plications in operation. The survey results document that today, over 75 electric utilities have these cost-effective applications in operation in their service territory. Over 1,850 cost-effective PV installations were identified; they have been installed by all types of utilities: investor-owned, municipal, rural cooperatives, and government. In many cases, utilities have a large number of PV applications in operation; the Pacific Gas & Electric Co. has over 1,000 and another half-dozen utilities have each installed about 100. The majority of the utilities, however, have less than 10 PV systems. The total installed capacity of these 1,850+ installations is 87 kW.

Information Sources

There is a considerable amount of information available relating to cost-effective PV applications for electric utility applications. However, it is not all in one place, so some effort is necessary to assemble it. The Electric Power Research Institute, Sandia National Laboratories' PV Design Assistance Center, and the National Renewable Energy Laboratory are good places to start the search.

In 1990, EPRI began a series of eleven 1-day workshops for utility personnel to introduce them to PV technology, PV applications for utilities and their customers, the economics of PV applications, and the latest directions in PV development. These were conducted in major cities around the United States. In 1991, the Western Area Power Administration (WAPA) also began a series of workshops for its utility members. And in 1992, the Utility PhotoVoltaic Group initiated a series of workshops for its utility members; these will continue into 1993. Sandia National Laboratories is also conducting PV applications workshops both for utilities and for other state and federal government organizations.

Today, over a dozen industry, federal, state, private, and utility organizations conduct workshops to help introduce consumers, government organizations, and utility personnel to photovoltaic technology and applications. These range from half-day introductory sessions to week-long intensive hardware-oriented courses.

It is also recommended that utility personnel interested in obtaining information about PV systems contact their local and regional PV equipment vendors and distributors to learn their products, capabilities, and limitations. In addition, major equipment manufacturers can provide considerable information on all the major PV system components: modules, inverters, etc. An excellent source of information is the Solar Energy Industry Association; they can supply an extensive membership list of manufacturers, consultants, system integrators, and regional suppliers.

Photovoltaic Power System Applications

David E. Hasti, Sandia National Laboratories

Photovoltaic power systems range in size from watts to megawatts. They are the most modular of all electric power generating systems. PV systems produce electricity for a wide variety of applications. They can be sited in almost any location in the world, and beyond when space applications are included. When PV power for watches, calculators, and similar consumer electronic products is included in the definition of PV power system, system sizes are even smaller and applications more numerous.

In operation, these systems have the least environmental impact of any form of electric power generation, with no emissions, noise, or other potentially disturbing characteristics. There are, however, environmental concerns associated with manufacturing and disposal of photovoltaic components. The semiconductor industry has similar concerns and deals successfully with them on a daily basis. The direct conversion of sunlight into electricity with PV is an appealing method for electricity generation. Today, more than 300 megawatts of photovoltaic electricity is being generated in the world. This number is growing by 20 percent per year.

PV systems supply energy for basic lighting to people in remote parts of the world, for communications links in remote locations, for powering environmentally sensitive parks, for powering military installations for added energy security, for providing electricity for electric utilities, and for many other applications.

PV System Configurations

Photovoltaic power systems can be configured as stand-alone, hybrid, or grid-tied systems.

A stand-alone photovoltaic power system consists of a photovoltaic array, a storage component, and control and power processing components. The PV array converts sunlight into dc electricity. The array is made up of interconnected PV modules. The storage component (usually batteries) stores the electrical energy for use when needed. The control components manage the operation of the system. They may include a tracker to point the PV array towards the sun to improve energy collection. The power processor converts the dc output of the photovoltaic array into the form needed by the user.

Hybrid systems couple photovoltaics, controls, power processing, and storage with an engine-generator. Other renewable energy generating sources (e.g., wind) can also be included in hybrid systems. Hybrids can be configured to reduce energy storage requirements, to provide uninterruptable power for long periods of inclement weather, or to operate larger intermittent loads with smaller PV arrays. In all cases, engine-generator nul time is reduced, and the engine can be run at maximum efficiency, reducing fuel consumption and maintenance. Controls to coordinate the renewable energy sources, engine-generator, and storage components of the system are necessary.

Grid-tied systems operate in conjunction with utility generated electricity. For these systems, the utility grid provides both the storage and the alternate power source for the system. These systems require a dc-ac inverter with ac output compatible with utility power quality requirements. A block diagram of a photovoltaic power system is shown in Figure 1.

System Design Considerations

When designing PV power systems, the available solar resource, the electrical load requirements for the application,

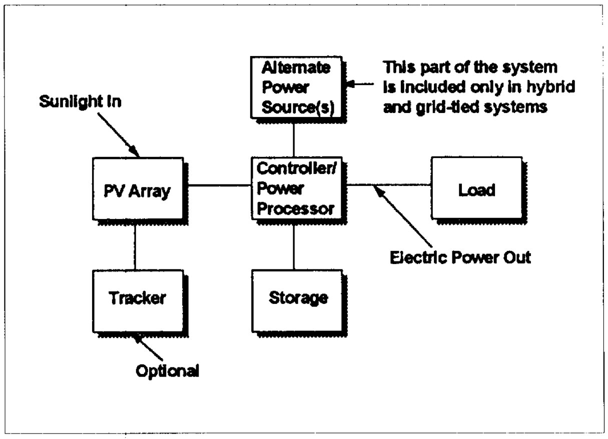

Figure 1. Photovoltaic power system

and the consequence of not having enough energy to power the load must be considered. The average annual solar energy availability in the United States ranges from 5-6 kWh/m^2/day in the desert Southwest to 2-3 kWh/m^2/day in the Northeast. Seasonal and local variations will have a large effect on solar availability and system design. Electrical power output depends on the efficiency of the modules in the array. Most commercial modules sold today are made with crystalline silicon solar cells. These modules have efficiencies of 10 to 12 percent for converting sunlight into electricity. Module sizes range from 5 to over 200 watts. The electrical load for the design application determines the size of the PV array and the power processor and battery requirements. An inverter is required for ac loads. Direct current loads may need dc-dc converters to match the output voltage of the array to the battery bank or dc load voltage. For applications that need a high availability of energy, larger arrays and a larger battery bank will be required. For uninterruptable power, a hybrid system may be needed. In the following paragraphs, some PV systems applications are described in more detail.

Small Stand-Alone System Applications and Benefits

Small stand-alone systems range in size from a few watts to several hundred watts. For electrical energy storage, batteries are used. These systems provide electrical energy to power lights, signals, water pumps, navigational aids, call boxes, sectionalizing switches, and many other small power applications. All of these systems are cost effective. In some applications (e.g., water pumping), the photovoltaic array can be matched to directly drive a dc pump, and the water storage tank becomes the storage component for the system. PV water pumping is a popular application of photovoltaics. Many western utilities offer this service to ranchers, since it is more cost effective than line extensions. The PV systems industry has offered this service for years. In many parts of the world, systems of about 100 watts provide basic lighting for large segments of the population. These systems are the most economical and environmentally sound method of providing this service. Governments recognize that providing basic electric services increases productivity and improves the quality of life for their citizens, which promotes political stability. Rural electrification programs in many countries, including Brazil, Indonesia, and Mexico for example, are using renewable energy to meet these needs. In the United States, the Hopi and Navajo Nations are providing basic electric service for many of their remote home owners with photovoltaics.

Large Stand-Alone System Applications and Benefits

Large stand-alone systems, including hybrids, range from a few to hundreds of kilowatts. These systems provide power for villages and islands, for larger communications systems, for military facilities, and remote parks that are not on the electric grid. Many of these systems, especially hybrids, power mini-grids that supply power to island or village homes and businesses. The addition of battery storage, photovoltaics and other renewable energy sources is being used to reduce the dependence on fossil fuels for existing engine-generators. In remote locations, fuel delivery costs are high, enhancing the value of a hybrid system. Reduced fuel shipments also reduce potential for fuel spills. Rural electrification programs in developing countries are using hybrid systems to power villages. Stand-alone systems in this size range are also used for cathodic protection of pipelines and other structures. In many cases, these systems are effective without storage. Cost-effective applications for large stand-alone systems are estimated to have the potential for installation of hundreds of megawatts worldwide. A growing number of utilities are offering these systems to power remote homes instead of extending power lines. The PV systems industry also offers this service.

Grid-Tied System Applications and Benefits

Grid-tied systems range from a few kilowatts to several megawatts. Today, most of these systems are being used to validate applications studies and are not yet cost effective. Current systems are being used to reduce peak power demands at the utility customer's location or to provide voltage support at the end of long power lines. In some cases, providing additional power near the load during peak periods reduces overloads on a substation, thus extending its life. The value of the PV power is higher than just the energy that is generated. PV helps utilities avoid costs such as equipment upgrades, can improve service and reduce costs to the customer. How to value the avoided costs and other benefits are areas of study for the Department of Energy (DOE), utilities, regulators and the PV industry. PV systems up to several MW have been built to demonstrate power generation for the electric grid. The DOE, utilities, PV industry, regulators, state energy/ offices, and consumer advocates are working to identify and demonstrate applications that can expand markets and reduce costs for grid-tied photovoltaic power systems.

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Issues in Utility-Interactive Photovoltaic Generation

Ward Jewell, Wichita State University

A utility considering the use of solar photovoltaic (PV) generation should consider the following issues: power conditioning, protection, islanding, intermittent output, and installation.

Power Conditioning

Power conditioners convert the dc output from PV arrays to ac. The power conditioner also provides the interconnection with the utility, and any protection needed for the utility and PV system. A common concern regarding PV power conditioners is distortion in the current waveform. Current distortion can result in both current and voltage distortion on the utility system. Today's conditioners, however, produce almost pure voltage and current waveforms.

Figure 2 compares the current distortion from a PV power conditioner with that of a common fluorescent light fixture

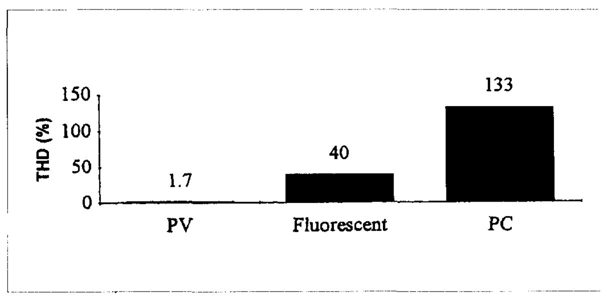

Figure 2. Current distortion