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PHOTOVOLTAICS IN THE UNITED STATES DEPARTMENT OF DEFENSE

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ABSTRACT Over the last few years, the United States Department of Defense (DoD) has sponsored the installation of nearly 2 megawatts (MW) of photovoltaics (PV). Approximately 1.7 MW has been for systems at test or training ranges with an additional 300 kW for small applications. The emphasis of this paper is on those larger systems which range in size from 80 to 450 kilowatts (kW). Most of them are PV-diesel hybrid systems, while one (at the Army Yuma Proving Grounds) is a grid interactive project. A summary of the equipment and initial results from the new power processing test facility at Sandia National Laboratories is also provided.

1. THE CASE FOR THE USE OF PHOTOVOLTAICS AT REMOTE FACILITIES The Department of Defense operates hundreds of test & evaluation and training facilities. These facilities are often remote and isolated from the utility grid. The normal method of powering these isolated facilities has historically been manned diesel generators since unmanned generators do not provide adequate reliability for many of these missions. A single power failure can be extremely costly as a result of slipped schedules and damage to sensitive test equipment. Having operators attend the generators full time does increase reliability, but the savings from increased reliability is offset by higher labor costs.

The cost of energy from remote diesel generators can easily exceed \$1/kWh and can be as high as \$2/kWh. To illustrate, because the generators must be sized to handle the peak facility load, the generators are typically run at low load factors which can reduce the fuel efficiency by a factor of two. Inefficient loading, combined with delivered fuel costs

of up to \$2/gallon, can bring the fuel component of the energy cost to \$0.40/kWh. Preventative maintenance costs are on the order of \$3/run-hour. Both the fuel costs and the preventative maintenance costs are far outweighed by the operator costs of typically \$75/run-hour (1.5 operators at a loaded rate of \$50/hour). A typical DoD facility might require 1000 kWh over a ten-hour day, five days per week which equates to 2,600 run-hours or 260,000 kWh per year. This translates to \$0.03/kWh for preventative maintenance and \$0.75/kWh for the operators for a total energy cost of \$1.18/kWh. These high costs do not include the effect of fuel or oil spills or generator permitting. Clean-up from a single two-hundred-gallon fuel spill or accumulated oil leaks can easily cost in excess of \$250,000. In some instances, the test facilities are in an air quality management district that requires permits to run diesel generators. Although permits are typically relatively inexpensive, the regulating agency often limits the generator capacity (and resulting air emissions) for a given area. Many facilities are to the point where additional power requirements would result in exceeding air emission allowances.

Shrinking operation and maintenance budgets and restrictive air emission regulations have motivated facility managers to seek ways to reduce the usage and cost of operating generators. The first priority is to reduce generator run-time followed by increasing generator efficiency and then displacing fuel with alternative sources. The hybrid photovoltaic/diesel generator option meets all these criteria. First, the battery/power processing system decouples the generator from the load so that the generator can run at a high loading to maximize efficiency and minimize run-time. Second, the fuel usage is reduced proportionally by the

amount of installed photovoltaics. In addition, this approach offers the reliability of redundant power sources, one mechanical and the other electronic. The hybrid option can, in many cases, effectively reduce the cost of energy to about \$0.40/kWh.

2.0 ORGANIZATION To advance the usage of PV in the military, the DoD has established the Photovoltaics Review Committee. This committee is composed of a Chairman and a member from each of the three principal military departments (who are co-authors of this paper). Sandia National Laboratories provides technical assistance. Procurement management for specific projects is tailored to the end-user and is managed by the respective military organizations.

3. FUNDING Funds are primarily provided from the Energy Conservation Investment Program (ECIP), a component of the Military Construction Program, and the Strategic Environmental Research and Development Program (SERDP), a joint DoD-DOE-EPA program that addresses environmental issues. All ECIP projects are required to be life cycle cost-effective as part of the internal DoD project approval process. In addition, there are many systems procured at the installation level, usually from operation and maintenance budgets.

4. SPECIFIC PROJECTS CURRENTLY IN PROCUREMENT OR INSTALLATION Various DoD organizations purchase many small systems. Typical applications include lighting, cathodic protection, power for various electronic instrumentation, and as a battery charger for a wide variety of equipment. We estimate that to date approximately 2 MW of PV are in use at various DoD installations, mostly for small applications. In this paper we will highlight those projects for which the DoD PV Review Committee has been most active. Most of these projects are PV-diesel hybrid systems ranging in size from 80 to 350 kW and they total about 1.7 MW in size. The following is a compilation of those projects; they are also included as a summary in Table 1.

4.1 Superior Valley, China Lake, California This system is a PV-diesel hybrid system at the bombing complex at Superior Valley on the Naval Air Warfare Center Weapons Division at China Lake, California. The system is comprised of a 350 kW PV array with associated power processing equipment, battery storage system, and a diesel generator. PV was an attractive option because the Superior Valley location is remote from the grid and other Center functions. The prime contractor, Photocomm, Inc. was awarded \$3,570,850 to design, manufacture, and install the

system. The modules are ASE-DG/50 4' x 6' modules supplied by ASE Americas, and the power conditioning supplier is Abacus Controls Inc. This project is a SERDP-funded research and development project designed to advance power processing technology to allow "ganging" of multiple power processing units to achieve the power capacity required for larger DoD applications. The system also provides increased power capacity required by the expanding mission of the facility. The Superior Valley project was dedicated in November 1995 and declared operational in January 1996.

4.2 Mountain Home Air Force Base, Grasmere Range This project provides power to electronic equipment located on Grasmere Range, approximately 80 miles from Mountain Home Air Force Base and many miles from the nearest grid. Previously, power had been furnished by diesel engines. The expanding mission of the Grasmere Point facility now requires year-round power with 24-hour power during the winter. Because of the severe winter weather at the site, 24-hour power with diesels alone is impractical. This project allows the Air Force to reduce the diesel engine run time thereby providing year-round power at a reasonable cost. The integrating contractor was Idaho Power; the module supplier - Solarex; and the power conditioning equipment supplier - AES. The system was declared operational in March 1995.

4.3 Ascension Island Runway Lighting This project will result in the construction of an 80 kW PV-island grid interactive system that will provide power for the runway lighting system with the additional ability to also supply power into the base distribution system. The project will save approximately 1400 barrels of fuel oil (annually) that would otherwise have to be transported and distributed to the generators to produce power. Proposals have been evaluated and an award announcement is expected soon.

4.4 Range Electronic Warfare Simulator (REWS), San Clemente Island, California Most of the facilities on San Clemente Island are served by a group of diesel generators that produce power for the island grid. However, the REWS facility is isolated even from the island grid and depends on a series of generators to provide power to the equipment and housekeeping loads at the facility. The proposed system addresses the excessive costs associated with providing 24-hour power with diesel generators. The PV array size will be about 80 kW. The system will provide autonomous operation during weekends which will substantially reduce operation costs. The systems contractor is Integrated Power; modules are supplied by ASE Americas; batteries by C&D; and power processing equipment by Kenetech. The procurement office is the Naval Facilities Engineering Command Southwest Division (SWDIV) in San Diego and

the Navy user is the Southern California Off-shore Range with headquarters at North Island in San Diego. The system is projected for completion in late 1996.

4.5 Yuma Proving Ground (YPG) In early 1995, Utility Power Group (UPG) won both prime contracts for the 450 kW PV array and the complementary battery storage/load leveling projects for a total amount of about \$7 million. The two systems will be integrated into a PV/battery-enhanced peaking station. UPG will be using Siemens modules, Kenetech power conditioning equipment, and C&D batteries. Under normal operating conditions during the summer peak demand season, the system will be capable of delivering up to 900 kW to the grid to help YPG with high demand rates. The system will also be capable of operating in a stand-alone mode if an extended power outage is experienced. On a limited basis, the stand-alone system would continue to operate YPG's nearby water treatment plant and other emergency communications loads. Preliminary design is nearly complete and construction is expected to begin by March 1996.

4.6 Marine Corps Air Ground Combat Center, Twentynine Palms California, Range 500 Range 500 is a remotely located tank target practice range isolated from the grid. Presently, diesel generators power a mechanism that drives tank pop-up targets along a track. PV will supplement those generators and provide improved power quality and reliability. The PV array will be about 80 kW in size. The procuring agency is the Naval Facilities Engineering Command at San Diego (SWDIV). Proposals have been evaluated and a contractor selection is expected by March 1996.

4.7 Mobile Power Center (MPC) For the 1st Marine Expeditionary Force at Camp Pendleton, California, a mobile power center is under development. It is designed to interface with utility and conventional generators and will have about 3.2 kW of PV, 1 kW of wind, and 6 kW output from the generators, and 58 kWh of battery storage. The MPC is a partially SERDP-funded research and development project designed to incorporate hybrid capabilities in a mobile package that is compatible with standard military equipment and suitably robust for military operations. The unit addresses the need to simplify the logistics of power requirements for tactical military exercises as well as enhance the reliability of the missions. A prototype unit is under construction at the Naval Research and Development (NRAD) unit in San Diego.

4.8 Fort Carson Water Pumping: The Fort Carson PV project was approved as an ECIP project in 1992 to install some 41 different water pumping systems to replace aging windmills on the military reservation. In early 1995, Fort

Carson personnel attended a PV water pumping workshop, hosted by members of the Photovoltaic Services Network (PSN). Working with the PSN, Fort Carson decided to turn its project into a demonstration of currently available PV water pumping technologies. Through summer-1995, eight different systems, using both AC and DC submersible pumps, were installed. The systems include: SolarJack (DC centrifugal), Golden Photon (AC centrifugal), A.Y. McDonald (DC centrifugal), Applied Power Corp. (AC centrifugal), EPV (AC centrifugal), Photocomm (DC centrifugal), and a South African made Otter pump. Two additional DC systems were also installed, leaving about 20 to 30 more systems to be installed during 1996. These eight systems are being monitored for performance, but early data has been inconclusive because of the wide range of well characteristics. This project is being implemented by Fort Carson's Directorate of Environmental Compliance and Management. Steve Snyder, the Pollution Prevention Division Chief, says, "The water pumped by these systems will create small riparian areas for the wildlife that we share the ranges with."

4.9 Four Projects at China Lake, California A multiple-system contract for \$6.3 million was recently awarded to Plateau Electric for the design and installation of four separate PV hybrid systems at China Lake, California. These systems are for existing, remotely located test sites. They are:

Junction Ranch - 110 kW
Ship Site - 25 kW
NATO Site - 130 kW
Kim Site - 200 kW

The modules for all four systems are ASE Americas and the power processing equipment is supplied by Kenetech. The procurement office is the Naval Air Warfare Center Weapons Division at China Lake.

4.10 Solar Regenerative Fuel Cell Cooperative Project This is a cooperatively funded demonstration project with the Jet Propulsion Laboratory at Edwards Air Force Base. The Navy Energy Office based at China Lake is procuring and installing two different 25 kW Cadmium Telluride thin film PV arrays - one manufactured by Solar Cells Inc. (SCI) and the other by Golden Photon Inc (GPI). The direct current produced by the PV arrays will power the electrolyzer system that separates water into hydrogen and oxygen. The hydrogen and oxygen are recombined into the fuel cell to produce heat, electricity, and water. NASA regards a regenerative photovoltaic fuel cell power plant as a possible option for advanced human space exploration. The Department of Defense will gain operational experience with an emerging, potentially lower-cost PV technology.

5. PROSPECTIVE PROJECTS

5.1 Range Projects at Pohakuloa Training Area (Hawaii) A solicitation for several PV applications is in preparation and is scheduled for release in March 1996. The solicitation will call for multiple PV systems to power range towers (lighting, communications, and public address system), the large track targets on the helicopter training range, and runway lighting for Bradshaw Army Airstrip. We estimate there will be approximately 50 kW of PV required.

5.2 Santa Cruz Island This project was the single Navy project approved in the FY 1996 budget cycle. It is to be a hybrid PV/diesel and will have about 200 kW of PV. Solicitation and award are expected by late 1996.

6. POWER PROCESSING TECHNOLOGY ADVANCES

This group of PV-hybrid systems represents an advance in hybrid systems power processing state-of-the-art. Prior to 1994, the largest commercially available PV-hybrid systems was about 50 kW. And there was no way to realistically test the power processing unit prior to it being put into the operational system. Sandia National Laboratories, in cooperation with the PV Review Committee, and with funding provided in part by SERDP, has designed, procured, assembled, and checked out a state-of-the-art power processing test facility designed primarily for PV/diesel/battery systems. It includes all components of an actual hybrid system including a flooded lead-acid battery (720 kWh), photovoltaic arrays (up to 60 kW), a diesel generator with autostart control and monitoring unit, utility intertie for utility interactive applications, and a system of resistive, inductive, and non-linear load banks as well as a variety of actual motor and switching loads. For a given evaluation, the test bed is configured as closely as possible to the actual system including operating voltages/currents, and the type and magnitude of load. The facility is thoroughly instrumented and all instruments are maintained to strict calibration standards. The existence of this test facility allows power processing contractors to test its equipment advancements before installing them in real-world systems. Specific test plans and procedures are developed for each unit to evaluate all performance specifications. Test parameters include not only efficiencies and power quality but all unit functions such as battery charge algorithms, operating mode logic, self-protection, and internal instrumentation/monitoring. Units may also be tested for environment considerations such as the electrical and audible noise they generate. This state-of-the-art facility and Sandia's engineering expertise have provided an essential service in developing the technology required to serve DoD's remote power needs with photovoltaics.

6.1 Approach For most of the DoD hybrid systems mentioned in this paper, the functional requirements representing the technology advances were specified as part of a system request-for-proposal (RFP). The RFP requires that the power processing unit and associated control system be brought to Sandia for evaluation before field installation. This approach places the development and engineering in the hands of the manufacturer, encourages open competition, and provides for comprehensive evaluation at Sandia's state-of-the-art power processing test facility, which is much more comprehensive than the manufacturer's in-house test capabilities. Development funding availability for DoD PV/diesel hybrid applications coincided with the introduction of IGBT (insulated gate bipolar transistor) based bi-directional power processing units (PPUs) developed in part with DOE research funding. This technology is the basic building block for DoD's hybrid applications. The bi-directional capability means that the same unit performs both the inverter and battery charging functions. In a typical application, facility loads are served by the PPU in the inverter mode as long as there is sufficient energy from the PV array and battery. When the battery is discharged to a preset level, the generator is started and the facility load is transferred from the PPU to the generator. The PPU then switches to the battery charger mode, becoming an additional load on the generator. The battery charge current is regulated to maintain the generator near its full output capability and within its most efficient operating regime. This approach maintains a high generator output per unit time to minimize generator run time, and provides the most direct use of generator power to minimize fuel consumption. DoD facilities require power processing capability up to 1 MW. The 1200V/600A IGBT module currently used by most manufacturers limits the PPU capacity to about 300 kW (for a three phase system) depending on the operating voltage. High capacities are achieved through either some form of parallel IGBTs or through increased capacity of the IGBTs themselves. The approach taken for the DoD applications was to establish building block PPUs that could be operated in parallel to achieve the required capacity of the application. The system that was recently installed as part of the Superior Valley hybrid system — a 300 kW, three phase PPU system with two 50 kW units operating in parallel per phase — was fully evaluated at Sandia's power processing test facility in July and August of 1995. In addition to meeting the higher capacity requirements, parallel PPUs pave the way for further increases in efficiency. As indicated earlier, the generator efficiency is maximized by decoupling the generator from the load and maintaining the generator at a constant loading within its most efficient operating regime. This strategy works because the PPU maintains its efficiency better than a generator at lower loading. The parallel units allow the PPU to be matched to the load by switching units in and out as required to meet the

demand, thereby maintaining higher and more efficient usage levels as compared with a single unit. This approach is only practical with parallel electronic inverters because a generator must be started and warmed up before it can accommodate a load whereas an electronic inverter can accommodate a load instantaneously.

Up to this point, the PPU was required to operate only in a stand-alone inverter mode. In other words, the load is served by either the PPU in the inverter mode, or by the generator. Consequently, both the PPU and the generator must be sized to serve the entire facility load. As indicated earlier, the first priority in reducing cost of operating the generator is to reduce the run-time. The run-time cost is labor intensive and is relatively independent of generator capacity. Consequently, the hybrid option becomes less cost-effective as the facility capacity requirements increase. The capability for the PPU to operate in both stand-alone and parallel inverter modes permits a cost-effective hybrid option for these higher capacity systems. The PPU can serve the load in the stand-alone mode during low demand periods, and in the parallel mode, level the load on the generator during high demand periods. This capability is also applicable to utility interactive systems for peak demand reduction in the parallel mode, and back-up service during a utility outage in the stand-alone mode. This advance was integrated into the Yuma Proving Ground RFP. This contract was awarded in June of 1995; evaluation of that PPU is scheduled for spring, 1996.

The final advance is actually a subset of the parallel inverter mode and involves the load transfer from the PPU in the inverter mode to the generator. The original bi-directional technology used a "hard" seamless load transfer. This term connotes that even though the generator has been started, warmed up, and the PPU and generator have been synchronized, the load transfer itself is instantaneous with no load sharing between the PPU and generator. A large facility load (60-80 percent of the generator capacity depending on the type of engine and governor) will cause substantial frequency and voltage transients which could interfere with and even damage sensitive loads. The possibility for any transients can be eliminated by a gradual or "soft" load transfer. In the case of an inverter-to-generator load transfer, the generator is still started, warmed up, and the PPU and generator are synchronized as with the "hard" transfer, but the generator is connected to the ac circuit at zero current. The generator current is then ramped up, while the inverter current is ramped down, at a rate that will not result in any voltage or frequency transients. After the load has been transferred from the inverter to the generator, the PPU switches to the battery charging mode and the charge current is ramped up at the same rate to load the generator within its optimum operating regime. The

same "soft" transfer is also applied when switching from the battery charging mode back to the inverter mode. This "soft" transfer feature was integrated into four systems (Junction Ranch, Kim Site, NATO Site, and Shipsite) at China Lake and for the Range Electronic Warfare Simulator on San Clemente Island. Contracts for these systems were awarded in the Fall of 1995. The first of these units is scheduled to be evaluated at Sandia beginning in April, 1996.

6.2 Initial Testing Results: The Sandia facility, which became operational in the second quarter of 1995, has now been used to fully evaluate three power processing units with associated system level controls. Two of these units were 30 kW prototypes of the first bi-directional hybrid PPU manufactured in the United States. The latest unit tested was the 300 kW hybrid PPU manufactured for the Superior Valley hybrid system. The facility provides a system level test environment that is critical to verifying performance and design but is beyond the capability of the manufacturers. This value became apparent during the evaluation of the Superior Valley unit. The manufacturer could not evaluate the unit at the 300 kW power levels or with an actual diesel generator and a fully functional battery bank. The Sandia facility's extensive instrumentation allowed the manufacturer to diagnose and correct several problems that did not show up during factory testing. The unit left Sandia's facility fully functional and was installed and started with only minor adjustments. The evaluation at Sandia possibly avoided months of field testing and hardware retrofits which would have substantially delayed completion and increased cost.

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TABLE 1. CURRENT DEPARTMENT OF DEFENSE PV PROJECTS STATUS SUMMARY.

Project/Location/Service	PV Array Size-kW	Cost (\$000)	System Type	System Contractor	Module Supplier	Power Cond.	Construction Status
Superior Valley; China Lake-Navy	350	3,600	Hybrid	Photocomm	ASE Americas	Abacus	Operational January, 1996
Grasmere Point; Mountain Home AFB, Idaho	80	1,300	Hybrid	Idaho Power	Solarex	AES	Operational March, 1995
Runway Lighting; Ascension Island - AF	80	1,350	Isolated Grid Tied	TBD	TBD	TBD	Contract Award Imminent
San Clemente Island - Navy	80	1,300	Hybrid	Integrated Power	ASE Americas	Kenetech	In Design Phase
Grid Support; Yuma Proving Grounds - Army	450	7,000	Utility Tied	UPG	Siemens Solar	Kenetech	Under construction
Twentynine Palms-Marine Corps	100	TBD	Hybrid	TBD	TBD	TBD	Contract award imminent
Mobile Power Center - Marine Corps	3.5	51	Mobile Hybrid	In-house Navy	Solarex	Abacus	Prototype under construction
Fort Carson, CO - Army	14	300	Water Pumping	Army	Various	Various	Under Construction
China Lake-Junction Ranch, Ship-NATO-Kim Sites	110, 25, 130, 200	6,300	Hybrid	Plateau Electric	ASE America	Kenetech	In Design Phase
Solar Regenerative Fuel Cell; NASA/Edwards AFB	50	530	Special	In-house Navy	SCI, GPI	N/A	Under Construction