to minimize the potential for internal short-circuits.

- Large electrolyte volume below plates to allow for shed materials to accumulate without causing short circuits.

- Sufficient electrolyte volume above plates to minimize frequency of water additions.

- Transparent battery containers to allow for visual inspections.

Size and Weight: Due to their large size and weight, the physical characteristics of batteries often place restrictions on battery selection. A typical 12 volt, 100 ampere-hour flooded lead-acid battery weigh anywhere between 50 and 75 pounds, depending on the weight of active material, grid and interconnect design and amount of electrolyte.

For remote PV applications where the transportation of heavy equipment is cumbersome or otherwise difficult, the designer may choose to use several smaller batteries or cells rather than a few larger batteries. The choice of batteries may also depend on the strength and dimensions of the enclosure or area in which they are to be installed.

Costs: First costs often determine which battery is selected by a designer. However, recurring costs, including battery maintenance and replacement, are the burden of the system owner/operator. The sum of the initial cost and amortized recurring costs are what determine a battery's life cycle cost. In many cases, a battery with high initial costs may indeed have the lowest life cycle costs, all factors being considered. This is sometimes the case in the use of higher cost nickel-cadmium cells used for critical applications. The best way to compare the cost of competing battery options is by developing a battery cost parameter, which can incorporate any desirable performance characteristics the designer may be interested in. For any battery cost parameter, the cost of the battery is divided by the parameters to be compared, for example the warranty period, depth of discharge limits, cycle or year life, etc. The lower the battery cost parameter, the more cost effective the battery, based on the parameters of interest to the designer.

Availability: Due to the weight and hazardous nature of batteries, shipping costs are high. For this reason, local markets typically carry batteries produced at regional plants. In developing regions, the optimal battery for a given application may not be locally available. So, availability is often limited when selecting proper battery, and special attention to proper sizing and treatment is required in order to maximize battery life.

Maintenance Requirements: The maintenance requirements for batteries varies significantly depending on the battery design and application. Maintenance considerations may include cleaning of cases, cables and terminals, tightening terminals, water additions, and performance checks.

Performance checks may include specific gravity recordings, conductance readings, temperature measurements, cell voltage readings, or even a capacity test. If applicable, auxiliary systems such as ventilation, fire extinguishers and safety equipment may need to be inspected periodically.

Generally speaking, flooded lead-antimony batteries require the most maintenance in terms of water additions and cleaning. Sealed lead-acid batteries including gelled and AGM types, remain relatively

clean and do not require water additions. Battery manufacturers often provide maintenance recommendations for the use of their battery. In addition to manufacturer's recommendations, the designer may reference the IEEE publications "Recommended Practice for Installation and Maintenance of Lead-Acid Batteries for Photovoltaic Systems" and "Recommended Practice for Installation and Maintenance of Nickel-Cadmium Batteries for Photovoltaic Systems" [2,3].

9.3.4.2 Battery System Design

Once a battery type and size have been selected for a PV system, the battery subsystem must be electrically integrated and connected in the system. Considerations include how many batteries, connect then in series or parallel, what are the overcurrent and disconnect requirements, and what wire sizes and types should be used Following are some of the more important aspects of battery system design.

Series Circuit: Batteries connected in a series circuit have only one path for the *current* to flow. Batteries are arranged in series by connecting the *negative* terminal of the first battery to the *positive* terminal of the second battery, the negative of the second battery to the positive of the third battery, and so on for all batteries in the series string. For similar batteries connected in series, the total *voltage* is the sum of the individual battery voltages and the total *capacity* is the same as for one battery. If batteries or cells with different capacities are connected in series, the capacity of the string is limited to the lowest battery capacity. Figure 9.10 illustrates the series connection of two similar batteries.

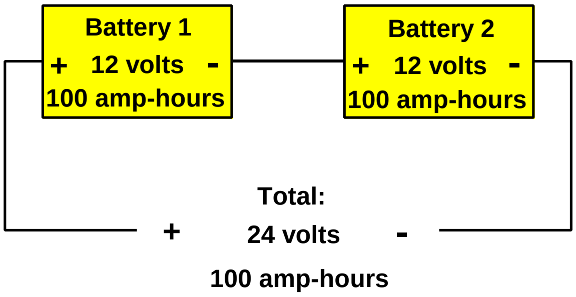

Figure 9.10 Series Connected Batteries

Parallel Circuits: Batteries connected in *parallel* have more than one current path, depending on the number of parallel branches. Batteries (or series strings of batteries) are arranged in parallel by connecting all of the *positive* terminals to one conductor and all of the *negative* terminals to another conductor. For similar batteries connected in parallel, the *voltage* across the entire circuit is the same as the voltage across the individual parallel branches, and the overall *capacity* is the sum of the parallel branch capacities. Figure 9.11 illustrates the parallel connection of two similar batteries.

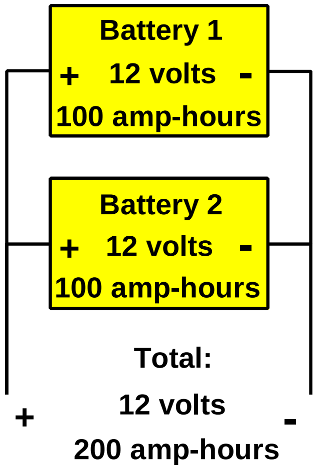

Figure 9.11 Parallel Connected Batteries

Series vs. Parallel Connection: In general, battery manufacturers recommend that their batteries be operated in as few parallel strings as possible to minimize the potential for equalization problems and to maintain better consistency between individual batteries in the system. Battery capacity requirements and the size and voltage of the battery selected dictate the series and parallel connections required. For systems with larger capacity requirements, larger cells (generally in nominal 2 volt cells for lead-acid) may allow the batteries to be configured in one series string.

Voltage Selection: Battery bank voltage selection is often dictated by load voltage requirements, most often 12 or 24 volts for small stand-alone PV systems. For larger loads requiring a larger PV array, it is sometimes best prudent to go to higher voltages if possible to lower the system currents. For example, a 120 watt dc load operating from a 12 volt battery draws 10 amps. However a 120 watt load operating from a 24 volt battery draws only 5 amps. Lower system currents minimize the size and cost of conductors, fuses, disconnects and other current handling components in the PV system.

Conductor Selection: Conductors connecting the battery to other circuits and components in a PV system must be selected based on the current or ampacity requirements, voltage drop limitations and the environmental conditions. Conductors should be adequately sized to handle the current and to limit the voltage drop to acceptable levels (generally less than 5 %) between the battery and other components at the peak rated currents. Conductor insulating materials should be selected based on temperature, moisture resistance or other application needs. Particular attention should be paid to selecting adequate size conductors for battery to inverter cabling.

Overcurrent and Disconnect Requirements: Batteries can deliver thousands of amperes under short circuit conditions, potentially causing explosions, fires, burns, shock and equipment damage. For these reasons, proper dc rated overcurrent and disconnect protection devices are required on all PV battery systems. Fuses or circuit breakers used for overcurrent protection must not only be able to

operate properly under 'normal' high currents resulting from load problems, but also operate under battery short-circuit conditions. The interrupt ampere rating (AIR) for over current devices must be considered with regard to the battery system, or the device could fail with disastrous results. For ungrounded systems, disconnects are required on both the positive and negative conductors leading to and from the battery. For grounded systems, disconnect and over current protection are only required on the ungrounded conductor. Figure 9.13 shows the over current and disconnect requirements for batteries in PV systems.

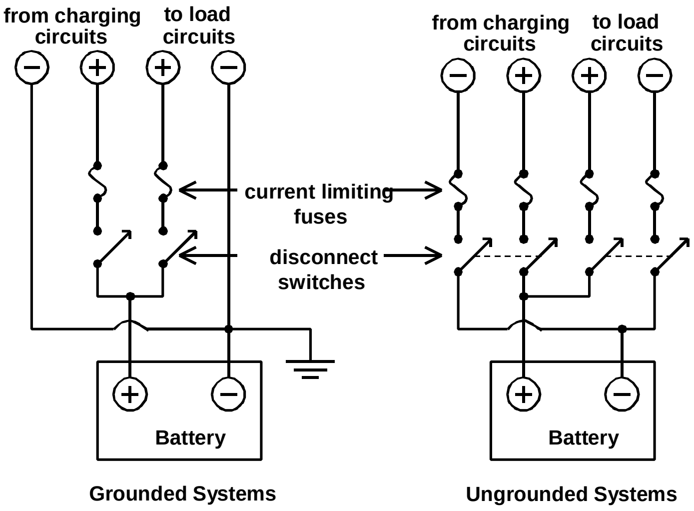

Figure 9.12 Battery Overcurrent and Disconnect Requirements.

5.3.4.3 Battery Test Equipment

Hydrometer: An instrument used to measure the *specific gravity* of a solution, or the ratio of the solution density to the density of water. In lead-acid batteries, the specific gravity of the electrolyte is related to the battery state of charge. Hydrometers may be constructed with a float ball using *Archimedes' principle*, or with a prism measuring the *refractive index* of the solution to determine specific gravity. *Temperature corrections* are generally required when taking hydrometer readings of solutions other than at room temperature.

Load Tester: An instrument which draws current from a battery with an electrical load, while recording the voltage, usually done at high *discharge rates* for short periods. Although not designed to measure *capacity*, a load test may be used to determine the general health or consistency among batteries in a system. Load test data are generally expressed as a *discharge current* over a specific *time* period.

9.3.4.4 Auxiliary Equipment and Systems

Enclosures: Batteries are generally required by local electrical codes and safety standards to be installed in an enclosure separated from controls or other PV system components. The enclosure may also be insulated or have other regulation mechanisms to protect the batteries from excessive temperature swings. Battery enclosures must be of sufficient size and strength hold the batteries, and can be located below ground if needed. If the enclosure is located above ground, care should be taken to limit the direct exposure to sunlight, or provide some type of shading.

Ventilation: Batteries often release toxic and explosive mixtures of gasses, namely hydrogen, so adequate ventilation of the battery enclosure is important. In most cases, passive ventilation techniques such as vents or ducts may be sufficient. In some cases, fans may be required to provide mechanical ventilation. Required air change rates are based on maintaining minimum levels of hazardous gasses in the enclosure. Under no circumstances should batteries be exposed and/or located in an area frequented by personnel.

Fire Protection: A fire extinguisher should be located in close proximity to the battery area if possible. In some critical applications, automated fire sprinkler systems may be required to protect facilities and expensive load equipment.

Monitoring Systems: Monitoring and instrumentation for battery systems can range from simple analog meters to sophisticated data acquisition systems. Lower level monitoring of battery systems might include voltage and current meters or battery state of charge indicators, while higher level monitoring may include automated recording of voltage, current, temperature, specific gravity and water levels. For small stand-alone PV systems, the battery condition is generally monitored only occasionally during maintenance checks.

Safety Systems and Considerations: Due to the hazardous manufacturing materials involved and the amount of electrical energy which they store, batteries are potentially dangerous and must be handled and used with caution. Depending on the size and location of a battery installation, readily accessible safety showers and eye washes may be required for personnel. Battery maintenance personnel should wear protective clothing, such as aprons, ventilation masks, goggles or face shields and gloves. Jewelry should be removed from hands and wrists, and properly insulated tools should be used to protect against inadvertent battery short-circuits. The physical characteristics of batteries should be considered, as they require special methods or mechanical lifting devices may be required to move them.

Catalytic Recombination Caps (CRC): A substitute for standard vented caps on lead-antimony batteries, CRCs primary function is to reduce electrolyte loss from the battery. CRCs contain particles of an element such as platinum or palladium, whose surface area adsorbs the hydrogen generated from the battery during finishing and overcharge. The hydrogen is then recombined with oxygen in the CRC to form water, which drains back into the battery. During this recombination process, heat is released from the CRC, as the combination of hydrogen and oxygen to form water is an exothermic process. This means that temperature increases in CRCs can indicate gassing in the battery. If CRCs are found to be at significantly different temperatures during recharge (meaning some cells are gassing and others are not), an equalization charge may be required. The use of CRCs on open vent, flooded lead-antimony batteries has proven to reduce electrolyte loss by as much as 50 %.

Flame Arrestor Caps: A commonly supplied component on larger, industrial battery systems, flame arrestor caps are vented through a charcoal filter. They are designed to contain a cell explosion and any ignition sources to that cell, minimizing the potential for a catastrophic explosion of the entire battery bank.

Battery Disposal and Recycling: Batteries are considered hazardous items as they contain toxic materials, such as lead, acids and plastics, which can harm humans and the environment. For this reason, laws have been established which dictate the requirements for battery disposal and recycling. In most areas, batteries may be taken to the local landfill, where they are in turn taken to approved recycling centers. In some cases, battery manufacturers provide guidelines for battery disposal through local distributors, and may in fact recycle batteries themselves. Under no circumstances should batteries be disposed of in landfills, the electrolyte be allowed to seep into the ground, or the battery be burned.

9.4 Battery Charge Controllers

A stand-alone photovoltaic system is designed so that it will meet the load requirements under reasonably determined worst-case conditions. When the array is operating under good-to-excellent weather conditions, electricity generated by the array often exceeds demand. To prevent battery damage resulting from overcharging, a *voltage regulator* or *charge controller* is used to protect the battery. A charge controller should prevent overcharge or overdischarge of a battery regardless of the system sizing/design and seasonal changes in the load profile, operating temperatures and insolation. The algorithm or control strategy of a battery charge controller determines the effectiveness of battery charging and PV array utilization, and ultimately the ability of the system to meet the load demands. Additional features, such as temperature compensation, alarms, meters, remote voltage sense leads and special algorithms, can enhance the ability of a charge controller to maintain the health and extend the lifetime of a battery, as well as provide an indication of operational status to the system caretaker.

9.4.1 Purpose of Charge Controllers in PV Systems

The primary function of a charge regulator in a stand-alone PV system is to maintain the battery at highest possible state of charge while protecting it from overcharge by the array and from overdischarge by the loads. Although some PV systems can be effectively designed without the use of charge control, any system that has unpredictable loads, user intervention, or optimized or undersized battery storage (to minimize initial cost) typically requires a battery charge regulator. Considerations for designs which can operate effectively without the use of charge regulation are discussed later in this chapter.

Seven of the more important functions of battery charge regulators and controls in PV systems are:

1. ***Prevents Battery Overcharge:*** to limit the energy supplied to the battery by the PV array when the battery becomes fully charged.

2. ***Prevents Battery Overdischarge:*** to disconnect the battery from electrical loads when the battery reaches low state of charge.

3. ***Provides Load Control Functions:*** to automatically connect and disconnect an electrical load at a specified time, for example operating a lighting load from sunset to sunrise.

4. ***Provides Status Information to System Users/Operators:*** to display or indicate system operational information such as battery voltage and current, charging status, load operation, and other data.

5. ***Interfaces and Controls Backup Energy Sources:*** to integrate alternative sources, such as a wind turbine and backup generator with the PV electrical system.

6. ***Diverts PV Energy to an Auxiliary Load:*** to supply energy to non-critical or secondary loads when the main battery bank reaches full state of charge and the array energy would otherwise be wasted.

7. ***Serves as a Wiring Center:*** to provide a termination or connection point for other components in the system, including the PV array, battery and electrical load.

9.4.1.1 Prevents Battery Overcharge

A remote stand-alone photovoltaic system with battery storage is designed so that it will meet the system electrical load requirements under reasonably determined worst-case conditions, usually for the month of the year with the lowest insolation-to-load ratio. When the array is operating under good-to-excellent weather conditions (typically during summer), energy generated by the array often exceeds the electrical load demand. To prevent battery damage resulting from overcharge, a *charge regulator* or *charge controller* is used to protect the battery.

Charge regulation is the primary function of a battery charge controller, and perhaps the single most important issue related to battery performance and life. The purpose of a charge controller is to supply power to the battery in a manner which fully recharges the battery without overcharging. If the battery is fully charged, unregulated charging will cause the battery voltage to reach exceedingly high levels, causing severe gassing, electrolyte loss, internal heating and accelerated grid corrosion. In most cases, if a battery is not protected from overcharge in PV system, premature failure of the battery and loss of load are likely to occur.

9.4.1.2 Prevents Battery Overdischarge

During periods of below average insolation and/or during periods of excessive electrical load usage, the energy produced by the PV array may not be sufficient enough to keep the battery fully recharged. When a battery is deeply discharged, the reaction in the battery occurs close to the grids and weakens the bond between the active materials and the grids. When a battery is excessively discharged repeatedly, loss of capacity and life will eventually occur. To protect batteries from over discharge, most charge regulators include an optional feature to disconnect the system loads once the battery reaches a low voltage or low state of charge condition.

Over discharge protection in charge regulators is usually accomplished by open-circuiting the connection between the battery and electrical load when the battery reaches a pre-set or adjustable *low voltage load disconnect (LVD) set point*. Most charge regulators also have an indicator light or audible alarm to alert the system user/operator to the load disconnect condition. Once the battery is recharged to a certain level, the loads are again reconnected to a battery.

9.4.1.3 Provides Load Control Functions

In some cases, regulators may have optional features that allow regulation or control of the system electrical load. Load control in PV lighting system regulators is a popular feature. This control can take place at sunset or sunrise as sensed by a photosensor or the array current or voltage output. In other cases the controller may have a timing function to cycle the load operation for a specified period or at a certain time of day. Experience has shown that these load control functions may require adjustment and proper specification for the array type and site conditions such as temperature and background lighting. While these features add to the cost and complexity of the controller, they can also greatly simplify the use and operation of the PV system.

9.4.1.4 Provides Status Information To Users

Many charge regulators used in PV systems can provide status information on the operation of the system and condition of the battery. These optional features allow users to intelligently manage their use of energy and gain a better understanding of how the system operates to take full advantage of its potential.

Battery voltage and state of charge are essential pieces of information that can be indicated by charge regulators. This can be incorporated as a "gas gauge" with a simple dial voltmeter showing green, yellow or red regions corresponding to different battery voltage ranges. Or a digital readout of exact battery voltage can be provided for more sophisticated users. While random battery voltage readings are interesting, the user must know how to interpret this information. For example, they must know at what voltage levels they should begin to curtail their energy usage, to prevent battery over discharge.

Many regulators also indicate with a lamp or ammeter whether the array is charging the battery, or if the array or load are disconnected. Load currents or even the net battery amp-hours can also be displayed on some regulator/controller designs. Knowledge of the array and load currents gives users a sense of how much energy they are producing with the array and consuming with electrical loads. This may allow them to plan their load usage to better correspond with the energy availability of their system during low insolation periods.

9.4.1.5 Interfaces and Controls Backup Energy Sources

In the case of a hybrid PV power system using one or more backup energy sources in addition to the array, more advanced system control centers may be designed to interface these alternate sources with the PV electrical system. One example would be a controller that activates a backup generator at low battery state of charge. The control center would start the generator at a pre-set low battery voltage, and turn it off when the battery is recharged or reaches a higher voltage limit.

The control of backup energy sources can also be performed by other components in the PV system. For example, some stand-alone inverters used in PV systems will start a backup generator or divert the loads to utility power when the battery reaches low state of charge. Once the battery has been recharged to a pre-set level, the loads are again connected to and powered by the battery bank.

9.4.1.6 Diverts PV Energy To Auxiliary Load

Batteries in photovoltaic systems are often fully recharged by the middle of the day during the summer. Normally, the charge regulator disconnects the array to prevent battery overcharging, wasting valuable array energy. To utilize this excess energy, some controllers allow the diversion of array energy to power an auxiliary load once the primary battery bank is fully charged. In most cases, the regulator will be bypassed, directly coupling the PV array to the auxiliary load. The auxiliary load is typically a backup battery, a DC water pump, a resistive element in a water heater, a fan or some other simple motor load that can be operated from the array without voltage regulation. In this way, all the energy that the array can produce is being utilized for some purpose. When the battery voltage falls and array power is once again needed to run the regular loads, the auxiliary load are disconnected. So the auxiliary load must be an optional, non-critical load that can be operated whenever excess array energy is available.

9.4.1.7 Serves As Wiring Center

In most cases, the charge regulator or system controller serves as the termination and connection point between the conductors leading to the various components in a PV system. For example, the charge regulator in a small residential lighting system commonly has the PV array, battery and load all connected to the regulator terminals. A fuse or circuit breaker for array and battery protection can be also be included in the regulator design.

Larger PV systems generally have overcurrent protection and disconnect devices included as part of the system control center. With these devices included in the system controller, the conductors leading to the PV array, battery and loads are connected at a centralized point in the system. The control center may also be the principle grounding point in the system and include surge suppression devices. With this centralized configuration for the system connection and controls, the installation, operation and maintenance of the system is greatly simplified.

9.4.2 Fundamentals of Charge Controllers and Terminology

While the specific regulation method or *algorithm* may vary among different charge regulators, all have basic functions and characteristics. Charge regulator manufacturer's data generally provides information about these functions and their specifications. Typical specifications provided by manufacturers include the ratings for PV array and load currents, operating voltages and temperatures, parasitic losses, regulation and load disconnect set points, and other information. It is up to the system designer to understand these specifications in order to properly select a charge regulator for a given PV application. The following discusses some of the more important terminology and characteristics of charge regulators and controls used in PV systems.

9.4.2.1 Nominal System Voltage

The *nominal system voltage* is the voltage at which the battery and charge regulator operate in a PV system. Most charge regulators are designed for operation at a specific nominal system voltage, while some may allow operation at multiple voltages, for example with 12 or 24 volt systems.

The selection of the nominal system voltage has important ramifications with respect to design and equipment selection. For systems with higher load power demands, a higher nominal system voltage is generally used to lower the peak operating currents, reducing the size and ratings of conductors, overcurrent and disconnect devices and the charge regulator. However, most equipment for small stand-alone PV systems is widely available in 12 or 24 volt dc models, and this may dictate the designer’s selection of the nominal system voltage.

9.4.2.2 Nominal Load and PV Array Current

Charge regulators are rated for their ability to handle certain maximum and nominal currents for the PV array and load. Often, surge conditions may exist from the array and loads, and the regulator must be tolerant of these conditions.

9.4.2.3 Charge Controller Set Points

The battery voltage levels at which a charge regulator performs control or switching functions are called the regulator *set points.* Four basic control set points are defined for most charge regulators that have battery overcharge and over discharge protection features. The voltage regulation (VR) and the array reconnect voltage (ARV) refer to the voltage set points at which the array is connected and disconnected from the battery. The low voltage load disconnect (LVD) and load reconnect voltage (LRV) refer to the voltage set points at which the load is disconnected from the battery to prevent over discharge. A list of each charge controller set point follows:

- Voltage Regulation (VR) Set Point
- Array Reconnect Voltage (ARV) Set Point
- Low Voltage Load Disconnect (LVD) Set Point
- Load Reconnect Voltage (LRV) Set Point

9.4.2.4 Adjustability of Controller Set Points

While some charge controllers use fixed resistors to pre-set the controller set points, many have the ability to adjust or change the regulation and load disconnect set points. Some also have provisions to adjust the hysteresis values as well. Adjustments are typically made with potentiometers (single or multi-turn), DIP (dual in-line package) switches, or circuit board jumpers. Although the system designer or installer may need access to properly set the controller for the type of battery and system configuration, user/operator access to regulator adjustments should be discouraged.

9.4.2.5 Environmental and Mechanical Specifications

The environmental and mechanical specifications of charge regulators are an important consideration for most PV applications. Generally, PV systems and components are installed in remote areas, in unconditioned spaces, and are subject to the extremes of the weather. For these reasons, most regulators have minimum and maximum ratings for ambient temperature, battery temperature and relative humidity. Where extreme environmental conditions exist, the designer should consider these specifications when selecting charge regulators.

The packaging and physical characteristics are another important characteristic of charge regulators. In general, the regulator circuitry should be sealed from the environment, either by conformably coating or 'potting' the circuitry. A rigid case should protect the regulator, or the controller may be installed in a weather-proof enclosure. Terminations used to connect wiring to the charge regulator should be corrosion resistant, and be large and sturdy enough to accept the conductor sizes that may be used in the system.

9.4.2.6 Surge Protection and Grounding

Most regulators include some type of surge suppression devices on the array and load circuits. Commonly, these devices are metal-oxide varistors (MOVs), which are connected between the positive and negative terminals, and from these terminal to ground. Under normal operating conditions, MOVs are high impedance devices. However under surge conditions, MOVs shunt energy to ground, bypassing sensitive electrical circuits of the controller. While these devices do not always protect the controller circuitry from harmful surges, they are strongly recommended for regulators used in lightning prone areas and in dc/ac systems using inverters.

9.4.3 Charge Controller Designs

The discussion in the preceding section show the different ways battery charge regulation can be configured in photovoltaic systems. There are also a number of variations in the function and electronic design of charge regulators.

Two basic methods exist for controlling or regulating the charging of a battery from a PV module or array _shunt_ and _series_ regulation. While both of these methods are effectively used, each method may incorporate a number of variations that alter their basic performance and applicability. Simple designs interrupt or disconnect the array from the battery at regulation, while more sophisticated designs limit the current to the battery in a linear manner that maintains a high battery voltage.

The *algorithm* or control strategy of a battery charge regulator determines the effectiveness of battery charging and PV array utilization, and ultimately the ability of the system to meet the electrical load demands. Most importantly, the controller algorithm defines the way in which PV array power is applied to the battery in the system. In general, interrupting on-off type controllers require a higher regulation set point to bring batteries up to full state of charge than controllers that limit the array current in a gradual manner.

Some of the more common design approaches for charge regulators are described in this section. Typical daily charging profiles for a few of the common types of regulators used in small PV lighting systems are presented in the next section:

- Shunt-Interrupting Design
- Shunt-Linear Design
- Series-Interrupting Design
- Series-Interrupting, 2-step, Constant-Current Design
- Series-Interrupting, 2-Step, Dual Set Point Design
- Series-Linear, Constant-Voltage Design
- Series-Interrupting, Pulse Width Modulated (PWM) Design

9.4.4 Operating Without a Charge Regulator

In most cases a charge regulator is an essential requirement in stand-alone PV systems. However there are special circumstances where a charge regulator may not be needed in small systems with well defined loads. Beacons and aids to navigation are a popular PV application which operate without charge regulation. By eliminating the need for the sensitive electronic charge regulator, the design is simplified, at lower cost and improved reliability.

The system design requirements and conditions for operating without a charge regulator must be well understood because the system is operating without any overcharge and overdischarge protection for the batteries. There are two cases where battery charge regulation may not be required: (1) when a low voltage "self-regulating module” is used in the proper climate; and (2) when the battery is very large compared with the array. Each of these cases are discussed next.

9.4.4.1 Using Low-Voltage "Self-Regulating" Modules

The use of "low-voltage" or "self-regulating" PV modules is one approach used to operate without battery charge regulation. This does not mean that the modules have an electronic charge regulator built-in, but rather it refers to the low voltage design of the PV modules. When a low voltage module, battery and load are properly configured, the design is called a "self-regulating system."

Typical silicon power modules used to charge nominal 12 volt batteries usually have 36 solar cells connected in series to produce and open-circuit voltage of greater than 21 volts and a maximum power voltage of about 17 volts. Why do we generally use modules with a maximum power voltage of 17 volts when we are only charging a 12 volt battery to maybe 14.5 volts? Because voltage drops in wiring, disconnects, overcurrent devices and controls, as well as higher array operating temperatures tend to reduce the array voltage measured at the battery terminals in most systems. By using a standard 36 cell PV module we are assured of operating to the left of the "knee" on the array I-V curve, allowing the array to deliver its rated maximum power current. Even when the array is operating at high temperature, the maximum power voltage is still high enough to charge the battery. If the array were operated to the right of the I-V curve "knee," the peak array current would be reduced, possibly resulting in the system not being able to meet the load demands.

In the case of using "self-regulating" modules without battery charge regulation, we want to take advantage of the fact that the array current falls off sharply as the voltage increases above the maximum power point. In a "self-regulating" low voltage PV module, there are generally only 28-30 silicon cells connected in series, resulting in an open-circuit voltage of about 18 volts and a maximum power voltage of about 15 volts at 25 ^{o}C. Under typical operating temperatures, the "knee" of the IV curve falls within the range of typical battery voltages. As a battery becomes charged during a typical day, its voltage rises and results in the array operating voltage increasing towards the maximum power point or "knee" of the IV curve. In addition, the module temperature increases, resulting in a reduction of the maximum power voltage. At some point, the battery voltage is high enough that the operating point on the IV curve is to the right of the "knee". In this region of the IV curve, the current reduces sharply with any further increases in voltage, effectively reducing the charge current and overcharge to the battery.

In summary, a "self-regulating system" can greatly simplify the design by eliminating the need for a charge regulator. However these type of designs are only appropriate for certain applications and conditions. In most common stand-alone PV system designs, a charge regulator is required.

9.4.4.2 Using a Large Battery or Small Array

A charge regulator may not be needed if the charge rates delivered by the array to the battery are small enough to prevent the battery voltage from exceeding the gassing voltage limit when the battery is fully charged and the full array current is applied. In certain applications, a long autonomy period may be used, resulting in a large amount of battery storage capacity. In these cases, the charge rates from the array may be very low, and can be accepted by the battery at any time without overcharging. These situations are common in critical applications requiring large battery storage, such as telecommunications repeaters in alpine conditions or remote navigational aides. It might also be the case when a very small load and array are combined with a large battery, as in remote telemetry systems.

In general, a charging rate of C/100 or less is considered low enough to be tolerated for long periods even when the battery is fully charged. This means that even during the peak of the day, the array is charging the battery bank at the 100 hour rate or slower, equivalent to the typical trickle charge rate that a regulator would produce anyway.

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10.0 PERFORMANCE AND RELIABILITY

There are tens of thousands of PV systems installed around the world producing megawatts of power daily. Most applications operate beyond daylight hours, requiring batteries for storing energy. The average battery storage capacity designed into a PV system is approximately 10 days, although storage capacities range from 2 days (e.g., streetlights) to more than 20 days (e.g., call boxes).

PV systems have performed successfully in various regions of the country, operating in varying climates, different seasons, and under differing solar resources. Operating experience and system testing indicates that on partly cloudy days, PV systems can produce up to 80% of their rated energy, while on hazy and humid days, about 50%. On heavy overcast days, when the full brightness of the sun is not available, they still produce about 30%of their rated energy.

Photovoltaics are environmentally benign, even the batteries are 98% recyclable. Additionally, for a stand-alone system, there is no need for fueling as the sun supplies an inexhaustible source of energy. No pollutants or wastes are released, while system operation is silent, another added benefit.

10.1 Module Performance

The amount of power photovoltaic modules produce over time (the energy) is the most important aspect of a PV system. The energy production is affected by the energy input and the efficiency of the power conversion. The efficiency of a PV device is

Efp = power output / (solar input per unit area x area)

Because efficiency cannot be measured directly, the output power of a device is measured under a given set of conditions. Photovoltaic modules and arrays are generally rated according to their maximun DC power output under Standard Test Conditions (STC). Since these conditions are not typical of how PV modules and arrays operate in the field, actual performance is somewhat less than at STC.

The physical size of a PV array is directly related to its maximum power rating at STC and the overall sunlight to electric power conversion efficiency of the modules, array and system components. The surface area requirements for a kilowatt of installed peak DC-rated PV array capacity are on the order of 8 to 12 m2 (86 to 129 ft2), depending on the overall sunlight to electrical power conversion efficiency of the modules and array. For example: a 10 percent efficient PV array with a 4-kWp DC-rated output at STC would require approximately 40 m2 (430 ft2) of array surface area.

10.1.1 Module Performance Specifications

Module output parameters (e.g., Voc, Isc, Vmp, Imp, Pmax) only have meaning when the rating conditions under which these outputs occur are specified.

10.1.2 Rating Conditions

Standard Test Conditions (STC)
Irradiance = 1000 watts/m^2
Cell temperature = 25C
Air mass = 1.5

Standard Operating Conditions (SOC)
Irradiance = 1000 watts/m^2
Cell temperature = NOCT
Air mass = 1.5

Nominal Operating Conditions (NOC)
Irradiance = 800 watts/m^2
Cell temperature = NOCT
Air mass = 1.5

Nominal Operating Cell Temperature (NOCT) is measured under the following conditions:

- Irradiance on surface of array = 800 watts/m^2
- Ambient air temperature = 20°C
- Photovoltaic array electrically open-circuit
- Wind speed = 1.0 m/sec

10.1.3 Manufacturer's Performance Data

Manufacturer's specification sheets usually provide data on module output under standard test conditions. Output under other conditions of irradiance and temperature is sometimes but not always provided.

10.1.4 Efficiency

Commercially available silicon cells have efficiencies as high as 15%. Laboratory efficiencies of about 20 % have been achieved. Considerable research is in progress to improve the efficiency, lower cost and increase durability

10.2 Selecting Arrays

The size of the photovoltaic array is determined by considering electrical loads, available solar insolation, tilt of the array and characteristics of the individual photovoltaic modules that make up the array.

10.2.1 Selection Criteria

The system designer establishes the array selection criteria which vary according to the application. When choosing modules for an array, the following factors should be considered:

- Voltage-current characteristics of the module
- Long-term reliability of the modules
- Power output density
- Suitability for high-temperature operation
- Suitability for self-regulated operation
- Material and performance stability over time
- Laminate construction
- Dimensions and weight
- Junction box/wiring configuration
- Framing materials: strength and corrosion resistance
- Bypass diode arrangement
- Availability of auxiliary hardware
- Reputation of manufacturer
- Cost and warranty.

10.2.2 Procurement Specifications

Procurement specifications for modules and arrays can be either very simple and brief or much more detailed. One or more of the following module specifications may be selected:

- Module manufacturer and model number
- Module dimensions
- Number and wiring arrangement of cells in the module

- Junction box configuration

- Module bypass diode arrangement

- Module maximum power, maximum power current, maximum power voltage, short-circuit current, open-circuit voltage and associated rating conditions

- Module current and voltage temperature coefficients

- Module laminate materials

- Module framing materials.

To adequately describe an array and accessory components in a procurement specification, the following items should be considered, although not all of them are normally required:

- Number and wiring arrangement of modules in the array
- Total number of modules in array
- Total array area
- Array dimensions
- Array bypass diode arrangement
- Array source circuit-disconnect arrangement
- Overcurrent protection
- Surge protection
- Number and arrangement of blocking diodes
- Intermodule and array wiring specification
- Power, current and voltage ratings at standard operating conditions
- Array circuit grounding arrangement
- Mounting type, materials and structural specification
- Fastener specification
- Module framing and array mounting hardware grounding arrangement
- Instrumentation and provisions for diagnostics.

10.3 Maximizing Array Performance

To maximize array performance, potential shading problems should be eliminated in the site selection process. The array operating temperatures should be kept as low as possible to maximize the array output and system life using simple, passive techniques. Irradiance enhancement from tracking the sun may also be considered when designing an array mounting configuration.

10.3.1 Shading Considerations

Even slight shading can significantly affect array performance. Keeping the array clean and entirely free from shading will help maximize power output.

When specifying the array mounting configuration and location, determine the sun's path for the site in order to identify potential shading of the array during different seasons of the year. For the maximum energy production, shading should not be permitted on any part of the array between one and one half hours after sunrise and one and one half hours before sunset. If some shading cannot be avoided, consider alternative array layouts and wiring strategies.

10.3.2 Array Cooling

Array cooling improves efficiency, increases reliability and extends the lifetime of the array. JPL found that by cooling an array 10°C, the lifetime of the modules doubled. When designing the array mounting configuration, use passive techniques to promote cooling airflow over the back surface of the array. Table 10.1 compares how different module mounting configurations affect operating temperatures. The installed normal operating cell temperatures (INOCT) are temperatures to be expected in service for a given mounting configuration and the manufacturer's stated normal operating cell temperature (NOCT). INOCT is lowest for rack mounted panels because both sides of the panel have unrestricted airflow. Direct-mounted panels are exposed to the ambient air on only one side; consequently, INOCT is the highest for this configuration.

Table 10.1 Installed normal operating cell temperature

Rack Mount	**INOCT = NOCT - 3°C**
Direct Mount	**INOCT = NOCT + 18°C**
Standoff and Integral Mount	**INOCT = NOCT + X**

W (inches)	**X (°C)**
1	**11**
3	**2**
6	**-1**

Where W is the standoff, entrance, or exit height or width, whichever is less. Add 4°C if channeled.

Source: SAND85-0330

10.3.3 Irradiance Enhancement

Irradiance can be enhanced by optimizing the array orientation and tilt, sun tracking in various modes, and concentrating. For roof-mounted arrays and ground-mounted arrays with a fixed tilt, the array should face within twenty degrees of south to capture the maximum amount of insolation. For optimum annual performance, tilt the array at an angle from the horizontal equal to the site latitude. A tilt angle of site latitude plus 15 degrees will optimize winter performance, while a tilt angle of site latitude minus 15 degrees will optimize summer performance. Sun tracking and concentrating do not generally apply to roof-mounted arrays.

10.3.4 Dissimilar or Unmatched Devices

In section 8, dissimilar or unmatched cell or module performance is discussed. Voltage or current outputs of cells, modules or arrays are determined by the series or parallel connection of the devices.

10.3.5 Aesthetics.

It is important that modules, arrays or systems on building or any site locations be aesthetically pleasing by designing them to blend into the building lines, colors or soundings

10.4 Module Reliability

Since the mid-1970s, the Jet Propulsion Laboratory (JPL) has been tasked with the responsibility of improving the reliability of flat-plate modules. Significant reliability improvements have been accomplished for crystalline silicon modules through considerable research, development and testing by JPL, the photovoltaics industry and other research organizations. JPL has established design specifications for modules and associated qualification testing to ensure that the modules meet reliability goals. A module passing the test has met environmental, electrical, and mechanical requirements that will ensure many years of reliable operation.

Qualification tests for Block V rating were developed to achieve 30-year module lifetimes. Some of the specific JPL Block V test requirements are as follows:

- Thermal Cycling - The module is subjected to 200 thermal cycles of -40C to +90C to verify its ability to withstand thermal stress caused by diurnal and climatic variations.

- Humidity-Freezing - The module is subjected to +85C @ 85% relative humidity and then dropped to -40C once a day for a total of 10 days to verify its ability to tolerate exposure to moisture during service.

- Cyclic Pressure Loading - The module is subjected to 10,000 pressure cycles of -50 psf to +50 psf to verify its ability to withstand variable pressure loads caused by gusting winds.

- Twisted Mounting Surface Requirement - The module surface is twisted 20 mm per meter of length to ensure that it can function under sustained distortion caused by mounting on a nonplanar structure.

Modules must pass several other electrical and mechanical tests to meet JPL Block V specifications, including being shot with a hailstone at 60 miles per hour. Modules that pass JPL Block V testing should be extremely reliable in the field. There are now several standards by which PV modules are tested.

Real life studies by various national laboratories indicate that today's PV modules are exhibiting lifetimes of about 20 years. This statistic is supported by users’ experiences over many years. PV modules contain no moving parts to wear out and degradation from the environment is minimal. Manufacturers are providing warranties that range from 5 to 15 years.

In 1984, the U.S. Coast Guard started converting battery power navigational aids to PV power. PV reliability is so high that the Coast Guard has more than 14,000 PV-powered navigational aids operating in coastal locations throughout the United States. Also, the military employs remote communications stations, radar, and monitoring equipment powered by PV for more reliable operation and lower operating cost.

10.4.1 Design Guidelines

The mechanical design of a photovoltaic array addresses three areas: the strength requirements, the material requirements, and the array mounting system design.

There are several times during which array accessibility is needed: installation, maintenance, and repair. By providing adequate accessibility, labor cost can usually be reduced and safety enhansed.

10.4.2 Strength Requirements

The photovoltaic array support structure must meet the local building codes. If the array is mounted on the roof of a building, roof strength must also meet the local building codes for the additional load imposed by the photovoltaic array. Four types of loads are: dead loads, live loads, snow loads, and wind loads.

10.4.3 Structural Loads

Dead loads act downward and consist of the weight of the photovoltaic modules and the mounting hardware, approximately 5 pounds per square foot(psf).

Live loads are the loads experienced during maintenance activities. Generally these loads are small (3 psf) when compared with the wind loads (24 to 55 psf), and they may be ignored if it is assumed that maintenance activities will not be performed when it is extremely windy.

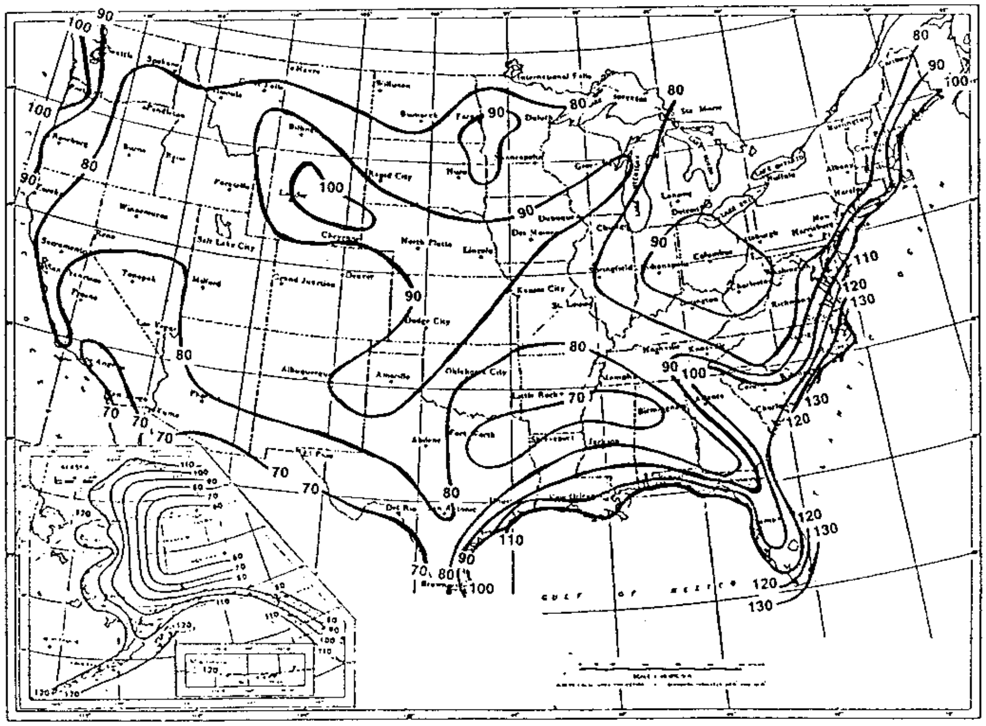
Snow loads can also increase the structural requirements. This is particularly evident in mountainous regions of the country with high annual snowfalls. Mounting the array further off the ground and at steeper tilt angles helps to minimize snow accumulations.

Wind loads are typically the highest of the load types. The array support structure should be designed to withstand the wind loads in combination with the dead loads and snow loads, if applicable.

10.4.4 Design Wind Load

Wind loads are region specific and the local building code is the authority on the design wind speed used. Typically, figures such as Figure 10.1 are included in the building code manuals for determining the design wind speed. With the design wind speed selected, a design wind load that acts normal to the array surface is calculated using the method outlined by the local building code.

Figure 10.1 Design wind speeds in miles per hour.



This method may be of the form:

Design Wind Load (psf) =
Velocity Pressure x Force Coefficient x Use Factor

The **velocity pressure** is a function of the design wind speed and the height of the array above the ground. A higher pressure is used for an increased wind speed or array height.

The **force coefficient** depends on the tilt of the array or roof. Wind forces are minimized for an array tilt angle of about 20 degrees from the horizontal, and they become a maximum for an array tilt angle of 90 degrees (vertical). Large wind forces also occur for array tilt angles of from 10 to 15 degrees. The array acts as an efficient airfoil for these angles.

The **use factor** depends on the consequence of a failure. A higher factor is used if the damage would be extensive, or if personnel injury would result.

10.4.5 Environmental Compatibility

In designing a photovoltaic system it is important that all exposed materials, such as module frames, junction boxes, terminations, wiring, mounting hardware (including beams, brackets, nuts, bolts, etc.) and sealants, be compatible with expected temperature, humidity, wind, rain and salt at the site. In particular, it is important to avoid the use of dissimilar metals and to select the proper type and size of wiring. It is especially important that exposed wiring be properly protected from ultraviolet radiation, moisture and salt. Aluminum hardware should not be in direct contact with concrete because the lye in the concrete will corrode the aluminum.

10.4.6 Recommended Hardware

The following hardware is well suited for use in photovoltaic systems:

Structural Members - Hot-dip galvanized steel per the specifications of ASTM A123 or ASTM A527. Corrosion resistant aluminum, type 6061 and 6063.

Fasteners - Stainless steel, cadmium or zinc plated, or hot-dip galvanized steel per ASTM A123. Avoid the use of poor quality fasteners that will corrode and make maintenance activities difficult, or that might cause structural failure.

Weather Sealants - Sunlight and weather resistant, long life.

10.4.7 Weathersealing

There are two types of weathersealing: dry and wet. Dry sealing consists of using flashing, hoods, boots, etc.. Wet sealants include caulk, roofing cement, tar, etc..

When choosing a sealant, look at the effect of temperature and ultraviolet radiation on the sealant. Other considerations include:

The number of attachments/penetrations
Corrosion protection and materials compatibility (avoid the use of dissimilar meterials)
Sealant lifetimes and cost.

10.4.8 Safety Considerations

Safety should be considered during installation, maintenance, repair and operation. Included are fire safety, wiring type, placement and protection , grounding and weather. Fire safety ratings for roof-mounted arrays are presented in UL Standard 790: Tests for Fire Resistance of Roof Covering Materials.

11.0 PV MAINTENANCE AND TROUBLE SHOOTING

Regular maintenance is required for any PV system, just as it is required for any equipment. Maintenance for stand-alone PV systems usually consists of monitoring and preventive measures several times a year (as required). Battery replacement only occurs after several years of operation. Without proper maintenance, PV systems can fail just as any other electrical power source.

Preventive maintenance schedules vary from annually to six times or more per year. The modules themselves require no maintenance unless they are in a very sandy or dirty location where they need periodic cleaning. Sealed batteries require little or no maintenance, but flooded (non-sealed conventional) batteries need to have water added periodically. Each battery manufacturer typically recommends a particular maintenance schedule for its batteries. The application or powered equipment may need other specific maintenance or repair, such as lamp replacement for lighting systems. Grounding and surge protection against lightning need monitoring. System components also need to be checked periodically for corrosion and other effects of weathering as any equipment would. Unless the system is a hybrid, there is no need for refueling and maintaining a generator.

11.1. Safety

With respect to both maintenance inspections and troubleshooting, a proper knowledge of safety and potential hazards cannot be overemphasized. Service personnel should familiarize themselves with the hazards and safety precautions listed below.

11.1.1 Current and Voltage Safety

Remember that photovoltaic systems produce enough current to cause serious injury.

- Check all safety disconnects for proper operation.
- Insure that all metal parts are grounded.
- Cover the modules when working on them during the day (or work on them at night).

11.1.2 Battery Safety

Special care must be used when working with and around batteries. When charging, lead acid batteries give off hydrogen gasses, which can be highly explosive. Smoking and spark producing activities must be avoided when working around these batteries.

Extra precaution must be taken when disconnecting wiring from batteries when batteries are charging, as this can create sparks and lead to explosions:

- Neutralize lead acid battery acid that gets on the skin with a mixture of baking soda and water.

- Neutralize Ni Cad battery acid that gets on the skin with boric acid or vinegar.

- Ensure that a portable eye wash kit is on hand in case acid is splashed into the eyes. Flush eyes for ten minutes and contact a physician immediately.

- Use eye protection and rubber gloves when working around batteries.

Low voltage batteries can still produce enough short-circuit current to cause physical harm.

11.1.3 Tools

Use tools that have insulation or tape on the handles or shanks to prevent potential short circuits and electric shocks. Ensure that brushes used to clean batteries are not spark producing.

11.2 Maintenance

All photovoltaic systems must be inspected and maintained on a regular basis. This preventive maintenance ensures that systems are operating effectively and, in many cases, prevents problems from occurring.

Maintenance inspections require a minimal amount of time and are very simple once the procedure is understood and maintenance records are developed. Some of the procedures can be carried out by the system owner, but most should be conducted only by trained technicians familiar with photovoltaic systems, subsystem components and proper safety procedures. A well maintained system is the best insurance against future problems.

11.2.1 Maintenance Inspection Procedures

Maintenance inspections of a photovoltaic system involve the examination of several subsystem categories. Each should be inspected in an orderly manner. Since some photovoltaic systems operate at high voltages and currents, proper safety procedures must be adhered to. The use of appropriate tools and materials is required for a successful inspection.

11.2.1.1 General Guidelines

- Inspect system twice per year (Spring and Fall).

- Develop and maintain inspection forms and records.

11.2.1.2 Wiring and Safety Equipment

- Check all safety disconnects for proper operation.

- Ensure that disconnect switches are open during operations that involve wiring.

- Examine wiring connections for corrosion and looseness.

- Inspect wire insulation for degradation.

- Measure voltage drop along wires during normal operation and record current.

- Ensure that all metal equipment cases and frames in the system are well grounded (all the way to the grounding object).

- Check the operation of all LEDs, meters, and instrumentation.

- Inspect circuit breakers and fuses.

- Inspect conduit connections for damage and water.

11.2.1.3 Array

- Conduct a visual check of all modules for delamination, discoloration, cracked or broken cells, excessive dirt or bird droppings.

- Check for shadows and shading in early morning and late afternoon.

- Inspect for excessive vegetation growth around array.

- Ensure that modules are well attached to the frame.

- Inspect array frame for corrosion.

- Inspect array frame bolts for tightness and corrosion.

- Inspect wiring connections for corrosion and looseness.

- Inspect junction box seals.

- Inspect junction box for cracks and moisture.

- Examine ventilation paths under modules.

- Make seasonal tilt adjustments as required.

11.2.1.4 Array - Electrical

- Measure short-circuit current of individual modules.
- Measure open-circuit voltage of individual modules.
- Measure short-circuit current and open-circuit voltage of entire array and array strings.
- For array modules connected in series, shade individual modules to determine the operation of the bypass diodes.
- For larger systems, shade modules or groups of modules to determine if the operating current decreases a corresponding amount.

11.2.1.5 Batteries (General)

- Inspect battery terminals for corrosion and loose cables.
- Examine battery surface for electrolyte leakage.
- Inspect battery tie downs.
- Ensure that batteries are not in direct contact with the floor.
- Check location and attachment of voltage regulator temperature compensation probe, if applicable.
- Inspect battery enclosure box.
- Check battery enclosure ventilation.
- Measure open-circuit battery voltage.
- If battery must remain connected, measure charge or discharge current.

11.2.1.6 Unsealed Batteries

- Check electrolyte levels.
- Measure specific gravity of cells after full charge.
- Determine state-of-charge.

11.2.1.7 Sealed Batteries

- Measure open-circuit voltage.

11.2.1.8 Electronic Equipment

- Verify voltage set points of charge controller with regard to battery specifications and system requirements.
- Inspect connections for corrosion and loose wires.
- Listen for unusual noises from charge controller such as relay chatter, etc.
- Insure that charge controller is in a sheltered, clean and well ventilated environment.
- Inspect junction and component boxes for insects, corrosion, etc.

11.2.1.9 Electrical Loads

- Check for proper operation.
- Ensure that loads are being used as designated.
- Perform any maintenance as required per manufacturers' specifications.

11.2.1.10 Inverters

- Check inverter stand-by feature.
- Ensure that inverter is in a well ventilated, dry, clean and safe environment.

11.3 Troubleshooting

When a problem or malfunction occurs, service personnel follow troubleshooting procedures, a specific progression of steps to determine the cause. Often problems are discovered during scheduled maintenance inspections. In most cases, though, troubleshooting begins when there is insufficient power to operate the loads. To find the exact source of the problem, personnel need a thorough knowledge of the system as well as the manufacturers' specifications on all of the various components.

11.3.1 Troubleshooting Checklists

When the symptoms have been identified, the following checklists can be used to determine the probable causes and corrective actions. During an evaluation, the complete system should be checked to identify other conditions that might lead to additional, future problems.

Troubleshooting checklists for photovoltaic systems are difficult to organize because no problem is more important than another. The following checklists are currently the most comprehensive and concise procedures available, providing reference tables for both overall system and specific component problems. They were developed by Architectural Energy Corporation, Boulder, CO, for the Naval Facilities Engineering Command (NFEC).

11.4 Maintenance Inspection and Troubleshooting Tools

Service personnel should always have the necessary tools on site so that they can conduct maintenance and troubleshooting procedures efficiently and without delay. Listed below are the required tools:

- Ammeter (clamp-on)
- Battery terminal cleaner
- Battery terminal clamp remover
- Compass
- Cell water filler
- Cleaning brush (non-sparking)
- Caulking gun
- Container (for mixing solutions)
- Diagonal cutters
- Flashlight
- First aid kit
- Hacksaw
- Hydrometer
- Inclinometer
- Insolation meter
- Light meter
- Linesman pliers
- Nutdriver set
- Needlenose pliers
- Paper/pencil
- Rubber gloves
- Safety goggles
- Soldering iron, portable
- Screwdriver set
- Shadeing material for array
- Solar site analyzer
- Stop watch
- Tape measurer
- Voltage test light
- Thermometer
- Tool pouch
- Utility knife
- Wire strippers
- Volt-Ohm meter

11.5 Maintenance Inspection and Troubleshooting Materials

Listed below are materials that should be on hand for photovoltaic system inspection and service:

- Cable
- Compound, anti-oxidizing
- Conduit
- Connectors, conduit
- Connectors, crimp
- Fuses
- Grease, wire pulling
- Hardware, mounting
- Inspection checklist
- Log book
- Manufacturers’ specifications (if determinable)
- Nails
- Nuts, wire
- Oil, standard for loads
- Rags
- Screws, assorted
- Sealant, silicone
- Service log
- Site map
- Soap
- Soda, baking
- Solder, electrical
- Tape, electrical
- Terminals, lug
- Ties, cable
- Water, distilled
- Wire

12.0 PV APPLICATIONS

For many years, no organization or infrastructure existed for using solar power for disaster relief. Neither the PV industry nor disaster relief organizations stored or maintained equipment for this specialized application. In recent years, though, a handful of portable photovoltaic systems have been used for disaster relief and are now available from FEMA and the PV industry. Many of the systems already existed, but others were developed by industry in response to disaster organizations' needs. To assist the federal disaster organization with selecting and procuring PV-powered equipment, both locally and nationally, generic specifications were developed and equipment was added to the GSA list. Many items are off-the-shelf equipment that can meet all of an organization's functional needs. Of course, if necessary, the PV industry can provide custom-made equipment to meet specific operational needs.

In the late 1990s, in a project funded by Sandia National Laboratories for the U.S. Department of Energy, FSEC documented the use and application of PV-powered equipment by disaster relief organizations. Some of the critical applications the organizations indicated were communications, medical support, shelters, and battery charging. Over the past several years, these and other applications have been used and evaluated by a number of disaster relief organizations. Their experiences are described on the following pages.

12.1 Metro/Dade Rescue Generator for Communications

As shown in Figure 12.1, this system was set up to provide power for communication with a satellite telephone system. The small, low-power phone operated successfully throughout the day to provide telephone and radio relay communications to firemen in the field. A larger and more powerful satellite telephone was connected to the PV system, but the larger phone required more power than the PV system could provide for long-term operation. The PV system was designed to be ganged in series for larger loads. It was determined that two more units would handle the load, but only one was purchased under this program.

The system was well designed and easy to deploy. It was packaged in quality casing, was lightweight enough to be carried, and the PV module came with its own stand-alone mount for remote setup. A second mounting system was added so that the module could be attached to the case when remote setup was not necessary.

The PV power system, designed to power communications equipment for field operations in disasters, was used in several training exercises over the year.


Figure 12.1 Field Day practice using PV system to power phone.

12.2 American Red Cross Generator for Field Sites

The power pack was successfully tested at three events to power amateur radio communication for disaster relief training: Tampa Walkathon, Hillsborough County Hurricane Exercise, and Hillsborough County Expo. The more often they use the system, the more comfortable they are in setting up and operating the equipment. For these short one-day exercises, the system met their needs in powering radios of 5-, 25- and 50-watts and various duty cycles. They plan to use it at shelters and field medical sites. Figure 12.2 shows the system being checked out by American Red Cross management and their radio operator.


Figure 12.2 American Red Cross checking out PV system.

12.3 National Hurricane Center PV-Powered Weather Station

FSEC first developed a prototype PV-powered weather station with amateur communication volunteers for the National Hurricane Center after Hurricane Andrew (Figure 12 3). This program allowed the commercialization of the original design. The system was redesigned for mass production and the added capability of GPS tracking (Figure 12.4). The redesigned system performed as well as the original system because the same weather station unit and packet radio communication network were used.

The unit can be pole-mounted or roof-mounted. The autonomy of the system is two days without sun. Amateur radio operators are responsible for frequency allocation and operating the 2-meter radio packet network.

Figure 12.3 Amateur radio communication center at the National Hurricane Center.

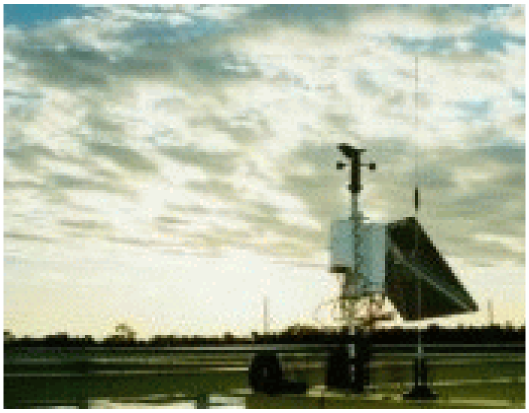


Figure 12.4 First new commercially built PV weather station for the National Hurricane Center.

12.4 Catholic Charities Generator for Shelters

The Miami diocese of Catholic Charities received two off-the-shelf systems, as shown in Figures 12.5 and 12.6. In addition to powering a small office consisting of a laptop computer, printer/fax and lighting, they were used to power cellular phones and to recharge batteries. Both systems had mounting brackets or stands for the PV modules.

Figure 12.5 Portable system being used at Catholic Charities Distribution center.

Figure 12.6 Some equipment being powered by the PV trailer at the Catholic Charities Distribution Center.

12.5 Radio Amateur Communications Emergency Services (RACES)/ Brevard Emergency Amateur Radio Service (BEARS) Generator for Communications

The PV power pack was first used for communications in support of a local parade. The first real disaster effort was in support of the firemen battling the Florida on Fire disaster in the summer of 1998. The system first provided power for communications near a fire station, as shown in Figure 12.7 and later was installed in a helicopter to power amateur radio TV. The emergency amateur radio operators provided communications in the field to the Emergency Operations Center where emergency management personnel and firemen directed the battle. As shown in Figure 12.7 and 12.8. The system powered at various times a 25- or 45-watt radio transceiver and fluorescent lamps.

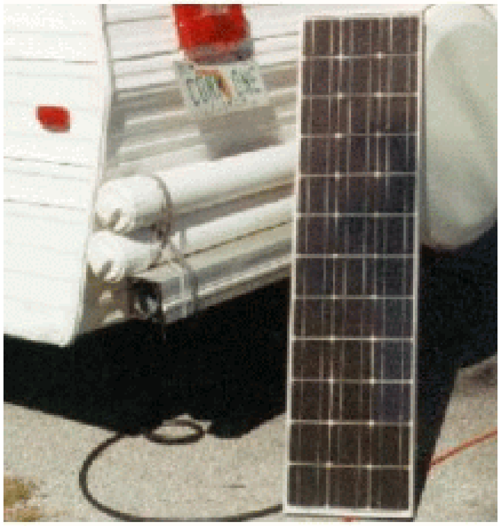


Figure 12.7 Brevard Emergency Amateur Radio Service (BEARS) using a PV system to power a radio.

Figure 12.8 A BEARS communication station using a PV system.

12.6 Sarasota K-9 Search/Rescue Battery Charger

This military man-pak PV module was first used at an annual regional disaster training workshop for search and rescue teams using dogs, as shown in Figure 12.9. The module was later used to help find people lost in the woods. The size and weight of the module allowed it to be carried in the field, making it valuable for long-term tasks. An adapter had to be made to connect the module to a hand-held radio 12VDC battery pack. As is, the module provides 12 VDC batteries, but a converter can be supplied to allow 6-, 7.5- and 9-volt battery charging.

Figure 12.9 Search & Rescue team looking at PV system.

12.7 Hurricane Hugo

In 1989, Hurricane Hugo cut across the island of St. Croix, disrupting power all over the island. A Florida PV distributor, 12 Volt Catalog, assembled PV systems using both Sovonics Solar System and ARCO Solar PV modules. Modules were individually connected to a deep-cycle Interstate battery to make a small portable system. The units were used at various disaster shelters, medical facilities, and emergency management offices to power 12 VDC fluorescent lights, fans and ham radios as shown in Figure 12.10 These companies have since become Geosolar, United Solar Systems and Siemens Solar.

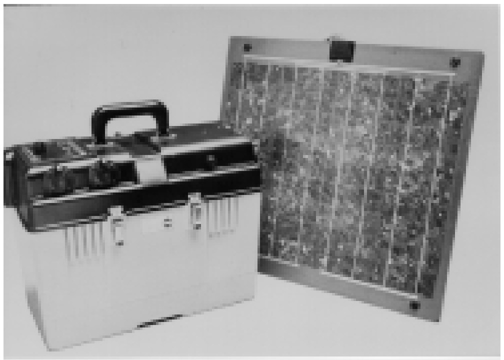


Figure 12.10 Portable PV Tote

When PV power is needed for a mainland disaster, workers rely on cars, trucks, and an infrastructure of roads, and usually have more than one access route for transporting supplies to a site. In contrast, when emergency power is needed on an island, workers must rely on ships or planes, which are expensive to operate, and likely have more limited access to a site via one or perhaps two ports or airstrips. Consequently, after Hurricane Hugo some large PV equipment never reached St. Croix. Some small, low power PV systems did make it to the island and maintained valuable communication services, a vital means of linking islanders to one another and to those outside—on other islands and on the mainland. Larger systems, though, which could have provided power at medical facilities, could not be shipped.

When Hurricane Hugo later struck South Carolina, a trailer-mounted, PV-powered generator was transported to the devastated area to assist with relief efforts. This Solar Emergency Response Vehicle powered a law enforcement traffic facility and an orphanage until utility power was restored. The unit, built by Arizona Solar Energy Office and Photocomm, supplied 12 VDC, and 115 and 220 VAC of electrical power (shown in Figure 12.11).

Figure 12.11 Trailer-Mounted PV Generator.

The unit operated 24 hours per day from a 200 peak watt PV array. The load at the traffic facility became greater than the unit could provide, as more and more people tried to use the unit. Several days after its arrival at the transportation facility, power was restored and the unit was moved to the orphanage. The unit operated more successfully at the orphanage, where demands for power were not as large and critical.

Weight and transport distance are important considerations in conveying a trailer-mounted PV system for emergency assistance, as commercial rush shipment across great distance is very expensive. The unit in Figure 12.11 weighed 5,000 lbs. and was transported almost 2,000 miles to South Carolina two days after requested. With the assistance of the U.S. Air Force, the unit was flown to the disaster.

12.8 Hurricane Bob

Block Island, off the coast of Rhode Island, took a direct hit from Hurricane Bob in 1991. Although the island lost power for days, an existing PV system suffered no damage and continued to provide power to the owners throughout the incident. This stand-alone photovoltaic project, built by Solar Design Associates, is shown in Figure 12.12. The ground-mounted array from ASE America, (formerly Mobil Solar) provides 2 kW of power to a battery bank, which powers the residence. The system continues to provide uninterrupted power today.

Figure 12.12 ASE America's Ground-Mounted Array

12.9 Northridge Earthquake

In the summer of 1991, an Emergency Mobile Communications and Lighting system was built by Barrett Manufacturing for use during the earthquake recovery efforts at Northridge in Los Angeles, California. The trailer-mounted PV system contained 4 Siemens 48-watt PV modules, as shown in Figure 12.13. The system provided reliable stand-alone electrical power at both 12 VDC and 120 VAC for site communication and lighting.

Figure 12.13. Emergency Mobile Communications and Lighting Unit

12.10 Hurricane Andrew

The Miami Emergency Management Office sent out requests for emergency communications assistance after Hurricane Andrew struck in August 1992. Staff at the Florida Solar Energy Center (FSEC) transported a small PV system to Miami to power an amateur radio station, which was used at a shelter. The system was a PV workshop training unit with two 40-watt modules. It was selected because of its capability to operate as a portable stand-alone PV system and was of sufficient size to power a 30-watt amateur radio as shown in Figure 12.14. This system successfully assisted with initial response emergency communication and was returned after one weeks of service.

Figure 12.14. FSEC Training System Powering Amateur Radio Communications

FSEC, together with Sandia National Laboratories, responded to a request from the University of Miami, Field Epidemiology Survey Team (FEST), for PV systems to power temporary medical clinics in south Dade County. Five PV systems were assembled in about a week and delivered to the disaster area. Each system consisted of a 1-kWp PV array, battery bank, controller, charger and a 2 kWh DC/AC inverter.

They provided power 24 hours per day for medical services desperately needed by people injured not only in the storm but also during the cleanup and rebuilding. One system, located at Saint Anne's Mission, is shown in Figure 12.15

Figure 12.15 FEST PV System

Lights, radios, fans and medical laboratory equipment were powered by these PV systems. Some old 12-volt DC vaccine refrigeration units were brought along and installed at three of the sites.
The refrigeration units were previously obtained for testing for the World Health Organization. Small refrigerators are most effective for medical clinics, as larger ones are used to cool everything and are opened so often that they consume more power than needed. Shown in Figure 12.16 are the balance of system components and appliances used at the clinics.

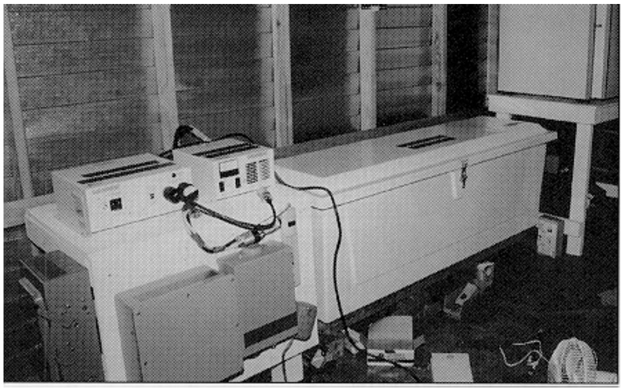


Figure 12.16 Balance of System Components

Because Andrew's destruction was so great, PV systems were used for weeks after deployment. However, the complete systems were designed and assembled two weeks after the disaster, and therefore were not in use when initially needed. For more effective use, PV systems need to be off-the-shelf units ready for immediate deployment. Because these systems were custom built and not mobile, final assembly was on site. Therefore, this application was very labor intensive and required technical expertise.

The manual switching of component and system controls was also too complicated for some users.

Automatic operation and a detailed status display are needed so users can fully benefit from the system. This PV system suffered from user overloading. Systems with dedicated loads would be more useful to inexperienced relief workers, since workers wouldn't need to switch loads, change components, or inadvertently overload the system.

Long before Hurricane Andrew struck, PV-powered street lights had been installed in Montego Bay, a south Miami suburb. After the storm, all 33 street lights were still standing and provided the only light in the area until utility power was restored. Each streetlight consisted of a pole-mounted fixture that contained a battery and controller enclosure, two PV modules and a fluorescent lamp. The street lights were manufactured locally by Solar Outdoor Lighting and were among the few lights still operating after the storm.

Later, additional lighting units were installed at command centers, security stations, temporary medical clinics, and shelters in the disaster area. Security lighting became very important for the safety of survivors trying to rebuild, offering protection from vandals and dangerous debris. A National Guardsman stationed in front of one unit is shown in Figure 12.17.

Figure 12.17 PV Lighting at Security Checkpoint

The Florida Department of Transportation was already equipped with numerous PV-powered traffic devices used for road construction. When Andrew struck, a PV-powered highway advisory radio unit, built by Digital Recorders, was operating along I-75 in the Everglades, transmitting messages about rest stops and tolls. After the storm, the unit’s AM radio transmitted road hazards and route changes in the disaster area. Additional trailer-mounted units were installed along the Florida Turnpike to provide further information to travelers, as shown in Figure 12.18. The system worked flawlessly, as if custom made for this application.

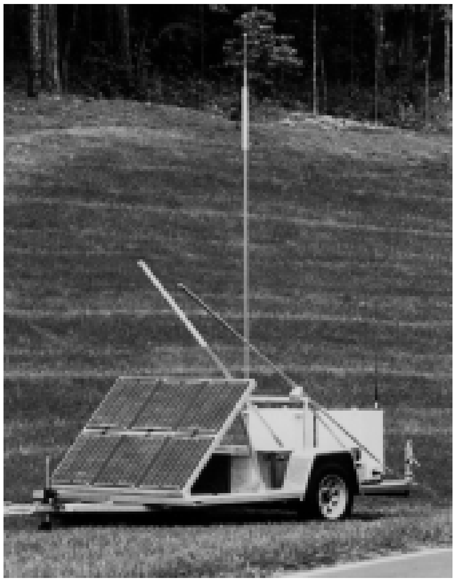


Figure 12.18 PV-Powered Radio Transmitter Along I-75

Other PV-powered traffic devices were transported to the disaster area to assist in the relief effort. Traffic control was increased by use of changeable highway message signs, flashing arrow boards, and warning signals and signs. Changeable highway message signs were invaluable to relief workers arriving from outside the area, directing them to staging areas and shelters (see Figure 12.19).

Figure 12.19 PV-Powered Changeable Message Sign

Two PV-powered traffic signals were developed, constructed, and shipped to the Dade County Transportation Department. The systems initially were underpowered and were modified by the manufacturers. Three months after Hurricane Andrew, they were tested at an intersection where power and traffic lights were not yet restored. However, after testing, the systems were not used. They were considered unsafe and did not meet all of the DOT standards.

Many families could not relocate and leave behind everything they owned. Since it took weeks for utility power to return to those families, flashlights became prize possessions and batteries were in great demand. Kyocera America provided several hundred solar lanterns to the American Red Cross, which distributed them at shelters. The lanterns had a 3-watt fluorescent lamp powered by a 2.5-watt PV module and a battery, as shown in Figure 12.20. The lanterns were very useful for close area lighting. But were in great demand and so were more likely to be stolen.

Figure 12.20 PV-Powered Lantern Used in Miami

12.11 Hurricane Erin

In 1995, Hurricane Erin cut across central Florida near the old location of FSEC in Cape Canaveral. Luckily, the storm was not strong enough to damage any of the PV-powered buildings at the center. Other PV-powered equipment located in the area continued to operate while utility power was in the process of being restored. Several security and street lighting systems were not damaged by the and continued to operate though power was out for several days. One such light is shown in Figure 12.21 PV lighting systems that offer little wind resistance seemed to survive the storm best.

Figure 12.21 PV Security Lighting

12.12 Hurricanes Luis and Marilyn

In 1995, Hurricanes Luis and Marilyn struck the Virgin Islands within a week of each other. The island of St. Thomas was totally devastated and without grid power for months. Ham radio operators at Emergency Operation Centers successfully used portable tote PV systems to power radios for local and between-island communications.

After Hurricane Luis, Miox Corporation provided PV-powered water purification units to the Virgin Islands. The unit shown in Figure 12.22 was capable of producing several hundred gallons of potable water per day. Two units were shipped but were never used because no one knew what they were or how to set them up.

Figure 12.22 PV Water Purification Unit

On the island of St. Thomas, two PV systems supplied power to a medical supply company, Supply Resources, Inc., and the supply company owners' home. Though the buildings were damaged, both PV systems survived the storms, allowing the store to re-open the next day. Repairs to the home and store were completed faster because electrical power was readily available. The owners offer testimony to the value of solar power, having enjoyed it in their daily lives, as well as having reaped its benefits after these devastating storms. Neighbors benefitted from use of the system in rebuilding their homes, too.

Two resorts, Maho Bay Camp and Concordia, on the Island of St. John in the Virgin Islands, were already PV powered when Hurricane Luis struck. The buildings received minimal damage, but the PV systems remained operational. Lights, refrigerators, fans, and communications equipment in the resorts used the PV-generated power as the owners repaired the resorts. Since PV already supplied the owners' needs each day, the utility power outage posed no problem for them. Because the resorts were two of the few places with power, they became shelters and medical centers for other residents affected by the storms.

12.13 Hurricane Iniki

When Hurricane Iniki struck the island of Kauai in the Hawaiian Islands, PV systems were already powering several buildings. Luckily, these systems were not affected by the storm and provided continuous power to the owners. In other buildings, connected only to the utility, residents were left without power for weeks. This is another example of a PV-powered building withstanding a storm and becoming a shelter and medical clinic in the recovery effort.

12.14 New FEMA Equipment

In 1998, the Federal Emergency Management Agency (FEMA) and U.S. Department of Energy purchased eight trailer-mounted PV systems for use in disaster response. Two sizes of systems were obtained: a 500-watt Applied Power Corporation system and a 1800-watt SunWize Corporation system. Presently (March 2000), six are stored and deployed out of three FEMA storage centers.

The first organization to use the trailers was North Carolina Solar Center on Knotts Island after Hurricane Bonnie in August 1998. The trailers were used for several days to power two homes for people with special needs, as shown in Figure 12.23 and 12.24.

Hurricane Georges was the next disaster (September 1998) in which two of the FEMA PV trailers were deployed. One trailer was used at a Catholic Charities disaster relief distribution center in Miami, Florida, as shown in Figure 12.25. The other trailer was used by Habitat for Humanity on Big Pine Island, Florida (Figure 12.26).

Figure 12.23 One of two FEMA PV trailer being used on Knotts Island after Hurricane Bonnie.

Figure 12.24 The second of two FEMA PV trailers being used on Knotts Island.

Figure 12.25 Catholic Charities disaster relief distribution center, Miami, after Hurricane Georges.

Figure 12.26 FEMA trailer at St. Peters Catholic church, Big Pine Key.

12.15 Tabulated Uses

Since 1989, PV systems have provided power for response and recovery efforts after disasters. The types of systems and their applications are shown in Table 1 below:

Table 1. PV Power Applications Used in Disaster Recovery Efforts
(H=hurricane)

Application	System	Disaster	Year	Location
Lighting/Communications	tote	H. Hugo	89	St. Croix
AC Power	trailer	H. Hugo	89	S. Carolina
Home Power	fixed system	H. Bob	91	Rhode Island
Lighting/Communications	trailer	Earthquake	91	Northridge, CA
Communication	portable	H. Andrew	92	Miami, FL
AC Power	fixed system	H. Andrew	92	Miami, FL
Security Lighting	fixed fixture	H. Andrew	92	Miami, FL
Radio Communications	trailer	H. Andrew	92	Miami, FL
Traffic Signs & Lights	trailer	H. Andrew	92	Miami, FL
Portable Lighting	fixture	H. Andrew	92	Miami, FL
Security Lighting	fixture	H. Erin	95	Titusville, FL
Building Power	fixed system	H. Erin	95	Cocoa Bch., FL
Water Purification	fixture	H. Luis & Marilyn	96	Virgin Islands
Radio Communication	tote	H. Luis & Marilyn	96	Virgin Islands
Building Power	fixed system	H. Luis & Marilyn	96	Virgin Islands
Building Power	fixed system	H. Iniki	96	Kauai, HI
Radio Communication	tote	Forest fires	98	Cocoa, FL
Building Power	trailer	H. Bonnie	98	Knotts Island, NC
Building Power	trailer	H. Georges	98	Miami, FL.

13.0 DISASTER RESISTANT BUILDINGS

Hurricanes, floods, tornados, and earthquakes are natural disasters that often destroy homes, businesses, and natural surroundings. Man-made disasters can also devastate homes, businesses, nature, and peoples lives. In a disaster, many people can be left without electrical service, functioning water and sewage systems, communications, and medical services for days, even weeks.

In large disasters, emergency management teams, the military and countless public and private organizations stage massive relief efforts. When supply and service businesses are destroyed or non-operational, the recovery process is hampered. Help must come from outside the area and long periods of time may be necessary to restore the community to its before-disaster condition. The cost may be measured in the billions and the waste and devastation, in the tons, as the weeks or months pass. Resources and economics are strained as communities rebuild, sometimes again and again.

As the population grows and dependance on technology increases, relief efforts become more massive and costly. But communities can take positive steps to prepare for the unexpected. Disaster resistant buildings are one such step where mitigation efforts are more productive than response. A disaster resistant building is one that is designed to minimize the destructive forces of nature and to supply the necessary comforts of an environmentally sound shelter while sustaining necessary energy resources. It should be the goal of every home and business owner, and is a cost effective means of reducing disaster response efforts and costs.

A disaster resistant building, whether a business or home, should be as energy efficient as possible. A healthy environment should be maintained in the building throughout the recovery effort and after life is returned to normal. The design, building materials, installation and appliances for the building should be selected for sustainability and quality of life, whether the building is disaster resistant or not. Energy efficiency should be an important consideration in every building. Our dependency on electrical utility power becomes a pronounced problem as emergency services are rendered to survivors and the rebuilding process starts.

Businesses vital to recovery, such as service station, hardware stores, grocery stores and banks, often find themselves without power. Gasoline cannot be pumped from underground tanks without electricity, so both public and private transportation is severely affected. Not only are rescue operations lindered, but workers cannot get to their jobs if their jobs still exist, further slowing economic recovery.

The insurance industry losses billions of dollars in replacement cost and business operating losses. The floods of North Dakota resulted in $ 1 billion in business property and inventory losses. On the average, a power outage cost each business about $7,500 per day. Power outages can affect losses due to spoiled food, perishables, and sales, and can also include intangible losses such as lost productivity, lost customers, and lost computer data. Many companies are forced to relocate to other cities, or even out-of-state, after a disaster taking valuable jobs, revenues, and property taxes with them.

13.1 PROPER BUILDING DESIGN

Much of the damage to the buildings in Dade County was due to the lack of building code enforcement. Many of the homes that lost their roofs was because the builder did not follow existing building codes and inspectors did not enforce the existing codes during construction. The wind speeds obtained during Hurricane Andrew prompted Dade County to upgrade their building standards for substained wind speeds of 120 mph. The structural integrity of the building should be design for disaster resistance of the Andrew kind and construction practices and code enforcement should be followed to meet that design requirement. Once the building envelope is designed to withstand the forces of natural or man-made disasters, the building needs to be energy efficient and designed to maintain a quality environment for its occupants.

13.2 Energy Efficient Buildings

Energy efficiency should be an important part of every building. The design, building materials, installation and appliances should be selected so that when the power goes out, the buildings is operational and the occupants can maintain a certain quality of life. Energy-efficient buildings and appliances reduce the amount of power needed. When energy efficiency, passive solar, and daylighting are combined with solar systems to generate electricity and hot water, partial or even full operation of the building can be maintained when traditional utility services disappear. Daylighting not only improves the living environment, it also reduces the lighting load. Solar water heating is a cost effective and energy efficient way of heating water in a home or business.

There are national programs that promote, educate and direct energy efficiency in buildings, such as Energy Gauge© and Energy Star© programs. Many states have mininum energy standards and codes that builders are required to follow. The use of the most energy-efficient technologies can reduce the energy consumption of most buildings by as much as 75%. The lower the building's energy needs, the less utility power required, which eases the disaster recovery effort. Some appliances have Seasonal Energy Efficiency Ratio (SEER) ratings that assist the builder or owner in selecting the right appliance for a building.

Many concepts and technologies can be applied to a building to enhance its energy efficiency, such as:

- Xeriscape landscaping
- Solar water heating
- Solar heating for winter
- Solar cooking
- Energy-efficient lighting
- Radiant barriers and insulation materials
- Ventilative and convective cooling
- Passive building techniques
- Seasonal Energy Efficiency Ratio (SEER) rated appliances

- Shading techniques and building orientation
- Daylighting techniques
- Effective Building materials and colors of finishes

13.3 Renewable Energy Sources

Renewables are viable, affordable and safe energy-generating technologies that can help speed up the recovery process following a disaster. Electricity from wind and photovoltaics can power communications, water purification, refrigeration, water pumping, medical equipment, lighting and other electrical appliances. PV can replace portable diesel and gasoline generators and reduce reliance on fuel sources that can be both expensive and scarce following a major disaster. Solar heating systems can provide two other precious commodities: space heating for buildings and hot water for medical clinics and industrial processes. Fuel cells, solar heating and other renewable technologies can also be used to supply needed power before a disaster as well as after a disaster.

13.4 Critical Power System

Typical methods of dealing with power outages include the use of fuel powered generators or an Uninterruptible Power Supply (UPS). UPS systems store energy from the electric utility and cannot function for an extended period of time unless their batteries are recharged. Generators alone cannot respond quickly enough to prevent problems with sensitive equipment due to mechanical start times. Also, stand-alone generators do not typically operate at maximum efficiency. A UPS coupled with a generator can provide an adequate backup system that meets minimum power needs when service is disrupted. However, there are drawbacks to these systems, including the difficulty of obtaining fuel in a crisis situation, operating fuel cost, and system reliability.

Figure13.1 Utility Interactive system.

One concept for backup power using renewables is a photovoltaic-powered Critical Power System

(CPS) for residential and business applications. The CPS can be designed to handle only critical and necessary power needs that allows people to stay in their homes or to operate their businesses after a disaster. The system can function as a utility-connected photovoltaic system during normal operation, a UPS during short outages and a backup power system during long-term power failures. As shown in Figure 13.1.

The CPS can be composed of a photovoltaic array, utility interface, critical power distribution panel, a sine-wave inverter, and a battery bank. The system is able to respond quickly enough to make the transition from utility power to backup power transparent to most computer equipment. A PV/generator hybrid system can operate at higher output and efficiency levels that either of the systems alone.

The CPS can supply energy to selected loads for either business or residential needs during short-term or long-term outages. The business loads usually identified as critical for operation during a disaster consist mostly of computer systems, communication systems and lighting. The residential loads usually consist of refrigeration, lighting, and communications/television. The CPS can be sized to meet the critical loads for several different building functions and home life styles.

The CPS also has applications where critical household or business functions cannot be sacrificed during outages caused by events other than hurricanes. Disruptions in service due to accidents, repairs, servicing, utility blackouts, etc., can leave buildings without communications, water and security.

13.4 Function

The CPS can be incorporated into the design of a hurricane-resistant structure that has been engineered to withstand damage from debris impact and wind forces associated with hurricanes or other disasters. The structure might include dedicated electrical branch circuits that the CPS can power and a protected area for the inverter and battery storage equipment. The PV array must be able to weather extreme wind forces and be protected from the impact of flying debris.

The CPS design can include the need to switch between grid-tied and stand-alone modes while maintaining the safety of utility workers and the user. The success of a CPS is its ability to operate reliably in a variety of modes, including utility-interactive and stand-alone. Although this is a typical design configurations, any combination of functions can be changed to meet the needs of the user.

13.4.2 Utility-interactive Mode

The system can operate in a utility-interactive mode under normal conditions. Typically, the total building electrical load is greater that the PV system can supply, so the utility supplies the remaining power. The batteries are kept charged by a small float current supplied by the PV panels. At night, all of the power is supplied by the utility. In the event that the PV system produces more than the building requires, no power is drawn from the utility and the excess power from the PV system flows into the utility grid, in areas where net metering is allowed.

13.4.3 Stand-Alone Back-up Mode

The system can serve as a power generation facility during long-term utility power outages. In the event of utility power outage, the system can switch over to backup power automatically. While in backup mode during a short term outage, the system draws stored power from the battery bank to supply the critical loads of the building. Only those loads to the dedicated critical load panel are powered by the backup system. Any loads that are not backed up will not receive power during the utility outage. Energy to support the dedicated load comes from the batteries. If the power failure is short, then the utility power is restored before the batteries are discharged. The utility resumes charging the batteries when the failure is over, making the system ready for another power interruption.

In the case of a longer outage, the system relies on energy provided by the PV array and battery pack. The PV charges the batteries and powers critical loads during the day, while at night only powering critical loads. The energy available in a stand-alone backup mode of operation is limited by design. Sometimes the loads on the system are too large or there is not enough sunlight to charge the batteries. In this case, a hybrid design with an optional generator may automatically start once the batteries have reached a certain depth of discharge, allowing the generator to power the backup loads.

13.4.4 Code Compliance

The electrical design should conform to the National Electric Code (NEC 97). Article 690 of the NEC applies specifically to photovoltaic systems in regards to consideration for the safety, protection and control of such systems. Other articles of NEC are also applicable.

The CPS should not produce excessive Electromagnetic Interface (EMI) and should comply with FCC EMI regulations/guideline, Part 15, Subpart j, FCC Regulations.

The CPS should shut down in the event of an internal fault or component failure, and automatically or manually indicate the fault. A Ground Fault Interrupter (GFI) should be included on the DC side to automatically interrupt the fault path and disable the array.

Limited surge protection at the PV array should be provided. Additional protection from vicinity lightning strikes and normal utility transients is required on both the DC and AC sections of the CPS. The protective circuits and components shall assure the other components and circuits are shielded from any explosive failures of the protective components.

The battery enclosure or enclosures should be suitable for indoors. The enclosure(s) may also contain control system components but must have a lockable access panel. Hardware should be provided to securely attach the enclosure(s) to the floor and/or the wall. The batteries should be accessible for maintenance.

14.0 MAKING THE RIGHT CHOICE

Whether man-made or natural, the size, strength, type, and location of the disaster gives each one a unique personality. Therefore, response, recovery and mitigation efforts are not the same for each disaster. For example, Hurricane Opal destroyed much of the shore line of western Florida. Fortunately, in most cases, the damage was isolated to within a few hundred feet of the shore. People could walk across the street and find shelter, food, water and electricity. Deployment of generators or solar equipment was very minor and, in many cases, not worth the effort. The utility restored power within a few days. Hurricane Andrew was a different story, as it made a wide path of destruction and some communities spent weeks restoring many of their resources.

Photovoltaic systems are a viable source of electrical power, converting an endless supply of light from the sun to electrical energy without pollution and noise. For some applications, the load uses low voltage electricity that is easily provided by PV, making it safer to operate in wet locations. Batteries store energy produced each day so refueling is effortless. The PV system requires little user interaction, making it easier to use. It is reliable and durable and can be designed to meet specific requirements of portability, stand-alone operation, various loads, and operating times.

However, photovoltaic power is not the right answer in every case. Large power needs (greater than 2 kW) may be better met by generators or utility power systems. A PV system has a higher initial cost than traditional power sources, making it more difficult to obtain or to store many units. In addition, PV cannot be located just anywhere because it requires sunlight. Permanent PV installations also suffer from the same destructive forces during disasters as conventional power sources.

To make an educated decision, you need to carefully consider your application and energy needs. Is equipment already available that is powered by solar or another renewable? Is the application for response, recovery or mitigation efforts? Are the power requirements so large that they can only be met by the utility or very large generators? Is the need short-term or long-term? To make the right choice, evaluate your needs and application; then determine what is available. Talk to those in the PV industry. Do they have something you can purchase off-the-shelf or can they customize to your specifications? If you need help, refer to the many sources in Section 16 and the many organizations listed in Section 18.

The question is not whether photovoltaics can be used to supply electrical power during emergencies, but rather for what applications and under what conditions is it the best choice. Although the photovoltaic community can be of valuable assistance, only the courageous individuals who risk their lives in an emergency can make the final decision.

14.1 Types of Energy Sources

Several energy sources are available, each with its own limitations and benefits. The U.S. relies on a dependable utility grid as its mainstay. When the grid is down, such as following a disaster, emergency organizations mainly depend on gasoline or diesel generators. Generators are usually powered by fossil fuels, but renewables are slowly replacing them. The advantage of renewables is that they are sustainable while offering energy security and environmental benefits.

The following is a list of energy sources other than gasoline/diesel generators and utility generators:

- Photovoltaic systems
- Solar thermal systems
- Fuel cell generators
- Hydro-generators
- Wind-generators
- Bio-mass systems

14.2 Applying PV

PV systems can provide power in any disaster situation, whether hurricane, earthquake, or other hazards. When designed for a specific response and recovery application, stand-alone PV systems can be deployed quickly and be ready for immediate use. One of the most effective applications may be a utility-interactive system with battery backup operating as a uninterruptable power supply. This application can be an important mitigation tool, because the more disaster resistant your building or facility is, the less disruptive and costly the disaster will be.

PV is also viable in a large-scale disaster situation, where power will be out for long periods of time and a large area has been destroyed. Massive infrastructure damage makes refueling generators a challenge because gasoline stations are often inoperable and roads impassable. Power distribution lines are difficult to fix because of the impassable roads, which also impedes transporting large amounts of materials for reconstruction. Survivor support is also difficult to provide because of this loss of infrastructure. In this scenario, PV systems are a natural solution for many applications because of their sustainable stand-alone operation. Some applications, such as medical clinics, require non-polluting operation, which PV can provide. It is a cost-effective resource for small portable and stand-alone applications because it is less expensive to operate than gasoline or diesel generators. Among its many possible applications for disaster relief, the best are those that require low power (less than 1 kW) for extended periods of time.

Another cost-effective application is a utility-interactive PV system in a disaster resistant building being used as a 2 kW or more UPS. Each business or home owner would have PV power for critical loads until utility power was restored. Insurance losses would be reduced and businesses could still function, providing services and jobs during the recovery effort.

14.3 System sizing

The easiest approach is to select an off-the-shelf system that is designed to power what you want or that already has PV power and is designed for your application. If you can't find something that fits your needs, you will need to use a simple routine to size your load.

After you have determined your application, look at the equipment and appliances you need to power. Their labels provide the power (watts) consumed, voltage and current ratings, and other information by which you determine their loads on the system. Make a list of equipment and the actual power consumed, including number of hours of operation and any cycling.

Next, using your list of equipment, add up the total watt-hours of energy consumed per day. You will use this to determine how much PV you need.

Using the solar radiation charts in Section 17, determine the amount of solar energy in kWh/m2/day for your location and system configuration. Use a rule-of-thumb conversion factor: 100 watts equals one square meter, which relates to a 10 % efficiency conversion. Using this rule, the solar radiation factor is equivalent to the number of hours of full sun in a day, which translates to the size of the PV array in watts.

Now, divide the load in watt-hours/day by the radiation factor or full sun hours. This gives you the size of the PV array in watts. You now have the size of the PV array in watts to within 10 to 20% of actual value. The actual design and components used in the PV system determine the actual performance.

For example:

> 1000 watt-hour/day load
> 4.8 kwh/m2/day average available solar energy for Daytona Beach for the year at 0 degree tilt
>
> Array size (watts) = 1000/4.8 = 208

Now you have an estimate of the wattage of the PV system you need for your application. With this information, you can estimate the cost, physical size, and other factors you need to make an informed decision.

15.0 GLOSSARY

ALTERNATING CURRENT (AC): Electric current (flow of electrons) in which the direction of flow is reversed at constant intervals, such as 60 cycles per second.

AMPERE (AMP or A): A measure of electrical charge that equals the quantity of electricity flowing in one second past any point in a circuit, or defined as one coulomb per second.

AMPERE-HOUR (AMP-HOUR or AHR): A measure of electrical charge that equals the quantity of electricity flowing in one hour past any point in a circuit. Battery capacity is measured in amp-hours.

ARRAY: A collection of photovoltaic modules electrically wired together in one structure to produce a specific amount of power.

AUTONOMOUS OPERATION: Self-contained operation. Capable of existing independently.

AZIMUTH: The angular measure between due south and the point on the horizon directly below the sun.

BALANCE OF SYSTEM (BOS): Components of a photovoltaic system other than the photovoltaic array and load.

CELL (PHOTOVOLTAIC): A semiconductor device that converts light directly into DC electricity.

CHARGE CONTROLLER: A component of a photovoltaic system that controls the flow of current to and from the battery subsystem to protect batteries from overcharge, overdischarge or other control functions. The charge controller may also monitor system operational status.

DIRECT CURRENT (DC): Electric current (flow of electrons) in which the flow is in only one direction.

ENERGY: The capacity for doing work.

GRID-CONNECTED: A photovoltaic system that is connected to a centralized electrical power network such as a utility.

HYBRID SYSTEM: A power system consisting of two or more power generating subsystems.

INSOLATION: The amount of energy in sunlight reaching an area. Usually expressed in watts per square meter (W/m2), but also expressed on a daily basis as watts per square meter per day (W/m2/day).

INVERTER: A device that converts direct current (DC) to alternating current (AC) electricity.

KILOWATT (KW): 1000 watts.

KILOWATT-HOUR (KWH): 1000 watt-hours. A typical residence in the United States consumes about 1000 kilowatt-hours each month at a price in the range of $.06 to $.15 per kilowatt-hour.

LIFE CYCLE COST (LCC) ANALYSIS: A form of economic analysis to calculate the total expected cost of ownership over the life span of the system. LCC analysis allows a direct comparison of the costs of alternative energy systems, such as photovoltaics, fossil fuel generators, or the extension of utility power lines.

LOAD: Any device or appliance in an electrical circuit that uses power, such as a light bulb.

MAINTENANCE COSTS: Any costs incurred in the upkeep of a system. These costs may include replacement and repair of components.

MODULE: A number of photovoltaic cells wired together to form a unit, usually in a sealed frame of convenient size for handling and assembling into arrays. Also called a "panel."

OPERATING COSTS: The costs of using a system for a selected period.

PARALLEL CONNECTION: A wiring configuration where positive terminals are connected together and negative terminals are connected together to increase current (amperage).

PEAK SUN HOURS: The equivalent number of hours when solar insolation averages 1000 watts per square meter and produces the same total insolation as actual sun conditions.

PEAK WATTS (WP): The maximum power (in watts) a solar array will produce on a clear, sunny day while the array is in full sunlight and operating at 25°C. Actual wattage at higher temperatures is usually somewhat lower.

PHOTOVOLTAIC (PV) SYSTEM: A complete set of interconnected components for converting sunlight into electricity by the photovoltaic process, including array, balance-of-system components, and the load.

POWER: The rate of doing work or energy is consumed or generated. Power is measured in watts or horsepower.

POWER CONDITIONER: The electrical equipment used to convert electrical power from a photovoltaic array into a form suitable for subsequent use, such as an inverter, transformer, voltage regulator, and other power controls.

SERIES CONNECTION: A wiring configuration in which the negative terminal of one module is connected to the positive terminal of the next module to increase voltage.

SILICON: A non-metallic element, the basic material of beach sand and the raw material used to manufacture most photovoltaic cells.

STAND-ALONE PHOTOVOLTAIC SYSTEM: A solar electric system, commonly used in a remote location, that is not connected to the main electric grid (utility). Most stand-alone systems include some type of energy storage, such as batteries.

VOLTAGE (V): A measure of the force or "push" given the electrons in an electrical circuit; a measure of electric potential. One volt produces one amp of current when acting against a resistance of one ohm.

WATT (W): A measure of electric power or amount of work done in a unit of time and equal to the rate of current flow (amps) multiplied by the voltage of that flow (volts). One amp of current flowing at a potential of one volt produces one watt of power.

WATT-HOUR (WH): A measure of electrical energy equal to the electrical power multiplied by the length of time (hours) the power is applied.

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17.0 SOLAR RADIATION DATA

Solar Radiation Data is needed to design and operate photovoltaic equipment effectively. The data listed in this section was obtained from *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors* produced by the National Renewable Energy Laboratory's Analytic Studies Division in April 1994.

City:	**PITTSBURGH**
State:	PA
WBAN No:	94823
Lat(N):	40.5
Long(W):	80.22
Elev(m):	373
Pres(mb):	973
Stn Type:	Primary

SOLAR RADIATION FOR FLAT-PLATE COLLECTORS FACING SOUTH AT A FIXED-TILT (kWh/m2/day), Percentage Uncertainty = 9

Tilt(deg)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	Average	1.7	2.5	3.5	4.6	5.5	6.1	5.9	5.2	4.2	3	1.8	1.4	3.8
	Minimum	1.4	2.2	3	3.5	4.5	5.1	5.2	4.7	3.7	2.5	1.5	1.2	3.6
	Maximum	2	3.1	4.2	5.4	6.2	6.8	6.7	5.8	4.9	3.8	2.1	1.6	4
Lat - 15	Average	2.4	3.2	4.1	4.9	5.5	5.9	5.9	5.5	4.8	3.8	2.4	1.9	4.2
	Minimum	1.7	2.5	3.4	3.7	4.5	4.9	5.2	4.8	4.1	3.1	1.8	1.3	3.9
	Maximum	2.8	4.2	5.2	5.9	6.3	6.7	6.7	6.2	5.7	5.2	3.1	2.3	4.5
Lat	Average	2.6	3.4	4.2	4.8	5.2	5.4	5.5	5.3	4.8	4.1	2.6	2.1	4.2
	Minimum	1.8	2.6	3.4	3.5	4.2	4.6	4.8	4.6	4	3.3	1.9	1.4	3.9
	Maximum	3.1	4.7	5.4	5.8	5.9	6.1	6.2	6	5.8	5.6	3.5	2.5	4.5
Lat + 15	Average	2.7	3.5	4.1	4.4	4.6	4.7	4.8	4.8	4.6	4.1	2.7	2.2	3.9
	Minimum	1.8	2.6	3.3	3.2	3.7	4	4.2	4.2	3.8	3.3	1.9	1.4	3.6
	Maximum	3.3	4.9	5.3	5.4	5.3	5.3	5.4	5.4	5.6	5.7	3.6	2.7	4.2
90	Average	2.5	3	3.1	2.9	2.6	2.5	2.6	2.9	3.2	3.3	2.3	2	2.7
	Minimum	1.7	2.2	2.5	2.1	2.2	2.2	2.4	2.6	2.7	2.7	1.5	1.1	2.5
	Maximum	3.2	4.5	4	3.5	3	2.8	2.9	3.3	3.9	4.6	3.2	2.5	2.9

AVERAGE CLIMATIC CONDITIONS

Element		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temp.	(deg C)	-3.3	-1.8	4.1	9.8	15.3	19.9	22.3	21.4	17.7	11.3	5.7	-0.3	10.2
Daily Min	(deg C)	-7.5	-6.5	-1.2	3.8	9.1	13.8	16.4	15.7	11.9	5.7	1.2	-4.2	4.8
Daily Max	(deg C)	0.9	2.7	9.4	15.7	21.4	26.1	28.1	27.1	23.5	16.9	10.2	3.7	15.5
Record Lo	(deg C)	-27.8	-24.4	-18.3	-10	-3.3	1.1	5.6	3.9	-0.6	-8.9	-18.3	-24.4	-27.8
Record Hi	(deg C)	20.6	20.6	27.8	31.7	32.8	36.7	39.4	37.8	36.1	30.6	27.8	23.3	39.4
HDD,Base	18.3C	670	564	441	257	119	20	3	8	56	222	378	577	3316
CDD,Base	18.3C	0	0	0	0	24	68	126	102	37	5	0	0	363
Rel Hum	percent	70	67	64	60	63	66	69	71	72	68	70	72	68
Wind Spd.	(m/s)	4.7	4.5	4.7	4.5	3.9	3.5	3.2	3	3.2	3.6	4.2	4.6	4

City:	CHICAGO
State:	IL
WBAN No:	94846
Lat(N):	41.78
Long(W):	87.75
Elev(m):	190
Pres(mb):	992
Stn Type:	Secondary

SOLAR RADIATION FOR FLAT-PLATE COLLECTORS FACING SOUTH AT A FIXED-TILT (kWh/m2/day), Percentage Uncertainty = 9

Tilt(deg)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	Average	1.8	2.6	3.5	4.6	5.7	6.3	6.1	5.4	4.2	3	1.8	1.5	3.9
	Minimum	1.5	2.2	3.1	4	4.8	5.7	5.4	4.8	3.6	2.5	1.4	1.2	3.7
	Maximum	2.1	3	3.9	5.3	6.8	7.2	6.6	6.1	4.9	3.5	2.1	1.7	4.2
Lat - 15	Average	2.7	3.5	4.1	5	5.8	6.1	6.1	5.7	4.9	3.9	2.5	2.2	4.4
	Minimum	2	2.8	3.6	4.2	4.8	5.5	5.4	5	4	3	1.7	1.6	4.2
	Maximum	3.1	4.2	4.8	5.9	6.9	7.1	6.6	6.6	5.9	4.7	3.3	2.9	4.8
Lat	Average	3.1	3.8	4.2	4.9	5.4	5.7	5.6	5.5	4.9	4.2	2.8	2.4	4.4
	Minimum	2.1	3	3.6	4.1	4.4	5.1	5	4.8	4	3.1	1.8	1.8	4.1
	Maximum	3.5	4.6	4.9	5.8	6.5	6.6	6.2	6.4	6.1	5.1	3.7	3.3	4.8
Lat + 15	Average	3.3	3.9	4.1	4.5	4.8	4.9	4.9	5	4.7	4.2	2.9	2.6	4.1
	Minimum	2.2	3	3.5	3.8	4	4.4	4.3	4.3	3.8	3.1	1.8	1.8	3.8
	Maximum	3.8	4.7	4.9	5.4	5.7	5.7	5.4	5.8	5.8	5.2	3.8	3.6	4.5
90	Average	3.1	3.5	3.2	3	2.8	2.6	2.7	3.1	3.4	3.4	2.5	2.4	3
	Minimum	2	2.5	2.7	2.5	2.4	2.5	2.5	2.8	2.7	2.5	1.5	1.7	2.7
	Maximum	3.7	4.3	3.8	3.6	3.2	3	2.9	3.5	4.2	4.3	3.5	3.5	3.3

AVERAGE CLIMATIC CONDITIONS

Element		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temp.	(deg C)	-6.1	-3.7	2.9	9.2	14.9	20.3	22.9	22.1	18	11.6	4.4	-3	9.4
Daily Min	(deg C)	-10.6	-8.2	-1.9	3.7	8.7	14.2	17	16.4	12.2	5.7	-0.2	-7.2	4.2
Daily Max	(deg C)	-1.7	0.8	7.7	14.8	21.2	26.4	28.7	27.7	23.8	17.4	9.1	1.1	14.8
Record Lo	(deg C)	-32.8	-27.2	-22.2	-13.9	-4.4	2.2	4.4	5	-2.2	-8.3	-17.2	-31.7	-32.8
Record Hi	(deg C)	18.3	21.7	31.1	32.8	33.9	40	38.9	38.3	37.2	32.8	25.6	21.7	40
HDD,Base	18.3C	758	616	479	273	131	19	3	11	47	217	417	661	3631
CDD,Base	18.3C	0	0	0	0	26	79	144	126	37	7	0	0	418
Rel Hum	percent	72	72	70	65	64	66	68	71	71	69	73	76	70
Wind Spd.	(m/s)	5.2	5.1	5.4	5.3	4.6	4.2	3.7	3.6	4	4.5	4.8	4.9	4.6

City:	**OMAHA**
State:	NE
WBAN No:	94918
Lat(N):	41.37
Long(W):	96.52
Elev(m):	404
Pres(mb):	976
Stn Type:	Primary

SOLAR RADIATION FOR FLAT-PLATE COLLECTORS FACING SOUTH AT A FIXED-TILT (kWh/m2/day), Percentage Uncertainty = 9

Tilt(deg)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	Average	2.1	2.9	3.9	5	5.9	6.7	6.6	5.7	4.5	3.3	2.1	1.7	4.2
	Minimum	1.6	2.3	2.7	3.9	5	5.7	5.7	5.1	3.6	2.3	1.6	1.5	3.7
	Maximum	2.4	3.3	4.6	5.7	6.7	7.4	7.4	6.5	5.4	3.9	2.5	1.9	4.4
Lat - 15	Average	3.3	4	4.7	5.5	6	6.5	6.5	6.1	5.2	4.4	3.2	2.7	4.9
	Minimum	2	2.8	3	4.1	5	5.6	5.6	5.4	4	2.9	2.1	2.1	4.1
	Maximum	4	4.9	5.7	6.3	6.8	7.2	7.4	6.9	6.6	5.4	4.1	3.2	5.2
Lat	Average	3.8	4.4	4.9	5.3	5.6	6	6	5.8	5.3	4.7	3.5	3.2	4.9
	Minimum	2.2	3	3.1	3.9	4.7	5.1	5.2	5.2	3.9	3	2.3	2.4	4
	Maximum	4.6	5.4	5.9	6.3	6.4	6.6	6.8	6.7	6.7	5.8	4.7	3.8	5.3
Lat + 15	Average	4.1	4.6	4.8	5	5	5.2	5.3	5.3	5.1	4.7	3.7	3.4	4.7
	Minimum	2.3	3	3	3.6	4.2	4.5	4.6	4.7	3.7	3	2.4	2.5	3.8
	Maximum	5	5.6	5.8	5.8	5.6	5.7	6	6.1	6.5	5.9	5	4.1	5.1
90	Average	3.9	4.1	3.8	3.2	2.8	2.7	2.8	3.2	3.6	3.9	3.3	3.2	3.4
	Minimum	2.1	2.6	2.3	2.5	2.4	2.4	2.5	2.9	2.6	2.3	2.1	2.3	2.7
	Maximum	4.7	4.9	4.7	3.9	3.1	2.9	3.1	3.7	4.6	4.8	4.5	4	3.7

AVERAGE CLIMATIC CONDITIONS

Element		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temp.	(deg C)	-6.4	-3.4	3.2	10.8	16.9	22.2	24.7	23.3	18.2	12	3.7	-4.2	10.1
Daily Min	(deg C)	-11.6	-8.6	-2.3	4.6	11	16.3	19.2	17.7	12.6	6.1	-1.3	-8.9	4.6
Daily Max	(deg C)	-1.3	1.7	8.7	16.9	22.7	28	30.3	28.9	23.8	17.8	8.7	0.5	15.6
Record Lo	(deg C)	-30.6	-29.4	-26.7	-15	-2.8	3.3	6.7	6.1	-3.9	-10.6	-22.8	-30.6	-30.6
Record Hi	(deg C)	20.6	25.6	31.7	36.1	37.2	40.6	45.6	43.3	40	35.6	26.7	22.2	45.6
HDD,Base	18.3C	767	608	470	230	86	6	0	6	50	202	438	699	3563
CDD,Base	18.3C	0	0	0	3	42	121	198	159	47	6	0	0	576
Rel Hum	percent	71	71	67	61	64	65	68	70	71	67	71	73	68
Wind Spd.	(m/s)	4.6	4.6	5.1	5.2	4.4	4	3.7	3.6	3.9	4.1	4.5	4.5	4.3

City:	**TAMPA**
State:	FL
WBAN No:	12842
Lat(N):	27.97
Long(W):	82.53
Elev(m):	3
Pres(mb):	1018
Stn Type:	Secondary

SOLAR RADIATION FOR FLAT-PLATE COLLECTORS FACING SOUTH AT A FIXED-TILT (kWh/m2/day), Percentage Uncertainty = 9

Tilt(deg)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	Average	3.2	4	5.1	6.2	6.4	6.1	5.8	5.5	4.9	4.4	3.6	3.1	4.9
	Minimum	2.6	3.4	4.3	5.8	5.7	5.1	5.1	4.6	4.3	3.6	3	2.7	4.5
	Maximum	3.7	4.5	5.6	6.8	7.1	6.9	6.4	6.3	5.4	4.9	4	3.5	5.2
Lat - 15	Average	3.9	4.6	5.5	6.4	6.4	5.9	5.7	5.5	5.2	5	4.2	3.8	5.2
	Minimum	3	3.8	4.7	5.9	5.7	5	5	4.7	4.5	4	3.4	3.1	4.7
	Maximum	4.6	5.3	6.1	7.1	7	6.7	6.3	6.3	5.8	5.6	4.8	4.4	5.5
Lat	Average	4.5	5.1	5.8	6.3	6	5.5	5.3	5.4	5.2	5.4	4.8	4.4	5.3
	Minimum	3.3	4.2	4.8	5.9	5.4	4.7	4.7	4.5	4.5	4.1	3.8	3.5	4.8
	Maximum	5.3	5.9	6.4	7	6.6	6.2	5.9	6.2	5.9	6.1	5.6	5.2	5.7
Lat + 15	Average	4.8	5.3	5.7	5.9	5.3	4.8	4.7	4.9	5	5.5	5.1	4.7	5.1
	Minimum	3.5	4.3	4.7	5.4	4.8	4.1	4.2	4.2	4.3	4.1	4	3.7	4.6
	Maximum	5.8	6.2	6.4	6.5	5.8	5.3	5.2	5.6	5.7	6.2	6	5.7	5.5
90	Average	4	4	3.5	2.8	2	1.7	1.8	2.2	2.9	3.9	4.2	4.1	3.1
	Minimum	2.8	3.2	3	2.6	1.9	1.6	1.7	2	2.4	2.8	3.1	3.1	2.7
	Maximum	5	4.8	4	3	2.1	1.8	1.9	2.4	3.2	4.4	5	5	3.3

AVERAGE CLIMATIC CONDITIONS

Element		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temp.	(deg C)	15.5	16.4	19.1	21.8	25.1	27.2	27.8	27.8	27.2	23.8	19.8	16.8	22.4
Daily Min	(deg C)	10	10.9	13.6	16	19.7	22.7	23.6	23.6	22.7	18.4	14	11.3	17.2
Daily Max	(deg C)	21	21.9	24.8	27.6	30.7	31.9	32.3	32.3	31.7	29.1	25.4	22.3	27.6
Record Lo	(deg C)	-6.1	-4.4	-1.7	4.4	9.4	11.7	17.2	19.4	13.9	4.4	-5	-7.8	-7.8
Record Hi	(deg C)	30	31.1	32.8	33.9	36.7	37.2	36.1	36.7	35.6	34.4	32.2	30	37.2
HDD,Base	18.3C	130	89	47	4	0	0	0	0	0	0	39	95	403
CDD,Base	18.3C	42	34	71	107	210	267	294	294	267	171	82	47	1887
Rel Hum	percent	75	73	72	69	70	74	77	78	77	74	75	75	74
Wind Spd.	(m/s)	3.9	4.1	4.2	4.1	3.9	3.6	3.3	3.1	3.4	3.8	3.8	3.8	3.8

City:	**LAS VEGAS**
State:	NV
WBAN No:	23169
Lat(N):	36.08
Long(W):	115.17
Elev(m):	664
Pres(mb):	938
Stn Type:	Primary

SOLAR RADIATION FOR FLAT-PLATE COLLECTORS FACING SOUTH AT A FIXED-TILT (kWh/m2/day), Percentage Uncertainty = 9

Tilt(deg)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	Average	3	4	5.4	6.9	7.8	8.4	7.9	7.2	6.2	4.7	3.4	2.8	5.7
	Minimum	2.3	3.4	4.8	6.1	7.2	7.8	6.6	6	5.4	4	3	2.2	5.3
	Maximum	3.4	4.5	6.1	7.4	8.3	8.9	8.4	7.8	6.7	5.1	3.7	3.1	5.8
Lat - 15	Average	4.4	5.3	6.4	7.5	7.8	8.1	7.7	7.5	7.1	6.1	4.8	4.2	6.4
	Minimum	3.2	4.4	5.6	6.4	7.2	7.6	6.5	6.2	6.1	5	4	3.1	5.9
	Maximum	5.3	6.1	7.3	8	8.3	8.6	8.2	8.2	7.7	6.7	5.4	4.8	6.7
Lat	Average	5.1	5.9	6.7	7.4	7.3	7.4	7.1	7.2	7.2	6.6	5.5	4.9	6.5
	Minimum	3.6	4.8	5.8	6.2	6.7	7	6.1	6	6.1	5.3	4.5	3.6	5.9
	Maximum	6.2	6.8	7.7	7.9	7.8	7.8	7.5	7.9	7.9	7.3	6.3	5.7	6.8
Lat + 15	Average	5.6	6.1	6.6	6.8	6.5	6.3	6.2	6.5	7	6.8	5.9	5.4	6.3
	Minimum	3.8	4.9	5.7	5.7	5.9	6	5.3	5.5	5.9	5.4	4.7	3.8	5.7
	Maximum	6.8	7.2	7.6	7.3	6.8	6.7	6.5	7.2	7.6	7.5	6.8	6.2	6.6
90	Average	5	5.1	4.7	3.9	3	2.6	2.6	3.4	4.5	5.3	5.2	5	4.2
	Minimum	3.4	4	4	3.3	2.8	2.4	2.4	2.9	3.8	4.2	4.1	3.5	3.7
	Maximum	6.2	6	5.4	4.1	3.1	2.7	2.7	3.7	4.9	5.9	6.1	5.8	4.5

AVERAGE CLIMATIC CONDITIONS

Element		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temp.	(deg C)	7.5	10.6	13.5	17.8	23.3	29.4	32.8	31.5	26.9	20.2	12.8	7.6	19.5
Daily Min	(deg C)	0.9	3.8	6.6	10.4	15.7	20.8	24.6	23.4	19	12.4	5.9	1.1	12.1
Daily Max	(deg C)	14.1	17.4	20.4	25.3	31	37.9	41.1	39.6	34.8	27.8	19.7	14.2	26.9
Record Lo	(deg C)	-13.3	-8.9	-5	-0.6	4.4	9.4	15.6	13.3	7.8	-3.3	-6.1	-11.7	-13.3
Record Hi	(deg C)	25	30.6	32.8	37.2	42.8	46.1	46.7	46.7	45	39.4	30.6	25	46.7
HDD,Base	18.3C	336	216	162	79	8	0	0	0	0	34	169	332	1337
CDD,Base	18.3C	0	0	12	64	163	332	449	408	258	91	0	0	1778
Rel Hum	percent	45	40	33	25	21	16	21	26	25	29	37	45	30
Wind Spd.	(m/s)	3.6	4.1	4.9	5.1	5.2	5.1	4.9	4.5	4.3	3.8	3.8	3.4	4.4

City:	**ALBUQUERQUE**
State:	NM
WBAN No:	23050
Lat(N):	35.05
Long(W):	106.62
Elev(m):	1619
Pres(mb):	838
Stn Type:	Primary

SOLAR RADIATION FOR FLAT-PLATE COLLECTORS FACING SOUTH AT A FIXED-TILT (kWh/m2/day), Percentage Uncertainty = 9

Tilt(deg)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	Average	3.2	4.2	5.4	6.8	7.7	8.1	7.5	6.9	5.9	4.7	3.5	2.9	5.6
	Minimum	2.6	3.4	4.4	6.2	6.9	7.4	6.8	5.9	5.4	4	2.8	2.2	5.1
	Maximum	3.7	4.7	6.2	7.3	8.3	8.7	7.9	7.4	6.6	5.3	3.9	3.3	5.9
Lat - 15	Average	4.6	5.4	6.3	7.3	7.7	7.8	7.4	7.2	6.6	5.9	4.8	4.3	6.3
	Minimum	3.6	4.3	5.1	6.5	6.8	7.2	6.7	6.1	6	4.9	3.8	3.1	5.7
	Maximum	5.4	6.1	7.3	7.8	8.3	8.3	7.8	7.7	7.4	6.8	5.5	5	6.6
Lat	Average	5.3	6	6.5	7.2	7.2	7.1	6.9	6.9	6.8	6.5	5.5	5	6.4
	Minimum	4.1	4.7	5.3	6.4	6.4	6.6	6.3	5.8	6.1	5.2	4.3	3.6	5.8
	Maximum	6.3	6.8	7.7	7.7	7.7	7.5	7.2	7.4	7.6	7.4	6.4	6	6.8
Lat + 15	Average	5.8	6.2	6.5	6.6	6.3	6.1	6	6.3	6.5	6.6	5.9	5.5	6.2
	Minimum	4.4	4.8	5.1	5.9	5.7	5.6	5.5	5.3	5.8	5.3	4.6	3.8	5.5
	Maximum	6.9	7.1	7.6	7.1	6.8	6.4	6.3	6.7	7.3	7.7	6.9	6.6	6.5
90	Average	5.2	5.1	4.5	3.7	2.8	2.4	2.5	3.2	4.2	5.1	5.2	5.1	4.1
	Minimum	3.9	3.9	3.5	3.4	2.5	2.2	2.3	2.8	3.7	4	3.9	3.5	3.5
	Maximum	6.4	5.8	5.4	4	3	2.5	2.7	3.4	4.6	6	6.2	6.2	4.4

AVERAGE CLIMATIC CONDITIONS

Element		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temp.	(deg C)	1.2	4.4	8.3	12.9	17.9	23.4	25.8	24.4	20.3	13.9	6.8	1.8	13.4
Daily Min	(deg C)	-5.7	-3.1	0.1	4.2	9.2	14.6	18	17	12.9	6.1	-0.4	-4.9	5.7
Daily Max	(deg C)	8.2	11.9	16.3	21.6	26.5	32.2	33.6	31.7	27.7	21.7	14.1	8.6	21.2
Record Lo	(deg C)	-27.2	-20.6	-13.3	-7.2	-2.2	4.4	11.1	11.1	2.8	-6.1	-21.7	-21.7	-27.2
Record Hi	(deg C)	20.6	24.4	29.4	31.7	36.7	40.6	40.6	38.3	37.8	32.8	25	22.2	40.6
HDD,Base	18.3C	531	389	312	167	49	0	0	0	10	144	345	512	2458
CDD,Base	18.3C	0	0	0	4	36	155	233	188	70	6	0	0	691
Rel Hum	percent	56	50	40	33	31	30	42	47	48	45	50	57	44
Wind Spd.	(m/s)	3.7	3.9	4.5	4.9	4.8	4.5	4	3.8	3.8	3.6	3.6	3.5	4.1

City:	**HONOLULU**													
State:	HI													
WBAN No:	22521													
Lat(N):	21.33													
Long(W):	157.92													
Elev(m):	5													
Pres(mb):	1016													
Stn Type:	Primary													
SOLAR RADIATION FOR FLAT-PLATE COLLECTORS FACING SOUTH AT A FIXED-TILT (kWh/m2/day), Percentage Uncertainty = 9														
Tilt(deg)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	Average	3.9	4.7	5.4	5.9	6.4	6.5	6.6	6.5	5.9	5	4.1	3.7	5.4
	Minimum	3.2	3.7	4.4	5	5.6	6.2	6.1	5.8	5.4	4.6	3.7	3.2	5
	Maximum	4.4	5.2	6.1	6.5	6.9	6.9	7	6.9	6.3	5.4	4.5	4.1	5.6
Lat - 15	Average	4.3	5	5.6	5.9	6.3	6.4	6.5	6.5	6.1	5.3	4.5	4.1	5.5
	Minimum	3.4	3.9	4.6	5.1	5.6	6.1	6	5.9	5.5	4.9	3.9	3.5	5.1
	Maximum	4.8	5.5	6.3	6.6	6.8	6.7	6.8	6.9	6.5	5.7	4.9	4.6	5.8
Lat	Average	4.9	5.5	5.8	5.9	5.9	5.9	6	6.2	6.2	5.7	5.1	4.8	5.7
	Minimum	3.8	4.2	4.7	4.9	5.2	5.6	5.6	5.7	5.6	5.2	4.3	3.9	5.2
	Maximum	5.7	6.2	6.7	6.5	6.4	6.1	6.3	6.6	6.6	6.2	5.6	5.4	5.9
Lat + 15	Average	5.3	5.8	5.8	5.5	5.3	5.1	5.3	5.7	6	5.8	5.4	5.2	5.5
	Minimum	4	4.3	4.6	4.6	4.7	4.8	4.9	5.2	5.4	5.3	4.5	4.2	5
	Maximum	6.2	6.5	6.6	6.1	5.6	5.3	5.4	6	6.4	6.4	6	5.9	5.7
90	Average	4.2	4	3.2	2.2	1.5	1.4	1.4	1.8	2.8	3.7	4.1	4.3	2.9
	Minimum	3.1	2.9	2.6	1.9	1.5	1.4	1.4	1.8	2.6	3.3	3.3	3.3	2.6
	Maximum	5	4.6	3.6	2.3	1.6	1.5	1.5	1.9	3	4.1	4.7	4.9	3.1
AVERAGE CLIMATIC CONDITIONS														
Element		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temp.	(deg C)	22.7	22.8	23.6	24.3	25.3	26.3	26.9	27.4	27.2	26.4	25.1	23.4	25.1
Daily Min	(deg C)	18.7	18.6	19.6	20.4	21.3	22.3	23.1	23.4	23.1	22.4	21.3	19.4	21.1
Daily Max	(deg C)	26.7	26.9	27.6	28.2	29.3	30.3	30.8	31.5	31.4	30.5	28.9	27.3	29.1
Record Lo	(deg C)	11.7	11.7	12.8	13.9	15.6	18.3	18.9	19.4	18.9	17.8	13.9	12.2	11.7
Record Hi	(deg C)	30.6	31.1	31.1	31.7	33.9	33.3	33.3	33.9	34.4	34.4	33.9	31.7	34.4
HDD,Base	18.3C	0	0	0	0	0	0	0	0	0	0	0	0	0
CDD,Base	18.3C	136	124	162	180	216	240	267	282	267	252	203	157	2486
Rel Hum	percent	73	71	69	67	66	64	65	64	66	68	70	72	68
Wind Spd.	(m/s)	4.3	4.3	5	5.1	5.1	5.5	5.7	5.4	4.9	4.6	4.6	4.3	4.9

City:	**SAN JUAN**
State:	PR
WBAN No:	11641
Lat(N):	18.43
Long(W):	66
Elev(m):	19
Pres(mb):	1014
Stn Type:	Primary

SOLAR RADIATION FOR FLAT-PLATE COLLECTORS FACING SOUTH AT A FIXED-TILT (kWh/m2/day), Percentage Uncertainty = 9

Tilt(deg)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	Average	4.3	4.9	5.7	6.1	5.8	6.1	6.1	6	5.5	4.9	4.3	4	5.3
	Minimum	4	4.7	5.2	5.4	4.4	5.3	5.5	5.2	4.8	4.3	3.7	3.4	4.9
	Maximum	4.6	5.3	6.2	6.5	6.6	6.8	6.5	6.5	6.1	5.4	4.9	4.5	5.5
Lat - 15	Average	4.5	5.1	5.8	6.1	5.7	6	6	6	5.6	5	4.5	4.1	5.4
	Minimum	4.1	4.8	5.3	5.5	4.4	5.2	5.5	5.2	4.8	4.4	3.8	3.5	5
	Maximum	4.8	5.5	6.3	6.6	6.5	6.7	6.4	6.5	6.2	5.5	5.1	4.8	5.6
Lat	Average	5.1	5.6	6.1	6.1	5.4	5.5	5.6	5.8	5.7	5.4	5.1	4.8	5.5
	Minimum	4.7	5.3	5.5	5.4	4.2	4.9	5.1	5.1	4.8	4.7	4.2	4	5.1
	Maximum	5.6	6.1	6.6	6.5	6.2	6.2	6	6.3	6.3	6	5.9	5.7	5.8
Lat + 15	Average	5.5	5.8	6	5.7	4.9	4.8	5	5.3	5.5	5.5	5.4	5.2	5.4
	Minimum	5	5.4	5.4	5.1	3.8	4.3	4.5	4.6	4.7	4.7	4.3	4.3	5
	Maximum	6.1	6.3	6.5	6.1	5.5	5.3	5.3	5.8	6.1	6.1	6.3	6.3	5.7
90	Average	4.2	3.9	3.1	2	1.5	1.5	1.5	1.7	2.5	3.3	3.9	4.1	2.8
	Minimum	3.8	3.6	2.8	1.9	1.4	1.4	1.4	1.6	2.2	2.8	3.1	3.3	2.7
	Maximum	4.8	4.2	3.3	2.1	1.6	1.5	1.5	1.7	2.7	3.7	4.7	5.1	3

AVERAGE CLIMATIC CONDITIONS

Element		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temp.	(deg C)	25	25.1	25.6	26.3	27.2	27.9	28.1	28.2	28.1	27.7	26.7	25.6	26.8
Daily Min	(deg C)	21.6	21.4	22	22.7	23.6	24.5	24.9	24.8	24.6	24.2	23.3	22.4	23.3
Daily Max	(deg C)	28.4	28.7	29.1	29.9	30.7	31.4	31.4	31.5	31.6	31.3	29.9	28.8	30.2
Record Lo	(deg C)	16.1	16.7	15.6	17.8	18.9	20.6	20.6	21.1	20.6	19.4	18.9	17.2	15.6
Record Hi	(deg C)	33.3	35.6	35.6	36.1	35.6	36.1	35	36.1	36.1	36.7	35.6	34.4	36.7
HDD,Base	18.3C	0	0	0	0	0	0	0	0	0	0	0	0	0
CDD,Base	18.3C	207	188	224	240	274	288	303	305	292	291	250	226	3088
Rel Hum	percent	74	72	71	71	75	76	76	76	76	77	76	75	75
Wind Spd.	(m/s)	3.5	3.8	4	3.8	3.5	3.8	4.1	3.7	3.2	2.9	3.2	3.5	3.6

City:	**RICHMOND**
State:	VA
WBAN No:	13740
Lat(N):	37.5
Long(W):	77.33
Elev(m):	50
Pres(mb):	1012
Stn Type:	Secondary

SOLAR RADIATION FOR FLAT-PLATE COLLECTORS FACING SOUTH AT A FIXED-TILT (kWh/m2/day), Percentage Uncertainty = 9

Tilt(deg)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	Average	2.3	3	4.1	5.2	5.8	6.3	6	5.4	4.5	3.5	2.5	2	4.2
	Minimum	2	2.4	3.4	4.5	5.3	5.5	5.2	4.8	4	2.8	2	1.8	4
	Maximum	2.5	3.5	4.6	6.1	6.4	6.8	6.7	6	5.1	4.1	2.9	2.3	4.4
Lat - 15	Average	3.2	3.9	4.8	5.5	5.8	6.1	5.9	5.7	5.1	4.4	3.5	2.9	4.7
	Minimum	2.5	2.9	3.8	4.7	5.3	5.3	5.2	4.9	4.4	3.3	2.7	2.4	4.5
	Maximum	3.8	4.8	5.4	6.7	6.5	6.6	6.7	6.3	5.9	5.2	4.3	3.6	5
Lat	Average	3.6	4.3	5	5.4	5.5	5.6	5.5	5.5	5.2	4.7	3.9	3.3	4.8
	Minimum	2.8	3	3.9	4.6	5	4.9	4.8	4.7	4.4	3.4	2.9	2.7	4.5
	Maximum	4.4	5.4	5.6	6.6	6.1	6.1	6.3	6.1	6	5.6	4.8	4.2	5.1
Lat + 15	Average	3.9	4.4	4.9	5	4.9	4.9	4.8	5	4.9	4.8	4.1	3.6	4.6
	Minimum	2.9	3	3.7	4.3	4.5	4.3	4.2	4.3	4.2	3.3	3	2.8	4.3
	Maximum	4.7	5.6	5.5	6.1	5.4	5.3	5.5	5.6	5.8	5.7	5.2	4.6	4.9
90	Average	3.5	3.7	3.5	3.1	2.6	2.4	2.4	2.8	3.3	3.7	3.6	3.3	3.2
	Minimum	2.5	2.4	2.7	2.7	2.4	2.2	2.2	2.5	2.8	2.5	2.6	2.5	2.9
	Maximum	4.4	4.7	4.1	3.7	2.7	2.5	2.7	3.1	3.9	4.5	4.6	4.3	3.4

AVERAGE CLIMATIC CONDITIONS

Element		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temp.	(deg C)	2.1	3.7	8.9	14.1	18.9	23.3	25.6	24.9	21.1	14.8	9.8	4.5	14.3
Daily Min	(deg C)	-3.5	-2.2	2.4	7	12.3	17.1	19.7	19.1	15	8.1	3.3	-1.2	8.1
Daily Max	(deg C)	7.6	9.6	15.3	21.1	25.4	29.5	31.3	30.6	27.2	21.5	16.3	10.1	20.4
Record Lo	(deg C)	-24.4	-23.3	-11.7	-5	-0.6	4.4	10.6	7.8	1.7	-6.1	-12.2	-18.3	-24.4
Record Hi	(deg C)	26.7	28.3	33.9	35.6	37.8	40	40.6	38.9	39.4	37.2	30	26.7	40.6
HDD,Base	18.3C	504	409	293	134	34	0	0	0	13	129	257	429	2202
CDD,Base	18.3C	0	0	0	6	51	150	224	203	96	19	0	0	749
Rel Hum	percent	68	66	63	61	70	72	75	77	77	74	69	69	70
Wind Spd.	(m/s)	3.7	3.9	4.2	4.1	3.6	3.4	3.1	2.9	3	3.2	3.4	3.6	3.5

City:	**NEW ORLEANS**
State:	LA
WBAN No:	12916
Lat(N):	29.98
Long(W):	90.25
Elev(m):	3
Pres(mb):	1017
Stn Type:	Secondary

SOLAR RADIATION FOR FLAT-PLATE COLLECTORS FACING SOUTH AT A FIXED-TILT (kWh/m2/day), Percentage Uncertainty = 9

Tilt(deg)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	Average	2.7	3.6	4.5	5.5	6.1	6.1	5.7	5.5	4.9	4.3	3.1	2.6	4.6
	Minimum	2.3	3	3.8	4.7	5.3	5	5.3	4.7	4.3	3.7	2.3	2.3	4.3
	Maximum	3.2	4.2	5.2	6.6	7	7.1	6.6	6.1	5.5	5	3.6	3	4.8
Lat - 15	Average	3.3	4.2	4.9	5.7	6	6	5.7	5.6	5.3	5	3.8	3.2	4.9
	Minimum	2.6	3.3	4	4.8	5.3	4.8	5.2	4.7	4.6	4.1	2.5	2.8	4.6
	Maximum	4.1	5	5.8	6.9	7	6.9	6.5	6.3	6	5.8	4.4	3.9	5.1
Lat	Average	3.7	4.5	5	5.6	5.7	5.5	5.3	5.4	5.3	5.3	4.3	3.7	5
	Minimum	2.8	3.5	4.1	4.7	5	4.5	4.8	4.5	4.6	4.3	2.7	3.1	4.7
	Maximum	4.7	5.5	6.1	6.8	6.6	6.3	6.1	6.1	6.1	6.3	5.1	4.6	5.2
Lat + 15	Average	3.9	4.6	4.9	5.3	5.1	4.8	4.7	4.9	5.1	5.4	4.5	3.9	4.8
	Minimum	2.8	3.6	4	4.4	4.4	4	4.3	4.1	4.4	4.3	2.7	3.3	4.5
	Maximum	5.1	5.7	6	6.3	5.8	5.4	5.3	5.5	5.9	6.5	5.4	4.9	5
90	Average	3.3	3.5	3.2	2.7	2.1	1.8	1.9	2.3	3	3.9	3.7	3.4	2.9
	Minimum	2.3	2.7	2.6	2.3	1.9	1.7	1.8	2.1	2.7	3	2.1	2.7	2.7
	Maximum	4.4	4.4	3.9	3	2.2	1.9	2	2.5	3.5	4.7	4.5	4.4	3

AVERAGE CLIMATIC CONDITIONS

Element		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temp.	(deg C)	10.7	12.4	16.4	20.3	23.8	26.7	27.7	27.5	25.6	20.6	16.2	12.5	20.1
Daily Min	(deg C)	5.4	6.9	10.9	14.7	18.4	21.6	22.8	22.7	20.8	14.8	10.6	7.1	14.7
Daily Max	(deg C)	16	17.8	22	25.8	29.1	31.8	32.6	32.3	30.3	26.3	21.7	17.9	25.3
Record Lo	(deg C)	-10	-7.2	-3.9	0	5	10	15.6	15.6	5.6	1.7	-4.4	-11.7	-11.7
Record Hi	(deg C)	28.3	29.4	31.7	33.3	35.6	37.8	38.3	38.9	38.3	33.3	30.6	28.9	38.9
HDD,Base	18.3C	250	176	90	16	0	0	0	0	0	17	99	194	841
CDD,Base	18.3C	14	9	31	74	169	250	291	284	218	87	34	13	1475
Rel Hum	percent	76	73	73	73	74	76	79	79	78	75	77	77	76
Wind Spd.	(m/s)	4	4.3	4.2	4.1	3.6	3	2.6	2.6	3.1	3.3	3.8	4	3.5

City:	**KEY WEST**
State:	FL
WBAN No:	12836
Lat(N):	24.55
Long(W):	81.75
Elev(m):	1
Pres(mb):	1016
Stn Type:	Secondary

SOLAR RADIATION FOR FLAT-PLATE COLLECTORS FACING SOUTH AT A FIXED-TILT (kWh/m2/day), Percentage Uncertainty = 9

Tilt(deg)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	Average	3.7	4.4	5.5	6.3	6.3	6.1	6.1	5.8	5.2	4.6	3.8	3.4	5.1
	Minimum	3	3.7	4.6	5.7	5.5	5.2	5.6	5.2	4.6	4	3.3	3	4.9
	Maximum	4.1	4.9	6	6.9	6.8	6.7	6.4	6.2	5.5	5.1	4.3	3.8	5.3
Lat - 15	Average	4.2	4.9	5.8	6.5	6.3	6	6	5.9	5.4	5	4.4	4	5.4
	Minimum	3.4	4	4.9	5.8	5.4	5.1	5.5	5.3	4.8	4.3	3.7	3.4	5.1
	Maximum	4.8	5.4	6.4	7	6.8	6.6	6.3	6.2	5.8	5.6	4.9	4.5	5.6
Lat	Average	4.9	5.5	6.1	6.4	6	5.5	5.6	5.7	5.5	5.4	5	4.7	5.5
	Minimum	3.8	4.4	5.1	5.8	5.2	4.7	5.1	5.1	4.8	4.6	4.1	4	5.2
	Maximum	5.6	6.1	6.8	6.9	6.4	6.1	5.9	6	5.9	6.1	5.6	5.3	5.8
Lat + 15	Average	5.3	5.7	6	6	5.3	4.8	5	5.2	5.3	5.5	5.3	5.1	5.4
	Minimum	4	4.5	5	5.4	4.6	4.2	4.6	4.7	4.6	4.6	4.3	4.2	5.1
	Maximum	6.1	6.4	6.7	6.4	5.7	5.3	5.2	5.5	5.7	6.3	6	5.9	5.6
90	Average	4.3	4.2	3.5	2.5	1.7	1.5	1.6	2.1	2.8	3.7	4.2	4.3	3
	Minimum	3.2	3.3	2.9	2.3	1.7	1.5	1.5	1.9	2.4	3	3.3	3.5	2.8
	Maximum	5.2	4.7	3.9	2.6	1.8	1.6	1.7	2.1	3	4.3	4.8	5.1	3.2

AVERAGE CLIMATIC CONDITIONS

Element		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temp.	(deg C)	21.1	21.4	23.2	25	27	28.4	29.1	29.1	28.5	26.7	24.2	21.9	25.4
Daily Min	(deg C)	18.3	18.7	20.6	22.3	24.5	25.8	26.4	26.3	25.8	24.2	21.8	19.3	22.8
Daily Max	(deg C)	23.8	24.1	25.9	27.6	29.5	30.9	31.7	31.8	31.1	29.1	26.7	24.5	28.1
Record Lo	(deg C)	5	7.8	8.3	8.9	18.3	20	20.6	20	20.6	15.6	9.4	6.7	5
Record Hi	(deg C)	30	29.4	30.6	32.2	32.8	34.4	35	35	34.4	33.9	31.7	30	35
HDD,Base	18.3C	24	17	4	0	0	0	0	0	0	0	0	11	56
CDD,Base	18.3C	109	102	155	200	269	302	334	332	305	258	177	123	2666
Rel Hum	percent	76	74	73	70	72	74	72	73	75	75	76	76	74
Wind Spd.	(m/s)	5.2	5.4	5.5	5.3	4.8	4.5	4.3	4.1	4.3	5.2	5.5	5.3	5

City:	**JACKSONVILLE**
State:	FL
WBAN No:	13889
Lat(N):	30.5
Long(W):	81.7
Elev(m):	9
Pres(mb):	1017
Stn Type:	Secondary

SOLAR RADIATION FOR FLAT-PLATE COLLECTORS FACING SOUTH AT A FIXED-TILT (kWh/m2/day), Percentage Uncertainty = 9

Tilt(deg)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	Average	2.9	3.7	4.7	5.9	6.1	6	5.8	5.4	4.6	4	3.2	2.7	4.6
	Minimum	2.6	3.2	4	5.1	5	5.3	4.9	4.7	3.6	3.3	2.5	2.2	4.4
	Maximum	3.5	4.3	5.2	6.9	7.1	6.8	6.4	5.9	5.4	4.5	3.8	3.2	4.8
Lat - 15	Average	3.6	4.3	5.2	6.1	6.1	5.8	5.7	5.5	5	4.5	3.9	3.4	4.9
	Minimum	3.2	3.7	4.4	5.3	4.9	5.1	4.8	4.7	3.7	3.7	2.9	2.6	4.7
	Maximum	4.5	5.2	5.8	7.2	7.1	6.7	6.3	6.1	5.9	5.3	4.8	4.2	5.2
Lat	Average	4.2	4.7	5.5	6	5.7	5.4	5.4	5.3	5	4.9	4.4	3.9	5
	Minimum	3.5	4	4.5	5.3	4.7	4.8	4.5	4.6	3.7	3.9	3.1	2.9	4.7
	Maximum	5.3	5.8	6.1	7.1	6.7	6.1	5.8	5.9	6	5.7	5.5	5	5.3
Lat + 15	Average	4.4	4.9	5.4	5.6	5.1	4.7	4.7	4.9	4.8	4.9	4.7	4.2	4.9
	Minimum	3.7	4.1	4.4	4.9	4.2	4.2	4	4.2	3.5	3.8	3.2	3	4.5
	Maximum	5.8	6	6.1	6.7	5.9	5.3	5.1	5.4	5.8	5.8	5.9	5.5	5.2
90	Average	3.8	3.8	3.5	2.9	2.1	1.8	1.9	2.3	2.9	3.6	3.9	3.7	3
	Minimum	3.1	3.1	2.9	2.6	2	1.8	1.8	2.1	2.1	2.7	2.6	2.5	2.7
	Maximum	5	4.7	4	3.3	2.3	1.9	2	2.5	3.5	4.2	5	4.9	3.2

AVERAGE CLIMATIC CONDITIONS

Element		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temp.	(deg C)	11.3	12.9	16.2	19.4	23	26.2	27.6	27.3	25.6	21	16.6	12.8	20
Daily Min	(deg C)	4.7	6.3	9.6	12.7	16.7	20.6	22.2	22.1	20.6	15.2	10.1	6.3	13.9
Daily Max	(deg C)	17.9	19.4	22.8	26.2	29.3	31.8	33	32.6	30.7	26.8	23.1	19.3	26.1
Record Lo	(deg C)	-13.9	-7.2	-5	1.1	7.2	8.3	16.1	17.2	8.9	2.2	-6.1	-11.7	-13.9
Record Hi	(deg C)	29.4	31.1	32.8	35	37.8	39.4	40.6	38.9	37.8	35.6	31.1	28.9	40.6
HDD,Base	18.3C	234	164	94	21	0	0	0	0	0	17	83	184	797
CDD,Base	18.3C	17	12	27	54	144	235	286	279	218	99	31	14	1417
Rel Hum	percent	75	72	71	69	73	77	78	80	81	79	78	77	76
Wind Spd.	(m/s)	3.6	3.9	3.9	3.7	3.4	3.2	3	2.8	3.1	3.4	3.3	3.3	3.4

City:	**DAYTONA BEACH**
State:	FL
WBAN No:	12834
Lat(N):	29.18
Long(W):	81.05
Elev(m):	12
Pres(mb):	1017
Stn Type:	Primary

SOLAR RADIATION FOR FLAT-PLATE COLLECTORS FACING SOUTH AT A FIXED-TILT (kWh/m2/day), Percentage Uncertainty = 9

Tilt(deg)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	Average	3.1	3.9	5	6.2	6.4	6.1	6	5.7	4.9	4.2	3.4	2.9	4.8
	Minimum	2.7	3.2	4.2	5.6	5.3	5.4	5.5	4.8	4.3	3.5	2.9	2.4	4.6
	Maximum	3.7	4.4	5.5	6.8	7	7	6.6	6.3	5.5	4.8	3.7	3.3	5.1
Lat - 15	Average	3.8	4.5	5.5	6.4	6.4	6	5.9	5.8	5.2	4.7	4.1	3.6	5.2
	Minimum	3.2	3.7	4.5	5.8	5.3	5.3	5.4	4.8	4.5	3.8	3.4	2.8	4.8
	Maximum	4.6	5.2	6.1	7.1	7	6.8	6.4	6.5	6	5.5	4.6	4.1	5.5
Lat	Average	4.3	4.9	5.7	6.3	6	5.5	5.5	5.6	5.3	5	4.6	4.1	5.2
	Minimum	3.6	4	4.6	5.7	5	4.9	5.1	4.6	4.5	4	3.8	3.1	4.9
	Maximum	5.4	5.8	6.3	7	6.6	6.3	6	6.3	6.1	5.9	5.2	4.9	5.7
Lat + 15	Average	4.6	5.1	5.6	5.9	5.4	4.8	4.9	5.1	5.1	5.1	4.8	4.4	5.1
	Minimum	3.8	4.1	4.5	5.3	4.5	4.3	4.5	4.2	4.3	4	3.9	3.3	4.7
	Maximum	5.8	6	6.3	6.5	5.8	5.5	5.3	5.7	5.9	6	5.6	5.3	5.5
90	Average	3.9	3.8	3.6	2.9	2.1	1.8	1.9	2.4	3	3.6	4	3.9	3.1
	Minimum	3.1	3.1	2.9	2.7	2	1.6	1.8	2	2.5	2.7	3.1	2.8	2.8
	Maximum	5.1	4.7	4	3.1	2.2	1.9	2	2.6	3.4	4.3	4.7	4.7	3.3

AVERAGE CLIMATIC CONDITIONS

Element		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temp.	(deg C)	14.2	15	17.9	20.7	23.7	26.3	27.3	27.2	26.3	23	18.8	15.6	21.3
Daily Min	(deg C)	8.3	9.1	12.2	14.8	18.3	21.6	22.5	22.7	22.2	18.4	13.5	9.8	16.1
Daily Max	(deg C)	20	20.8	23.8	26.7	29.2	31.1	32.1	31.7	30.4	27.5	24.2	21.3	26.6
Record Lo	(deg C)	-9.4	-4.4	-3.3	1.7	6.7	11.1	15.6	18.3	11.1	5	-2.8	-7.2	-9.4
Record Hi	(deg C)	30.6	31.7	32.8	35.6	37.8	38.9	38.9	37.8	37.2	35	31.7	31.1	38.9
HDD,Base	18.3C	157	114	62	12	0	0	0	0	0	0	46	115	505
CDD,Base	18.3C	28	21	50	83	167	240	279	276	240	147	61	31	1622
Rel Hum	percent	75	72	71	69	72	77	78	80	79	75	76	76	75
Wind Spd.	(m/s)	3.8	4.1	4.2	4.1	3.8	3.4	3.2	3	3.5	4	3.7	3.6	3.7

City:	**BRADFORD**
State:	PA
WBAN No:	4751
Lat(N):	41.8
Long(W):	78.63
Elev(m):	600
Pres(mb):	940
Stn Type:	Secondary

SOLAR RADIATION FOR FLAT-PLATE COLLECTORS FACING SOUTH AT A FIXED-TILT (kWh/m2/day), Percentage Uncertainty = 9

Tilt(deg)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	Average	1.8	2.6	3.6	4.6	5.4	5.9	5.8	5	3.9	2.8	1.7	1.4	3.7
	Minimum	1.5	2.2	3.2	3.5	4.4	5	5.2	4.7	3.2	2.4	1.4	1.2	3.5
	Maximum	2	3	4	5.5	6.4	6.7	6.6	5.7	4.5	3.7	2	1.6	3.9
Lat - 15	Average	2.4	3.4	4.3	5	5.4	5.8	5.8	5.3	4.5	3.6	2.3	1.9	4.2
	Minimum	2	2.7	3.7	3.6	4.3	4.8	5.2	4.9	3.5	2.9	1.7	1.5	3.9
	Maximum	2.9	4.2	5	6.1	6.6	6.6	6.5	6.1	5.3	5.2	2.8	2.4	4.5
Lat	Average	2.7	3.7	4.4	4.8	5.1	5.3	5.4	5.1	4.5	3.8	2.4	2.1	4.1
	Minimum	2.2	2.8	3.8	3.5	4	4.4	4.8	4.7	3.5	3	1.8	1.5	3.9
	Maximum	3.3	4.6	5.2	6	6.2	6.1	6.1	5.9	5.3	5.6	3.1	2.7	4.5
Lat + 15	Average	2.8	3.8	4.4	4.5	4.5	4.6	4.7	4.6	4.3	3.8	2.5	2.2	3.9
	Minimum	2.3	2.8	3.7	3.2	3.6	3.9	4.2	4.3	3.3	2.9	1.8	1.5	3.6
	Maximum	3.5	4.8	5.1	5.6	5.5	5.3	5.3	5.3	5.1	5.7	3.3	2.8	4.3
90	Average	2.7	3.5	3.6	3	2.7	2.5	2.6	2.9	3.1	3.1	2.2	2.1	2.8
	Minimum	2.1	2.5	2.9	2.2	2.2	2.3	2.5	2.6	2.4	2.3	1.5	1.3	2.6
	Maximum	3.4	4.5	4.2	3.9	3.1	2.8	2.9	3.3	3.7	4.7	3	2.7	3.1

AVERAGE CLIMATIC CONDITIONS

Element		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temp.	(deg C)	-7.1	-6.1	-0.4	5.7	11.5	16.1	18.4	17.6	13.8	8.1	2.3	-4	6.3
Daily Min	(deg C)	-11.2	-10.9	-5.5	0	5	9.7	12.2	11.4	7.9	2.7	-1.8	-7.8	0.9
Daily Max	(deg C)	-3	-1.3	4.6	11.4	17.9	22.4	24.7	23.7	19.7	13.5	6.3	-0.3	11.7
Record Lo	(deg C)	-32.8	-32.2	-27.8	-14.4	-7.8	-3.3	0.6	-3.3	-3.9	-12.2	-18.9	-28.9	-32.8
Record Hi	(deg C)	15.6	16.7	25.6	29.4	30	31.1	34.4	33.3	29.4	25.6	22.8	20.6	34.4
HDD,Base	18.3C	787	683	582	378	217	81	38	54	142	317	482	692	4454
CDD,Base	18.3C	0	0	0	0	5	13	42	31	6	0	0	0	96
Rel Hum	percent	78	75	73	68	70	75	77	79	81	77	80	81	76
Wind Spd.	(m/s)	4.4	4.1	4.2	4.1	3.5	3.1	2.6	2.6	2.9	3.4	4.1	4.3	3.6

City:	**BOULDER**
State:	CO
WBAN No:	94018
Lat(N):	40.02
Long(W):	105.25
Elev(m):	1634
Pres(mb):	836
Stn Type:	Primary

SOLAR RADIATION FOR FLAT-PLATE COLLECTORS FACING SOUTH AT A FIXED-TILT (kWh/m2/day), Percentage Uncertainty = 9

Tilt(deg)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	Average	2.4	3.3	4.4	5.6	6.2	6.9	6.7	6	5	3.8	2.6	2.1	4.6
	Minimum	2.1	2.8	3.7	4.8	5.1	5.7	5.6	5.2	4	3.1	2.3	1.9	4.3
	Maximum	2.7	3.5	5	6.1	7.2	7.8	7.4	6.6	5.5	4.2	2.8	2.3	4.8
Lat - 15	Average	3.8	4.6	5.4	6.1	6.2	6.6	6.6	6.3	5.9	5.1	4	3.5	5.4
	Minimum	3.2	3.8	4.3	5.3	4.9	5.5	5.6	5.3	4.6	4	3.4	2.8	4.9
	Maximum	4.4	5.1	6.2	6.8	7.3	7.6	7.4	7.1	6.7	5.8	4.6	4.1	5.7
Lat	Average	4.4	5.1	5.6	6	5.9	6.1	6.1	6.1	6	5.6	4.6	4.2	5.5
	Minimum	3.6	4.2	4.4	5.2	4.6	5.1	5.2	5.1	4.6	4.2	3.9	3.2	5
	Maximum	5.1	5.7	6.5	6.7	6.8	6.9	6.8	6.8	6.8	6.4	5.2	4.8	5.8
Lat + 15	Average	4.8	5.3	5.6	5.6	5.2	5.2	5.3	5.5	5.8	5.7	4.8	4.5	5.3
	Minimum	3.9	4.3	4.4	4.8	4.1	4.4	4.5	4.6	4.4	4.2	4.1	3.5	4.8
	Maximum	5.6	5.9	6.5	6.2	6	5.9	5.9	6.2	6.6	6.5	5.6	5.3	5.6
90	Average	4.5	4.6	4.3	3.6	2.8	2.6	2.7	3.2	4	4.6	4.4	4.3	3.8
	Minimum	3.6	3.7	3.5	3	2.3	2.2	2.3	2.7	3.1	3.4	3.7	3.4	3.4
	Maximum	5.4	5.2	5	4	3.1	2.8	2.9	3.6	4.6	5.3	5.1	5.2	4.1

AVERAGE CLIMATIC CONDITIONS

Element		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temp.	(deg C)	-1.3	0.8	3.9	9	14	19.4	23.1	21.9	16.8	10.8	3.9	-0.6	10.2
Daily Min	(deg C)	-8.8	-6.6	-3.4	1.4	6.4	11.3	14.8	13.8	8.7	2.4	-3.7	-8.1	2.3
Daily Max	(deg C)	6.2	8.1	11.2	16.6	21.6	27.4	31.2	29.9	24.9	19.1	11.4	6.9	17.9
Record Lo	(deg C)	-31.7	-34.4	-23.9	-18.9	-5.6	-1.1	6.1	5	-8.3	-16.1	-22.2	-31.7	-34.4
Record Hi	(deg C)	22.8	24.4	28.9	31.7	35.6	40	40	38.3	36.1	31.7	26.1	23.9	40
HDD,Base	18.3C	608	492	448	280	141	39	0	0	80	238	433	586	3344
CDD,Base	18.3C	0	0	0	0	6	71	148	113	35	4	0	0	377
Rel Hum	percent	55	56	54	50	52	49	48	49	50	49	56	56	52
Wind Spd.	(m/s)	3.7	3.8	4.1	4.4	4.1	3.8	3.6	3.5	3.4	3.4	3.5	3.6	3.8

City:	**BOSTON**
State:	MA
WBAN No:	14739
Lat(N):	42.37
Long(W):	71.03
Elev(m):	5
Pres(mb):	1015
Stn Type:	Primary

SOLAR RADIATION FOR FLAT-PLATE COLLECTORS FACING SOUTH AT A FIXED-TILT (kWh/m2/day), Percentage Uncertainty = 9

Tilt(deg)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	Average	1.9	2.7	3.7	4.7	5.6	6.1	6.1	5.4	4.3	3	1.9	1.5	3.9
	Minimum	1.5	2.2	3.2	4	4.8	5.3	5.2	4.8	3.9	2.7	1.5	1.2	3.7
	Maximum	2.2	3.3	4.4	5.4	6.4	7	6.6	6	4.7	3.5	2.2	1.8	4.1
Lat - 15	Average	3	3.8	4.6	5.2	5.7	6	6	5.7	5	4.1	2.8	2.5	4.5
	Minimum	2.2	2.8	3.7	4.3	4.8	5.2	5.2	5	4.5	3.5	2.1	1.7	4.2
	Maximum	3.7	5	5.6	6	6.6	6.9	6.6	6.5	5.7	4.8	3.5	3.1	4.8
Lat	Average	3.4	4.2	4.7	5	5.3	5.5	5.6	5.5	5.1	4.3	3.1	2.9	4.6
	Minimum	2.5	3	3.8	4.1	4.6	4.7	4.8	4.8	4.5	3.7	2.3	1.9	4.2
	Maximum	4.3	5.5	5.8	5.9	6.2	6.4	6.1	6.2	5.8	5.1	4	3.6	4.9
Lat + 15	Average	3.6	4.3	4.6	4.7	4.7	4.8	4.9	5	4.9	4.4	3.3	3.1	4.4
	Minimum	2.6	3	3.7	3.8	4.1	4.1	4.3	4.4	4.3	3.7	2.4	2	4
	Maximum	4.6	5.8	5.8	5.5	5.5	5.5	5.3	5.7	5.5	5.2	4.2	3.9	4.7
90	Average	3.4	3.9	3.7	3.1	2.8	2.6	2.8	3.1	3.5	3.6	3	2.9	3.2
	Minimum	2.4	2.6	2.8	2.6	2.5	2.4	2.5	2.8	3.1	3	2.1	1.8	2.9
	Maximum	4.5	5.3	4.9	3.7	3.2	2.9	3	3.5	4	4.3	3.8	3.8	3.5

AVERAGE CLIMATIC CONDITIONS

Element		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temp.	(deg C)	-1.9	-0.9	3.7	8.9	14.6	19.8	23.1	22.2	18.2	12.7	7.4	0.9	10.7
Daily Min	(deg C)	-5.8	-5	-0.4	4.6	9.9	15.1	18.4	17.8	13.8	8.3	3.5	-2.9	6.4
Daily Max	(deg C)	2.1	3.1	7.7	13.3	19.2	24.6	27.7	26.6	22.7	17.1	11.2	4.7	15
Record Lo	(deg C)	-24.4	-20	-14.4	-8.9	1.1	7.2	10	8.3	3.3	-2.2	-9.4	-21.7	-24.4
Record Hi	(deg C)	17.2	21.1	27.2	34.4	35	37.8	38.9	38.9	37.8	32.2	25.6	22.8	38.9
HDD,Base	18.3C	627	540	454	282	123	18	0	3	40	178	328	541	3134
CDD,Base	18.3C	0	0	0	0	6	63	147	122	37	3	0	0	377
Rel Hum	percent	62	62	63	63	67	68	68	71	72	68	67	65	67
Wind Spd.	(m/s)	6.2	6.1	6.1	5.9	5.5	5.1	4.9	4.8	5.1	5.4	5.8	6.1	5.6

City:	**ATLANTA**
State:	GA
WBAN No:	13874
Lat(N):	33.65
Long(W):	84.43
Elev(m):	315
Pres(mb):	981
Stn Type:	Primary

SOLAR RADIATION FOR FLAT-PLATE COLLECTORS FACING SOUTH AT A FIXED-TILT (kWh/m2/day), Percentage Uncertainty = 9

Tilt(deg)		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	Average	2.6	3.4	4.5	5.7	6.2	6.4	6.2	5.7	4.8	4.1	2.9	2.4	4.6
	Minimum	2.2	2.9	3.7	5	5.5	5.5	5.3	5	4	3.4	2.4	2	4.3
	Maximum	3	4.1	5.3	6.5	7.2	7.3	7.3	6.3	5.6	4.9	3.4	2.8	4.9
Lat - 15	Average	3.4	4.2	5.1	6	6.2	6.3	6.1	5.9	5.3	4.9	3.8	3.2	5
	Minimum	2.7	3.3	4.1	5.2	5.5	5.4	5.3	5.1	4.3	3.8	2.9	2.6	4.7
	Maximum	4.2	5.3	6.2	6.9	7.2	7.1	7.2	6.4	6.2	6	4.5	3.9	5.4
Lat	Average	3.8	4.6	5.3	5.8	5.8	5.8	5.7	5.7	5.4	5.2	4.2	3.7	5.1
	Minimum	2.9	3.6	4.2	5.1	5.2	5	4.9	4.9	4.2	4	3.1	2.9	4.8
	Maximum	4.9	5.9	6.5	6.8	6.8	6.6	6.7	6.2	6.3	6.6	5.2	4.6	5.4
Lat + 15	Average	4.1	4.7	5.1	5.4	5.2	5.1	5	5.2	5.1	5.3	4.5	3.9	4.9
	Minimum	3	3.6	4	4.7	4.6	4.3	4.4	4.5	4	4	3.2	3	4.6
	Maximum	5.3	6.1	6.4	6.3	6	5.7	5.9	5.7	6.1	6.7	5.5	5	5.2
90	Average	3.5	3.7	3.5	3	2.4	2.2	2.2	2.7	3.2	4	3.8	3.5	3.1
	Minimum	2.5	2.8	2.7	2.6	2.2	2	2.1	2.4	2.5	2.9	2.6	2.6	2.9
	Maximum	4.8	5	4.3	3.4	2.6	2.3	2.6	2.9	3.8	5.1	4.8	4.6	3.4

AVERAGE CLIMATIC CONDITIONS

Element		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temp.	(deg C)	5	7.1	11.9	16.4	20.7	24.4	26	25.6	22.6	16.8	11.7	6.9	16.3
Daily Min	(deg C)	-0.3	1.4	5.8	10.1	14.8	19	20.8	20.6	17.5	11.1	6	1.7	10.7
Daily Max	(deg C)	10.2	12.8	17.9	22.6	26.4	29.9	31.1	30.6	27.7	22.6	17.4	12.2	21.8
Record Lo	(deg C)	-22.2	-15	-12.2	-3.3	2.8	7.8	11.7	12.8	2.2	-2.2	-16.1	-17.8	-22.2
Record Hi	(deg C)	26.1	26.7	29.4	33.9	35	38.3	40.6	38.9	36.7	35	28.9	26.1	40.6
HDD,Base	18.3C	413	314	203	77	15	0	0	0	6	77	204	353	1662
CDD,Base	18.3C	0	0	4	18	87	183	238	226	134	30	6	0	926
Rel Hum	percent	68	63	62	61	67	70	74	75	74	68	68	68	68
Wind Spd.	(m/s)	4.4	4.6	4.5	4.3	3.8	3.5	3.4	3.2	3.5	3.7	3.9	4.2	3.9

18.0 SOURCES OF INFORMATION

There are many sources of information, equipment, and technical assistance on PV technology. Years of research and hundreds of books have been written about PV by industry, government and individuals.

18.1 Sources for Photovoltaic Systems Information

Cross, Bruce M., Ed. *World Directory of Renewable Energy Suppliers and Services*, 1995, London, United Kingdom: James & James (ph: 703-435-7064, Fax: 703-689-0660).

Derrick, Anthony, Catherine Francis and Varis Bokalders. *Solar Photovoltaic Products: A Guide for Development Workers*. Second Edition, London, United Kingdom: IT Publications, 1991. (IT Power, The Warren, Bramshill Road, Eversley, Hampshire, RG27 OPR, United Kingdom, ph: 44-1734-730073)

Photovoltaic Products & Manufactures Directory, 1990. Florida Solar Energy Center, 1679 Clearlake Road, Cocoa, FL, 32922 (ph: 407-638-1000)

Firor, Kay, Editor. *PV People Phone and Address List*, Aug. 1994. Blue Mountain Energy, 59943 Comstock Road, Cove, OR 97824-8100 (ph: 541-568-4473, Fax: 541-568-4882)

Maycock, Paul. *PV Yellow Pages*. PV News, 8536 Greenwich Rd., Catlett, VA, 22019, 1993. (ph: 540-788-9626)

Solar Energy Industries Association (SEIA). *Solar Industry Journal,* First Quarter 1995, Volume 6, Issue 1. (122 C Street, N.W., Fourth Floor, Washington, D.C. 20001-2109,
(ph: 202-383-2600)

"The 1995 International Competitive Industry Directory," *Independent Energy,* December 1994. (ph: 1-800-922-3736)

Procurement Guide for Renewable Energy Systems. Albany, NY, Interstate Renewable Energy Council, 1993.

Real Goods Solar Living Sourcebook: The Complete Guide to Renewable Energy Technologies and Sustainable Living. 8th ed., White River Junction, VT; Chelsea Green Publishing Co., 1994.

U.S.A.I.D. *A Directory of U.S. Renewable Energy Technology Vendors*, Washington, DC, Committee on Renewable Energy Commerce and Trade (CORECT), March 1990. (U.S.A.I.D., Office of Energy, Washington D.C. 20523)

Wilkins, Paul. *Solar Electricity Today*, 1995. PV Network News. 2303 Cedros Circle, Santa Fe, NM 87505 (ph: 505-473-1067).

Williams, Susan, Brenda G. Bateman. Power Plays: Profiles of America's Independent Renewable Electricity Developers, 1995. Investor Responsibility Research Center, 1350 Connecticut Avenue, N.W., Suite 700, Washington, D.C. 20036-1701.

18.2 Sources of Other Information

American Solar Energy Society, 2400 Central Ave., G-1, Boulder, CO 80301, ph: 303-443-3130 (United States section of the International Solar Energy Society).

Energy Efficiency and Renewable Energy Clearinghouse (EREC), P.O. Box 3048, Merrifield, VA 22116, ph: 1-800-363-3732, fax 1-703-893-0400, e-mail: energyinvo@delphi.com.

Florida Solar Energy Center, 1679 Clearlake Road, Cocoa, Florida 32922, ph: 407-638-1000, fax 407-638-1010.

National Renewable Energy Laboratory (NREL, formerly SERI), Technical Inquiry Service, 1617 Cole Blvd, Golden, CO 80401 ph: (303)275-4099, fax (303)275-4091, e-mail: rubin@tcplink.nrel.gov.

National Technical Information Service (NTIS), U.S. Dept. of Commerce, 5285 Port Royal Road, Springfield, VA 22161 ph: 703-487-4650.

North Carolina Solar Center, P.O. Box 7401, NC State University, Raleigh, NC 27695-7401.

Sandia National Laboratories, Design Assistance Center, Division 6218, P.O. Box 5800, Albuquerque, NM 87185 ph/fax: 505-844-3698.

Solar Energy Industries Association (SEIA),122 C Street, N.W., Fourth Floor, Washington, D.C. 20001-2109 ph: (202)383-2600.

Southwest Technology Development Institute, New Mexico State University, Dept. 3 SOLAR, P.O. Box 30001, Las Cruces, NM 88003-8001 ph: 505-646-1846, fax: 505-646-3841.

United States Department of Energy, Office of Energy Efficiency and Renewable Energy, 1000 Independence Avenue, S.W., Washington, DC 20585.