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PHOTOVOLTAICS APPLICATIONS

1993 International Joint Power Generation Conference Panel Session

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Cost targets for the large-scale entry of photovoltaic (PV) systems keep moving, subject to the vagaries of global oil prices and the economic health of the world. Over the last four decades since a practical PV device was announced, costs have come down by a factor of 20 or more and this downward trend is expected to continue, albeit at a slower pace. Simultaneously, conversion efficiencies have nearly tripled.

There are many applications today for which PV is cost-effective. In recognition of this, utility interest in PV is increasing and this is manifested by projects such as PVUSA and Central and South West's renewable resource development effort.

While no major technical barriers for the entry of PV systems have been uncovered, several key issues such as power quality, system reliability, ramp rates, spinning reserve requirements, and misoperation of protection schemes will have to be dealt with as the penetration of this technology increases.

PV is still in the evolutionary phase and is expected to grow for several decades to come. Fueled by environmental considerations, interest in PV is showing a healthy rise both in the minds of the public and in the planning realms of the electric power community. In recognition of this, the Energy Development Subcommittee of the IEEE Energy Development and Power Generation Committee organized a Panel Session on photovoltaics applications at the 1993 International Joint Power Generation Conference held in Kansas City, Missouri. Summaries of the four presentations are assembled here for the benefit of the readers of this Review.

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COST-EFFECTIVE APPLICATIONS OF PHOTOVOLTAICS FOR ELECTRIC UTILITIES: AN OVERVIEW

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Introduction

Traditionally, electric utilities have supplied service to small electric loads (<few kWh's/day) in one of three ways: 1) by extending an existing distribution feeder, 2) by installing a step-down transformer on a nearby transmission line, or 3) by installing a rechargeable/replaceable battery pack. When the complete costs for service to these small loads are calculated on a $/kW or $/kWh basis, they were found to be very high. Beginning in the late 1970's, a few utilities began to experiment with photovoltaic-powered systems to serve these small loads. However, by the late 1980's, the number of utilities with these cost-effective systems in operation was less than a dozen.

Cost-Effective Applications

Beginning in the late 1980's, a number of organizations initiated efforts to identify cost-effective applications of photovoltaic-powered applications. Today, over 70 cost-effective applications of PV have been identified by electric utilities [1], the Electric Power Research Institute [2,3,4,5], Sandia National Laboratories, and the Utility PhotoVoltaic Group [6]. These applications range in size from 5 Watts to over 7 kW and are found in all areas of an electric utility's operations. They provide electric service for the utility's own needs and in a few cases are used by utilities to meet customer needs.

The cost of these small PV applications ranges from about $10/Watt to over $30/Watt; they can serve either dc or ac loads. In the majority of applications, the PV systems are used to charge batteries which, in turn, provide power for the specific application. Although, initially this seems very high, when the cost of serving these small electric loads in the conventional manner is accurately known, the PV option can save the utilities money. In many cases the PV-powered option is more economic by a factor of 2 to 5; this is true for many applications, not only on a first-cost basis but also on a life-cycle basis.

In late 1992 - early 1993, the Electric Power Research Institute conducted a nationwide survey of electric utilities to document the number of utility-owned, cost-effective PV applications in operation. The survey results document that today, over 75 electric utilities have these cost-effective applications in operation in their service territory[7]. Over 1850 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 1000 and another half dozen utilities have each installed about 100. The majority of the utilities, however, have less than ten PV systems. The total installed capacity of these 1850+ installations is 87 kW.

What Utility Personnel Can Do Today

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; a list of contacts are given in the references[8] list.

In 1990, EPRI began a series of eleven one-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 U.S. In 1991, the Western Area Power Administration 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[9].

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Photovoltaic Power System Applications

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Photovoltaic (PV) 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 a 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, no emissions, noise or other potentially disturbing characteristics. There are 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% 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.

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 run time is reduced, and the engine can be run at maximum efficiency, reducing fuel consumption and maintenance. Controls to coordinate the renewable energy source(s), 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.

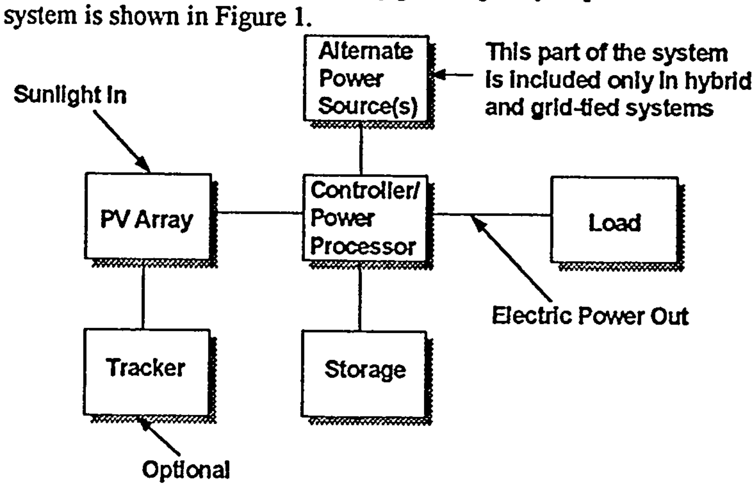

Figure 1. Block diagram of a photovoltaic (PV) power system

When designing PV power systems the available solar resource, the electrical load requirements for the application, 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 10-12% for converting sunlight into electricity. Module sizes range from 5 watts 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. AC loads require an inverter. DC 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 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 ~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 systems, including hybrids, range from a few kW to 100s of kW. 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 systems range from a few kW to several MW. 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.

ISSUES IN UTILITY-INTERACTIVE PHOTOVOLTAIC GENERATION

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Introduction

A utility considering the use of solar photovoltaic (PV) generation should consider the following issues:

- Power conditioning
- Protection
- Islanding
- Intermittent output
- 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 1 compares the current distortion from a PV power conditioner [1] with that of a common fluorescent light fixture and a personal computer. The light and computer were tested at WSU. The distortion from these common devices is much greater than that from the PV conditioner.

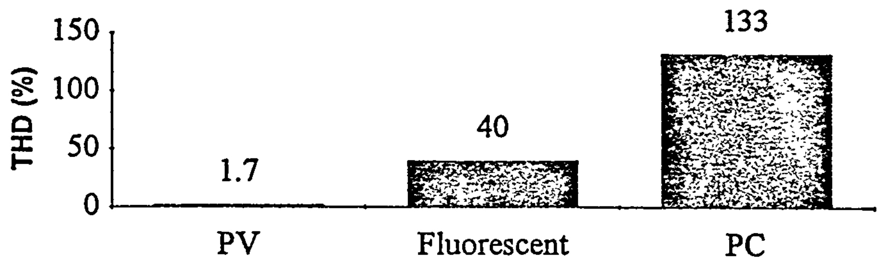

Figure 1. Current distortion.

Figure 2 shows the resulting voltage distortion on a distribution feeder with 37% penetration of PV generation [1]. This distortion was measured at the substation serving the feeder. Simulations revealed that even with a 100% penetration, the distortion would only increase to 1.8%. Such distortion is quite common on feeders with no PV generation.

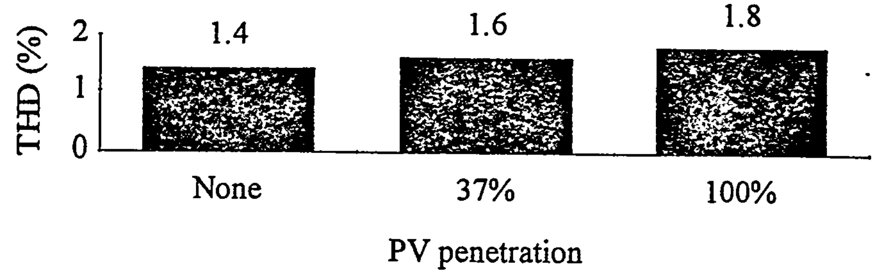

Figure 2. Voltage distortion.

Protection

PV generation contributes little to fault current on a faulted system. The short circuit current for a PV generator is only slightly higher than its load current. PV can, however, make distribution protection more difficult, because it is feeding power back into a feeder that has conventionally carried power only in one direction. Protection practices and relay settings may have to change to accommodate PV.

Islanding

Islanding, a condition in which PV generators continue to feed power to the grid after the utility source has been disconnected, is another common concern. Operating experience has shown, however, that power conditioners can reliably disconnect upon loss of utility service with voltage and frequency relays [2]. Such relays are usually built into the power conditioners.

Intermittent output

The output from PV systems is intermittent, depending totally on available sunlight. Utility-interactive PV systems use the utility grid as backup and storage. Figures 3, 4, and 5 show PV output on clear, overcast, and partly cloudy days, respectively [3]. These figures show that PV output can be reduced to almost zero, or can be varied rapidly by moving clouds.

Figures 6 and 7 shows how variations in sunlight can affect the output of PV generators [4]. A squall line, a line of dark clouds moving across an otherwise clear sky, will cause the loss of all PV generation. Figure 6 shows how rapidly this will occur for PV generation dispersed throughout service areas of various sizes. Cumulus clouds, well-defined clouds on an otherwise clear sky, will cause PV generation to increase and decrease repeatedly as they move across the sky. Figure 7 shows the possible loss of PV generation due to cumulus clouds.

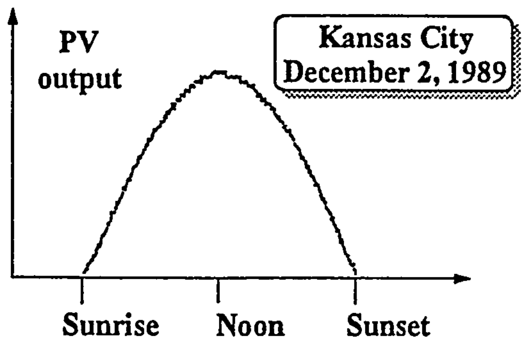

Figure 3. Clear day.

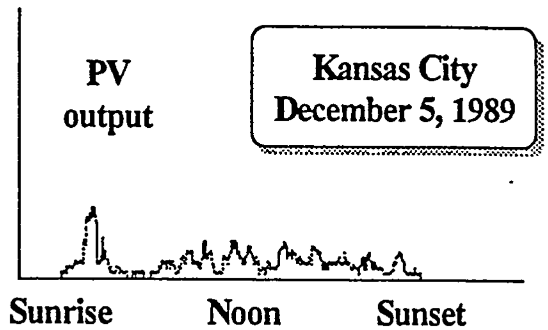

Figure 4. Overcast day.

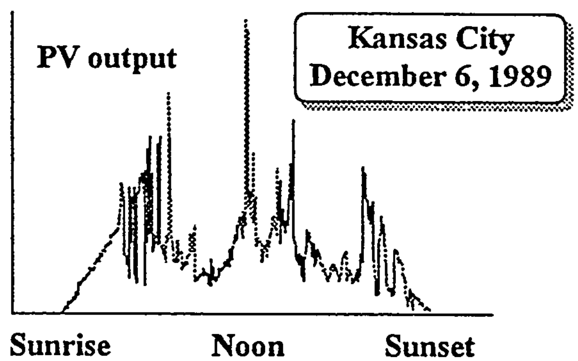

Figure 5. Partly cloudy day.

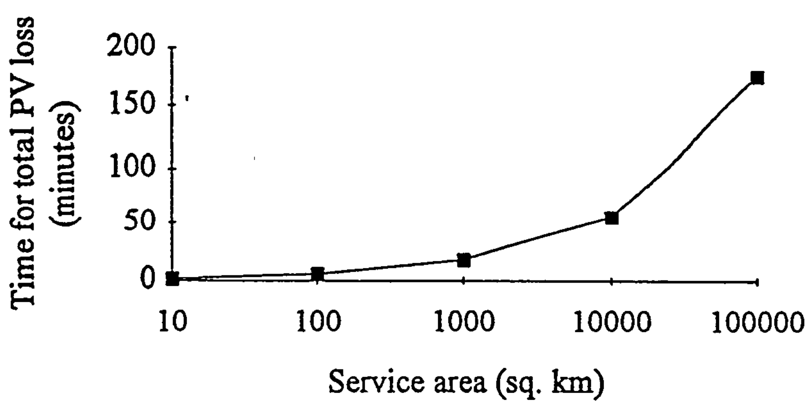

Figure 6. Squall line

For the Gardner, Massachusetts feeder with 37% PV penetration [5], moving clouds caused:

- Maximum PV ramp rate of 3% per second.
- No voltage flicker.
- Increased tap changer operations.

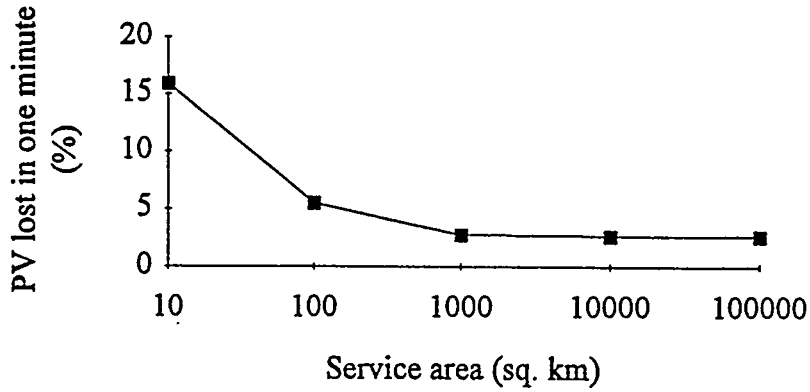

Figure 7. Cumulus clouds

A simulation of dispersed PV generation in the Public Service Company of Oklahoma system [6] showed that 15% penetration of PV in PSO's southeast Tulsa service area could cause power flow reversal on some subtransmission and transmission lines, and overloaded transmission lines in some cases. These would occur, however, only under isolated cloud conditions, and could be accomodated by changes in utility operating and protection practices.

Another simulation of a utility in Kansas [7] studied how much PV generation could be installed before system ramp rates were reached. The utility studied had a system ramp rate limit of 1% of load per minute. One PV generator with capacity equal to 1.3% of the system load could exceed the system ramp rate under certain weather conditions. The result would be inadvertent tie line flows into or out of the system.

Installation

The National Electrical Code 1993 edition [8]specifies installation practices for PV systems. Article 690 of the code, "Solar Photovoltaic Systems," includes:

- Circuit requirements
- Disconnecting means
- Wiring methods
- Grounding
- Marking
- Connection to other sources
- Storage batteries

Conclusion

PV generation, like many advanced electrical technologies, will at times require improved performance from the utility system. Operating and protection practices may have to change to accommodate PV. However, operating experience and studies show that PV generation will operate well with existing electric utility systems.

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Central and South West System
Renewable Energy Development Project

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Considerable advances in renewable energy technologies - particularly solar and wind - have been made in the last decade. The CSW System, which comprises Central Power and Light, Public Service Company of Oklahoma, Southwestern Electric Power, and West Texas Utilities, expects several of them to be cost-competitive to traditional forms of generation within the next 20 years. Accordingly, the System has initiated a five year, $17.3 million ($10 million is internally funded) effort to install and operate the most viable designs for our Texas, Oklahoma, Arkansas, and Louisianna service area.

Individual Projects

Photovoltaic 300 kW Array for Grid Support - CSW will install three 100 kW arrays near the end of a 12.5 kV distribution feeder northwest of Fort Davis, Texas. Two of the arrays will be flat plate and one will be ENTECH concentrating. Peak load on the feeder is 1.2 MW. The arrays will provide voltage support and power factor stabilization for the feeder. Land required for the arrays is about 8 acres. Two systems will be installed in the second quarter of 1994. The third will be about 9 months later. This project is jointly sponsored with the Electric Power Research Institute (EPRI).

Rooftop Photovoltaic 2 kW Arrays (five systems) - CSW will install five systems on customer rooftops to determine the benefits of distributed generation near its use point. These will be installed on a variety of buildings including residences and a working ranch. These systems will be installed in the fourth quarter of 1993. They are expected to be in service for three years of demonstration testing. Then, they will either be removed or offered to the host-site owner.

6,000 kW Advanced Turbine Design Wind Farm - Twenty advanced technology wind turbines will be installed in fourth quarter of 1994 and begin a three year trial. About 75 acres will be required for the installation. Wind resources throughout the CSW System will be measured at 23 sites to determine wind energy in other regions. This project is jointly sponsored with the U.S. Department of Energy and EPRI.

Cummins Solar Dish Stirling Engine Tests - CSW plans a one-year field trial for each of two models of the Cummins Solar Dish Stirling Engine. At the focal point of a concentrating mirror array, is a heat pipe/Stirling engine/electric alternator combination. The current size is 7.5 kW. A 25 kW design is under development. First installation would be in the first quarter of 1994 in Abilene, TX. Subsequent testing will be at the Solar Park. This project is jointly sponsored by EPRI.

PV + Heat Pump - A two-year field trial of a variable speed residential heat pump with photovoltaic assistance became operational in October, 1993. This project will be jointly sponsored with EPRI.

Photovoltaic End-use Applications - Several non-grid connected PV applications such as stock watering, irregation of a youth soccer field, and area all-night lighting are in operation. Many excellent opportunities exist for PV where utility line extension costs are prohibitive.

Location and Operation

The confluence of the best solar and wind resources in the CSW System service territory occurs near the town of Fort Davis, Texas. All projects are currently planned to be installed in the surrounding area. CSW will also pay close attention to environmental and societal concerns about renewable resource generation to provide valid input into our integrated resource planning process. West Texas Utilities (WTU) will operate the projects on behalf of the System. All projects will be visible to the general public and tours are available upon request. A descriptive video, companion brochure, and project newsletter are available. For further information about the project, please call us at (214) 77-RENEW.

CSW is a member of the Utility PhotoVoltaic Group, Photovoltaics for Utility Scale Applications, American Wind Energy Association and Texas Renewables Energy Industries Association.