Technology White Paper

on

Solar Energy Potential on the U.S. Outer Continental Shelf

Minerals Management Service
Renewable Energy and Alternate Use Program
U.S. Department of the Interior
Available for Downloading at http://ocsenergy.anl.gov

May 2006

SOLAR ENERGY POTENTIAL ON THE U.S. OUTER CONTINENTAL SHELF

INTRODUCTION

With the passage of the Energy Policy Act of 2005 (EPAct), Public Law 109-58 (H.R. 6), the Minerals Management Service (MMS), a bureau of the U.S. Department of the Interior, was given jurisdiction over Renewable Energy and Alternate Use Program projects, such as wind, wave, ocean current, solar energy, hydrogen generation, and projects that make alternative use of existing oil and natural gas platforms in Federal waters. A new program within MMS has been established to oversee these operations on the U.S. Outer Continental Shelf (OCS). MMS is developing rules to guide the application and permitting process for development of Renewable Energy and Alternate Use Program projects on the OCS. To apply the requirements of the National Environmental Policy Act (NEPA) in the establishment of national offshore alternate energy development policy and a national alternate-energy-related use program and rules, MMS plans to prepare a programmatic environmental impact statement (Programmatic EIS). The Programmatic EIS process will (1) provide for public input concerning the scope of national issues associated with offshore alternate-energy-related use activities; (2) identify, define, and assess generic environmental, sociocultural, and economic impacts associated with offshore alternate-energy-related use activities; (3) evaluate and establish effective mitigation measures and best management practices to avoid, minimize, or compensate for potential impacts; and (4) facilitate future preparation of site-specific NEPA documents—subsequent NEPA documents prepared for site-specific Renewable Energy and Alternate Use Program projects will tier off of the Programmatic EIS and Record of Decision. The Programmatic EIS will evaluate the issues associated with development, including all foreseeable potential monitoring, testing, commercial development, operations, and decommissioning activities in Federal waters on the OCS. Information defining the issues and current technology will be obtained primarily from Federal research organizations, MMS, industry, and other valid sources.

In preparation for the Programmatic EIS, MMS has developed a series of White Papers on topics of interest to the Renewable Energy and Alternate Use Program. The overall objective of the White Papers is to provide sufficient information on the prospective alternative technologies to support assessments of the potential environmental impacts of the technologies and of the viable impact mitigation strategies in the Programmatic EIS. The White Papers also will serve as sources of information for stakeholder outreach.

This paper discusses the generation of energy from solar radiation on the U.S. OCS. Resource potential and technologies for capturing the energy in solar radiation are discussed.[1] Major environmental and economic considerations that can be surmised from available literature at this time for the development of this energy resource are listed. Companion papers in the series address the generation of energy on the OCS from wind, waves, and ocean currents, and

---

[1] Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not represent its endorsement, recommendation, or favoring by MMS, the United States government, or any agency thereof.

the transportation of energy generated on the OCS to onshore as electricity or in the form of hydrogen.

RESOURCE POTENTIAL

The sun emits energy at an extremely large and relatively constant rate, 24 hours per day, 365 days per year. If all of this energy could be converted into usable forms on earth, it would be more than enough to supply the world's energy demand. However, this is not possible because (1) the earth intercepts only a small fraction of the energy that leaves the sun; (2) the earth rotates such that a collection device on the earth's surface is exposed to solar energy for only about half of each 24-hour period; and (3) conditions in the atmosphere, such as clouds and dust, sometimes significantly reduce the amount of solar energy reaching the earth's surface.

The intensity of solar energy on a surface oriented perpendicular to the sun's rays above the earth's atmosphere (known as the solar constant) has been measured by satellite to be between 1,365 and 1,367 W/m^2 (NASA 2003). This energy is transmitted through the atmosphere and reaches the earth's surface at a rate that varies over time at a particular location because of the angle at which the sun's rays strike the earth (called the zenith angle). This angle establishes the path length through the atmosphere for incoming sunlight and varies with latitude, date, and local time of day. Weather patterns and other atmospheric conditions, which scatter incoming rays, also affect the rate at which solar energy reaches the earth's surface. The summation of the amount of solar energy arriving at a unit of area (1 m^2) during 1 hour is called the solar radiation or insolation. The solar radiation is typically expressed in units of watt-hours or kilowatt-hours per square meter (Wh/m^2 or kWh/m^2) averaged over the period of a day, month, or year. Sometimes, solar radiation is expressed in British thermal units per square meter (BTU/m^2) per day, month, or year if conversion of solar energy into heat energy rather than electricity is being discussed. The solar radiation in the United States has an overall average rate of about 6 million BTU/m^2, or 1,758 kWh/m^2 (about 6,330 megajoules/m^2) per year (Morse and Simmons 1976).

It has been estimated that a desert area in the southwestern United States that measures 161 km on a side (0.3% of the land area of the United States) could theoretically meet the electricity needs of the entire country if the solar radiation in that area could be converted to electricity with 10% efficiency (Sandia National Laboratories 2001). The presence of clouds, which scatter and absorb solar energy, is the predominant atmospheric condition that determines the amount of solar energy available for conversion to other energy forms at any particular location. Thus, as Figures 1 and 2 illustrate, the annual average daily solar radiation in the United States (direct and global, respectively) is highest where the atmosphere is very dry. For example, in the western desert regions of Arizona, Nevada, and California, the annual average daily direct solar radiation (Figure 1) ranges from 8.5 to 9.0 kWh/m^2 at some locations. However, in most locations along the Pacific coastline, where moisture levels in the atmosphere are likely to be higher, it drops to less than 6.0 kWh/m^2, even without latitude changes. Similarly, the direct solar radiation is also lower along the Gulf of Mexico coastline in Texas and Louisiana than it is slightly inland at the same latitudes. Around Florida and up the East Coast, on the other hand, there does not appear to be a drop in the direct solar radiation along the

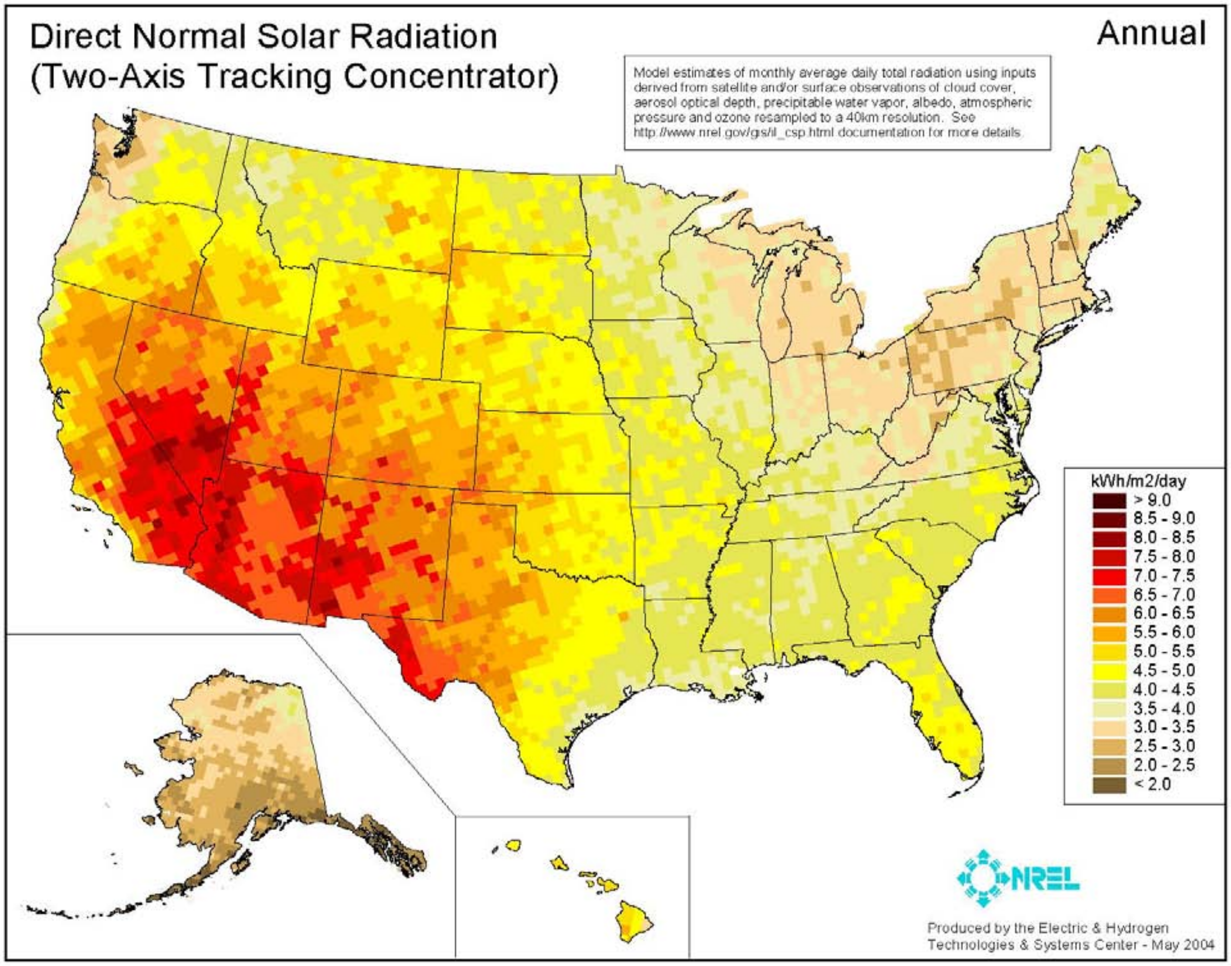

FIGURE 1 Annual Average Direct Solar Radiation (Source: NREL 2006a)

coastline, which may suggest that the atmospheric humidity levels do not increase significantly along the coast in these areas. No information was found about the solar radiation levels on the OCS.

RESOURCE UTILIZATION TECHNOLOGIES

Solar energy can be converted to other more usable energy forms through a variety of demonstrated technologies that are divided into two categories: thermal and photonic. Solar thermal technologies first convert solar energy to heat, which can be used directly (such as heating water for residential or commercial use), stored in a thermal medium (such as heating water or dry rocks) for later use, or converted to mechanical and/or electrical energy by an appropriate device (such as a steam turbine). Solar photonic technologies directly absorb solar photons—particles of light that act as individual units of energy—without complete conversion to heat. The absorber then either converts the photon energy to electricity (as in a photovoltaic [PV] cell) or stores it as chemical energy through a chemical reaction (as in photosynthesis or the dissociation of water into hydrogen and oxygen).

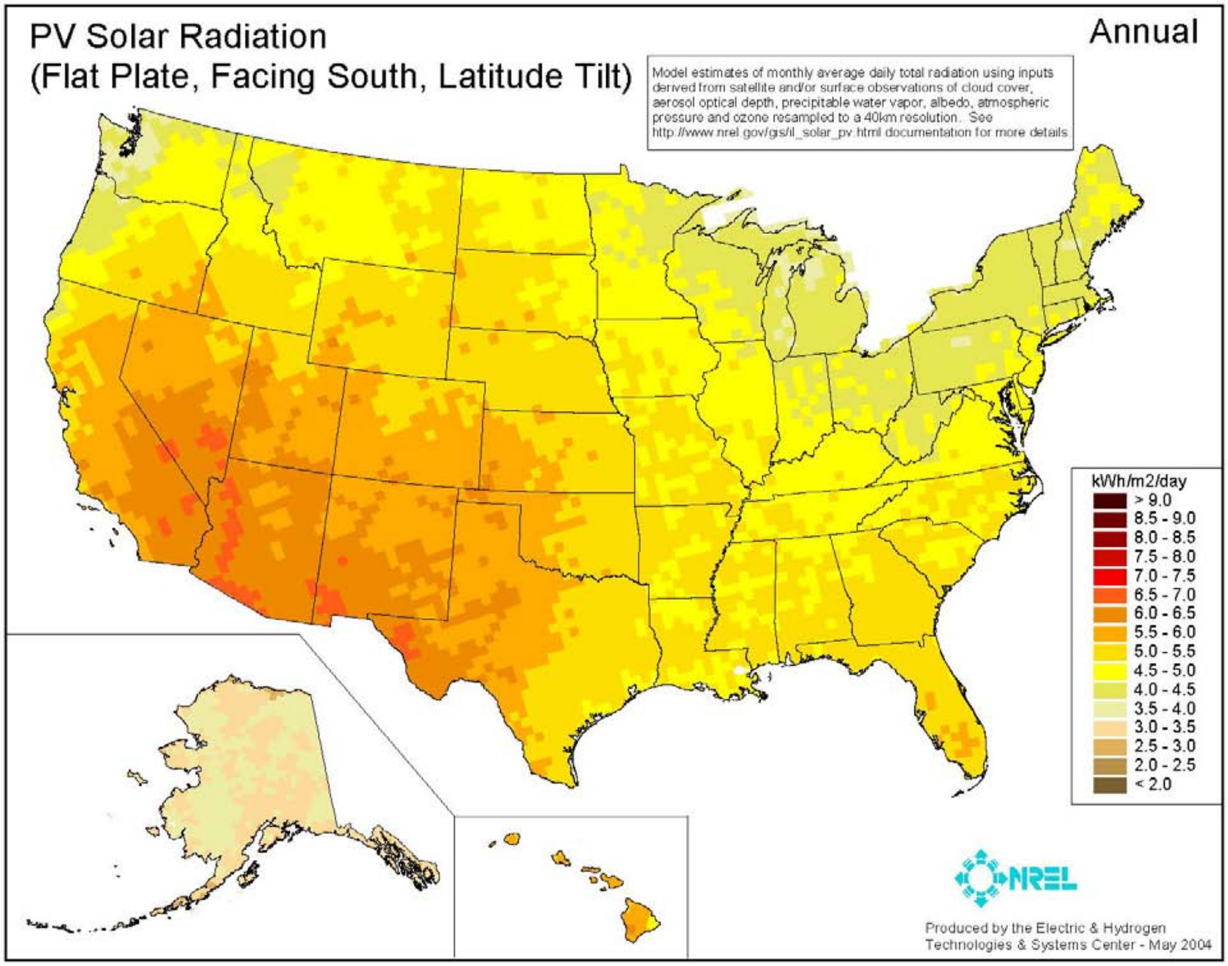

FIGURE 2 Annual Average Global Solar Radiation (Source: NREL 2006a)

Selecting a solar energy conversion technology for use in an offshore setting would be influenced by differences in technological approach. Such differences may favor one technology over another, when all factors contributing to the decision to utilize solar energy for a project have been considered. Available technologies and technological approaches are described below. Emphasis is placed on technologies with dispatchable applications, such as electricity generation for delivery to consumers over an onshore central utility grid (10 MW or greater) or hydrogen production for delivery to onshore consumers, rather than distributed applications, such as heating water for domestic or commercial use and generating electricity for off-grid use in remote or localized settings (10 kW to several MW). However, certain distributed applications relevant to offshore projects are mentioned.

Solar Thermal Technology

Solar thermal technology includes technological approaches for both localized uses and dispatchable uses. Approaches in the latter category comprise what is commonly referred to as concentrating solar power (CSP) technology. CSP technology utilizes mirrors to concentrate (focus) the solar radiation so that it can be captured in the form of heat. That heat is then converted to electricity by using conventional technology.

CSP technology was rapidly advanced as a result of research and development sponsored by the U.S. Department of Energy (then the Energy Research and Development Administration) in the aftermath of energy shortages that occurred in the 1970s. Commercial implementation of CSP was achieved in the mid-1980s with construction of nine parabolic trough plants in the California Mojave Desert, totaling 354 MW. Internationally, CSP technology has been implemented in several European Union countries, including Germany, Spain, and Italy, as well as in Israel and South Africa. However, no offshore CSP projects have been identified.

CSP technology encompasses three technological approaches—trough, power tower, and dish/engine. The trough and power tower approaches are suitable for producing dispatchable electricity. The dish/engine approach also may be configured to produce dispatchable electricity, but the modular character of dish/engine systems makes this approach suitable for small-scale distributed applications as well.

Trough Systems. A trough system consists of a large field of single-axis tracking parabolic concentrators, arranged in parallel rows that focus sunlight on receivers running along the focal lines of the concentrators. Figure 3 shows an onshore trough system solar field. Figure 4 illustrates a process flow typical of existing onshore solar trough system plants. The solar field is modular and the rows of concentrators are aligned on a north-south horizontal axis. The concentrators, which track the sun from east to west during the day in order to keep the sunlight focused on the linear receiver, are made up of parabolic reflectors (mirrors), metal support structures, receiver tubes, and tracking systems that include drives, sensors, and controls. A heat transfer fluid is pumped through the linear receiver where it becomes heated. The heat transfer fluid then circulates through a series of heat exchangers where the fluid is used to generate high-pressure superheated steam. The superheated steam is fed to a conventional reheat steam turbine/generator to produce electricity. The spent steam is condensed in a standard condenser and recycled. A cooling tower or once-through system removes excess heat from the condenser. The cooled heat transfer fluid is recirculated through the linear receiver. Plant output may range from 1.0 to 100 MW of electricity. Current solar trough technology produces about 100 kWh/yr per square meter of collector surface (DOE/EPRI 1997).

FIGURE 3 A Land-Based Parabolic Trough System (Source: NREL 2006b)

Power Tower Systems. In a power tower system (also called a central receiver), a field of large two-axis, flat, tracking mirrors reflects the solar energy onto a receiver that is mounted on top of a centrally located tower, as shown in Figure 5. The solar energy is absorbed by a working fluid (typically molten salt or water) and then used to generate steam, which powers a

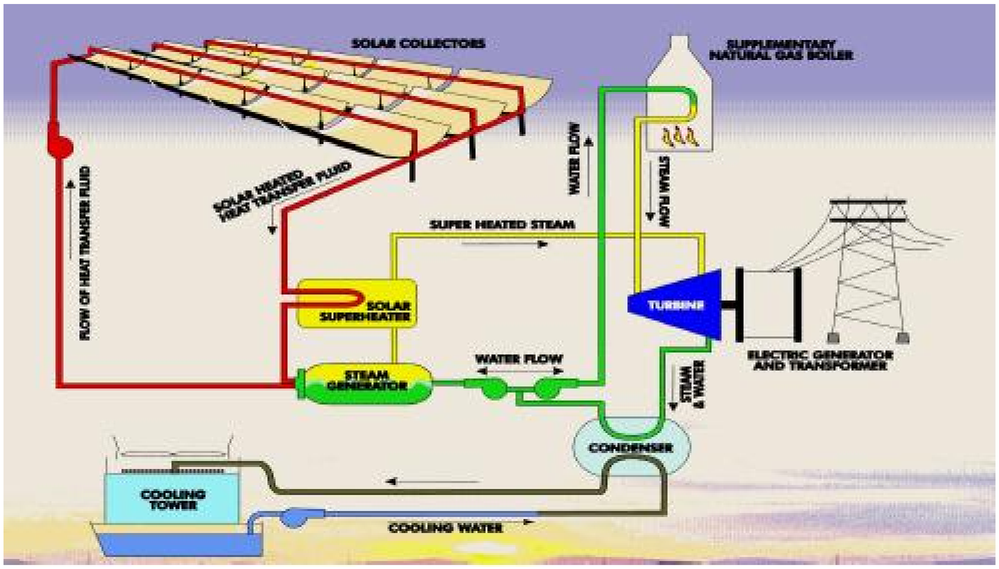

FIGURE 4 Solar Trough Process Flow Diagram (Source: DOE/EPRI 1997)

conventional turbine. Even when the sun is not shining, some designs can effectively store thermal energy for hours (either in the working fluid for molten salt systems or in such materials as rock or sand for a water/steam system) if desired, to allow electricity production during periods of peak need. In a molten salt system, the molten salt is pumped at 290ºC from a “cold” tank and cycled through the receiver, where it is heated to about 565ºC and returned to a “hot” tank. The hot salt can then be used during the next 3 to 13 hours to generate electricity when needed. Figure 6 illustrates the flows in such a molten salt power tower system.

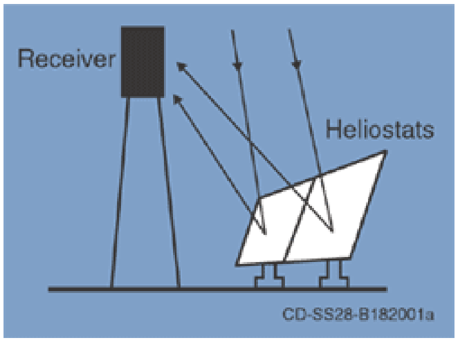

FIGURE 5 Power Tower Schematic Diagram (MMS 2006)

The first power tower, Solar One, was built in southern California and operated during the mid-1980s. Standing 91 m tall, it used a water/steam system and 1,818 heliostats, each having a reflective area of 39 m^2, to produce 10 MW of electricity. In 1995, Solar One was converted into Solar Two, by adding 108 heliostats, each having a reflective area of 95 m^2, around the existing central tower and converting the working fluid system to a molten nitrate salt system. Solar Two, which was decommissioned in 1999, had a total of 1,926 heliostats (a total reflective area of 81,162 m^2) and, like Solar One, produced 10 MW of electricity. A third power tower called Solar Tres is being built in Spain. It is a molten salt system with 2,493 heliostats, each with a reflective area of 93 m^2. Solar Tres is expected to generate 15 MW of electricity.

Dish/Engine System. The third CSP technological approach, the dish/engine system, uses a mirrored dish concentrator (about 10 times larger than a backyard satellite dish) to focus sunlight onto a thermal receiver and a heat engine/generator. As shown in Figure 7, the receiver

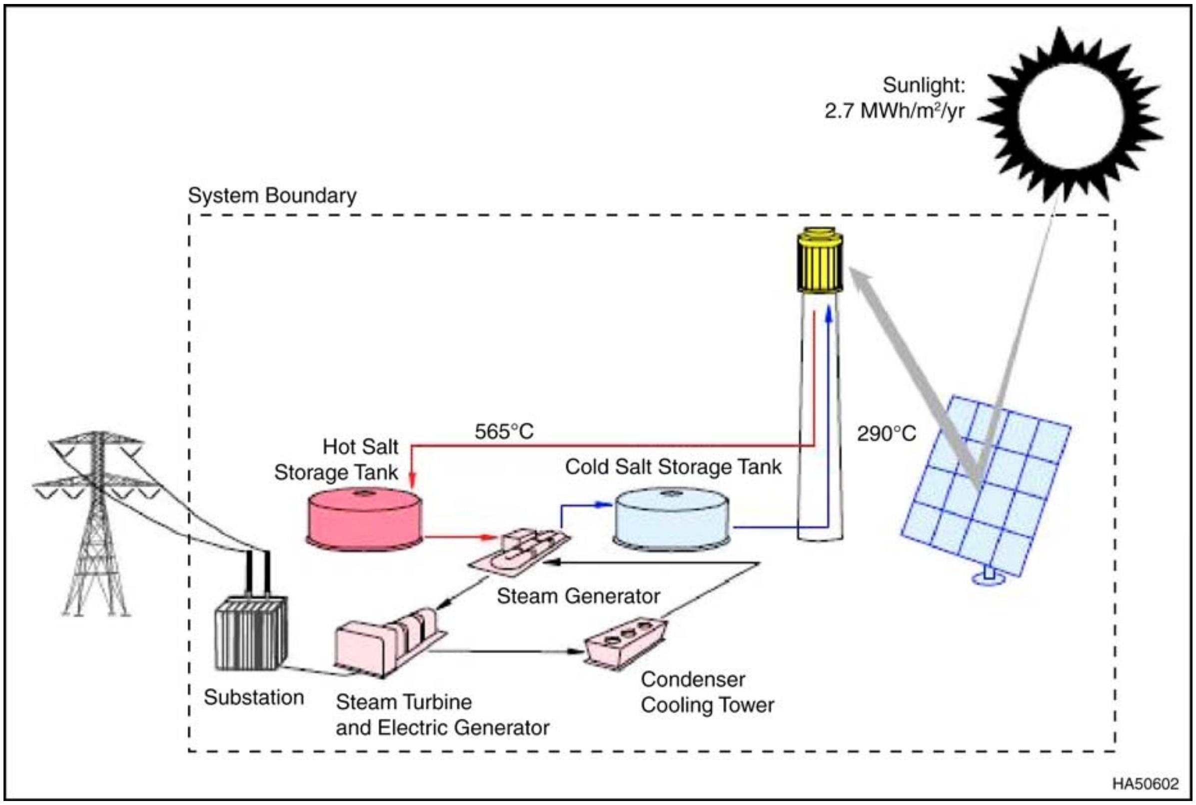

FIGURE 6 Molten Salt Power Tower Process Flow Diagram (Source: DOE/EPRI 1997)

is located at the focal point of the dish. To capture the maximum amount of solar energy, the dish assembly tracks the sun across the sky. The receiver is integrated into a high-efficiency "external" combustion engine. The engine has thin tubes containing hydrogen or helium gas that run along the outside of the engine's four piston cylinders and open into the cylinders. As concentrated sunlight falls on the receiver, it heats the gas in the tubes to very high temperatures, which causes hot gas to expand inside the cylinders. The expanding gas drives the pistons. The pistons turn a crankshaft, which drives an electric generator. The receiver, engine, and generator comprise a single, integrated assembly mounted at the focus of the mirrored dish.

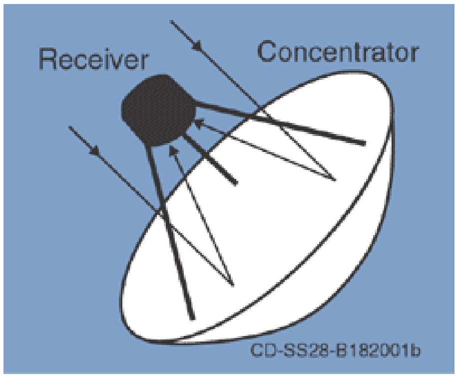

FIGURE 7 Dish/Engine System Schematic (MMS 2006)

This technology is the oldest of the solar technologies, dating back to the 1800s when a number of companies demonstrated solar-powered steam engines based on the Rankine and Stirling engine designs. Dish output may range from 2 to 25 kW of electricity. Dishes can be used individually or in small groups to provide distributed, remote, or village power. A 250-kW plant composed of ten 25-kW dish/engine systems requires less than an acre of land (DOE 2001). Dishes also can be connected in clusters to provide dispatchable electricity ranging from

1.0 to 10 MW. A number of prototype dish/Stirling systems are currently operating in Nevada, Arizona, Colorado, and Spain (Sargent & Lundy LLC 2003).

Solar Photonic Technology

Solar photonic technology converts solar energy into useful energy forms by directly absorbing solar photons—particles of light that act as individual units of energy—and either converting part of the energy to electricity (as in a PV cell) or storing part of the energy in a chemical reaction (as in the conversion of water to hydrogen and oxygen). In the latter case, the use of biological organisms (photobiological approaches) or semiconductor-based systems (photoelectrolysis approaches) might be options for solar photoproduction of hydrogen. However, solar photonic technology approaches that store energy in chemical reactions are all at early stages of development (OECD/IEA 2006). Thus, none are described in this White Paper.

PV cells provide a viable solar photonic technology approach for generating electricity for either distributed or dispatchable applications, especially considering recent advances in concentrating photovoltaic (CPV) systems. The first PV cells were produced in the late 1950s, and throughout the 1960s they were principally used to provide electrical power for earth-orbiting satellites. In the 1970s, improvements in manufacturing, performance, and quality of PV modules helped to reduce costs and opened up a number of opportunities for powering remote terrestrial applications, including battery charging for navigational aids, signals, telecommunications equipment, and other critical, low-power needs. In the 1980s, PV cells became a popular power source for consumer electronic devices, including calculators, watches, radios, lanterns, and other small battery-charging applications. Following the energy crises of the 1970s, significant efforts also were initiated to develop PV power systems for residential and commercial uses both for stand-alone, remote power as well as for utility-connected applications. During the same period, international applications for PV systems to power rural health clinics, refrigeration, water pumping, telecommunications, and off-grid households increased dramatically, and remain a major portion of the present world market for PV products. (FSEC 2006)

PV technology converts sunlight (direct and scattered) directly into electricity when a PV cell absorbs and transfers the energy of the light to electrons in the atoms of the cell. The energized electrons escape from their normal positions in the PV material (typically a semiconductor) and move from the PV cell into an electrical circuit. Thus, PV systems generate electricity wherever the sun shines, making them especially useful for producing electricity in places where no other form of electricity is available.

The efficiencies of flat-plate PV systems (typically between 7 and 12%) are often improved by using single- or dual-axis tracking to follow the sun across the sky, thus intercepting as much direct solar radiation as possible. Surface area requirements for PV array installations are on the order of 8 to 12 m^2 per kW of installed peak array capacity (FSEC 2006). For this reason, an array of PV cells covering a very large area is required to produce dispatchable electricity using a PV system. Enough PV cells to generate 1 MW, for example, would occupy between 8,000 and 12,000 m^2 (between 2 and 3 acres). Figure 8 provides a diagram for a PV system generating dispatchable electricity. Very few of these systems have been installed, but recent announcements indicate that two new projects are scheduled to begin construction during 2006: an 18-MW project in Nevada (Solarbuzz LLC 2006a) and a 7- to 10-MW project in Colorado (Solarbuzz LLC 2006b).

CPV systems use PV cells that are designed to convert a high percentage of sunlight into electricity when they are exposed to concentrated sunlight. These cells are typically mounted in a “concentrator” that uses mirrors or lenses to focus (concentrate) sunlight onto the cells at up to 1,000 times the normal strength of sunlight. To keep the light focused, the concentrators must track the sun. The use of CPV systems allows PV cells to be much smaller and more efficient than in flat-plate PV systems. Some CPV systems have reached efficiencies as high as 26%. The primary advantages of CPV systems are high efficiency, low system cost, and low capital investment to facilitate rapid scale-up; long-term durability and reliability have not yet been demonstrated, however, for this emerging technological approach.

Currently, there are no offshore PV or CPV projects generating dispatchable electricity. However, PV systems producing distributed energy are commonplace; for example, such systems are used to power navigational aides, such as buoys, and weather collection equipment in marine settings (Figure 9).

POTENTIAL ENVIRONMENTAL ISSUES

All CSP technological approaches and PV systems require relatively large areas for solar radiation collection when used to produce dispatchable electricity at the multimegawatt scale. On the OCS, this large surface area array of solar collectors would need to be supported on some

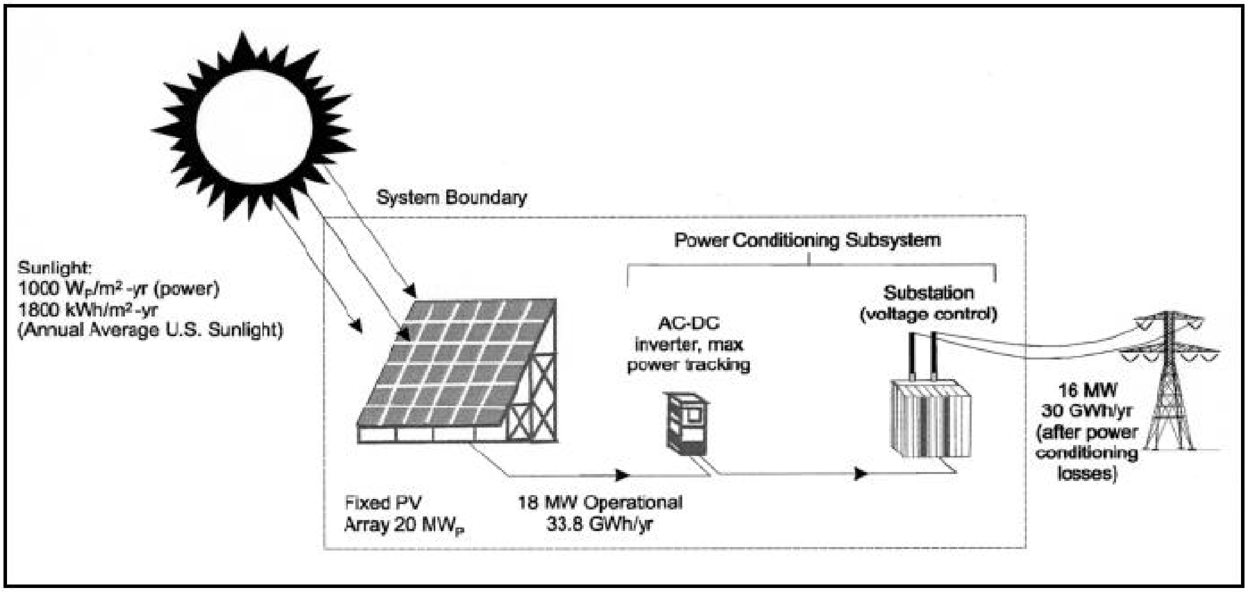

FIGURE 8 Diagram of a PV System Generating Dispatchable Electricity (Source: DOE/ EPRI 1997)

FIGURE 9 Solar-Powered Buoy Used to Collect Weather Data off the Coast of the Eastern United States (Source: NREL 2006b)

type of offshore floating or fixed structures. Such structures can be expected to have impacts, including the following:

- Interference with commercial and recreational fishing;
- Interference with recreational boating, surfing, and diving;
- Ecosystem disturbances from shading of the water surface; and
- Introduction of avian perching opportunities.

Other potential environmental impacts from CSP systems include accidental or emergency releases of toxic chemicals that may be used in the heat transfer systems; interference with aircraft operations if reflected light beams become misdirected into aircraft pathways; ecosystem disturbances from discharges related to the maintenance of cooling water systems; discharges related to the operation and maintenance of recycled steam systems; and ecosystem disturbances from construction, operation, and maintenance of both the solar energy conversion systems and the systems that transport electricity to onshore customers. Structures used for both CSP and photonic technologies in offshore applications would cause visual impacts in visible areas.

ECONOMIC CONSIDERATIONS

In 2001, the cost to provide delivered thermal energy from CSP systems operating in favorable sunlight conditions, such as those in the arid western United States, was reported to be higher than for natural gas, but was projected to be growing more competitive over time. Assumptions about the cost of natural gas were noted to strongly influence such projections (Teagan 2001). The cost for delivered thermal energy from CSP systems in an OCS setting has not been estimated. This cost would be influenced by factors affecting the competitiveness of electricity generated by using CSP systems. The cost also would be affected by the cost to construct, operate, and maintain appropriate support structures and large arrays of solar tracking mirrors in the offshore setting, and the cost to deliver produced electricity to shore. The sunlight conditions on the surface of the ocean due to humidity in the air also would be a factor because of its effect on the amount of light reaching the solar collectors.

The U.S. Department of Energy has long-term goals of reducing the end-user cost (including operation and maintenance) for large-scale PV facilities to $3,000/kW by 2010 and to $1,500/kW by 2020 (WEC 2001). Because of these comparatively high costs, the economic value of PV systems often can only be realized over many years in situations where grid power is readily available (FSEC 2006). In off-grid locations, such as on the OCS, however, there already is a proven market for PV systems to provide distributed electricity to weather collection equipment and navigational aides, such as buoys. Although the costs of the PV modules and equipment needed to provide electricity at such remote sites are high, the costs of generating and delivering electricity to those locations by other conventional means would be even higher. The costs for installing and operating large-scale PV systems on the OCS to generate dispatchable electricity have not been estimated.

SUMMARY

Solar energy can be converted to other more usable energy forms through a variety of demonstrated technologies that are divided into two categories: thermal and photonic. Dispatchable electricity can be produced using either thermal technological approaches, called CSP systems, or photonic technological approaches, called PV systems. CSP technology utilizes mirrors to focus the solar radiation so that it can be captured in the form of heat. That heat is then converted to electricity by using conventional technologies. PV technology converts sunlight (direct and scattered) directly into electricity when a PV cell absorbs and transfers the energy of the light to electrons in the atoms of the cell. PV cells may be arranged into flat-plate PV systems or CPV systems. Like CSP technology, CPV systems focus sunlight. However, rather than focusing sunlight to capture its heat energy as CSP technology does, CPV systems utilize mirrors or lenses to focus the sunlight onto PV cells designed to convert a high percentage of sunlight directly into electricity when the cells are exposed to concentrated sunlight.

Research for this paper identified no existing or planned projects for generating dispatchable electricity on the OCS with CSP or PV technologies. Existing CSP systems that might be used in this application include trough, power tower, and dish/engine. Flat-plate PV systems or CPV systems also are potential candidates for generating dispatchable electricity on the OCS.

The economic viability of generating dispatchable electricity by using solar energy on the OCS and delivering the electricity to onshore consumers has not been previously evaluated. However, there already is a proven market for PV systems to provide distributed electricity to satisfy remotely located small-scale power requirements.

The use of any solar energy technology to generate dispatchable electricity on the OCS would require that large areas be occupied for solar radiation collection, which would necessitate construction of some type of floating or fixed support structures. The presence of such structures could have environmental effects. In addition, operation of CSP systems could result in releases of pollutants to the water. PV systems, whether used to generate dispatchable or distributed electricity, are unlikely to release pollutants.

REFERENCES

Florida Solar Energy Center (FSEC), 2006, "Photovoltaics & Distributed Generation, Photovoltaic Fundamentals." Available at http://www.fsec.ucf.edu/pvt/pvbasics/. Accessed April 27, 2006.

Minerals Management Service (MMS), 2006, "OCS Renewable Energy and Alternate Use Programmatic EIS Information Center, Offshore Solar Energy Web Page." Available at http://ocsenergy.anl.gov/guide/solar/index.cfm. Accessed May 10, 2006.

Morse, F.H., and M.K. Simmons, 1976, "Solar Energy," *Annual Review of Energy* 1:131–158, Palo Alto, Calif.

National Aeronautics and Space Administration (NASA), 2003, "The Inconstant Sun." Available at http://science.msfc.nasa.gov/headlines/y2003/17jan_solcon.htm. Accessed April 23, 2006.

National Renewable Energy Laboratory (NREL), 2006a, "Dynamic Maps, GIS Data, & Analysis Tools, Solar Maps." Available at http://www.nrel.gov/gis/solar.html#csp. Accessed April 27, 2006.

NREL, 2006b, "Photographic Information Exchange." Available at http://www.nrel.gov/data/pix/. Accessed May 5, 2006.

Organization for Economic Cooperation and Development/International Energy Agency (OECD/IEA), 2006, *Hydrogen Production and Storage R&D Priorities and Gaps*, Hydrogen Coordination Group, Paris, France.

Sandia National Laboratories, 2001, *Research and Development Advances in Concentrating Solar Power*, SAND2001-3228P, Albuquerque, N.M., Dec.

Sargent & Lundy LLC, 2003, *Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts*, SL-5641, prepared for the U.S. Department of Energy and National Renewable Energy Laboratory, Chicago, Ill., May.

Solarbuzz LLC, 2006a, "Las Vegas, NV, USA: World's Largest Photovoltaic Project Planned in Nevada," Feb. 2. Available at http://www.solarbuzz.com/news/NewsNAPR611.htm.

Solarbuzz LLC, 2006b, "Denver, CO, USA: Xcel Energy Solicits Bids for Colorado's Largest Solar Facility," March 31. Available at http://www.solarbuzz.com/news/NewsNAPR627.htm.

Teagan, W.P., 2001, *Review: Status of Markets for Solar Thermal Power Systems*, Arthur D. Little, Cambridge, Mass., May.

U.S. Department of Energy (DOE), 2001, "Concentrating Solar Power: Energy from Mirrors," DOE/GO-102001-1147, March 2001. Available at http://www.nrel.gov/docs/fy01osti/28751.pdf.

U.S. Department of Energy and Electric Power Research Institute, Inc. (DOE/EPRI), 1997, *Renewable Energy Technology Characterizations*, TR-109496, Dec. Available at http://www.nrel.gov/docs/gen/fy98/24496.pdf.

World Energy Council, 2001, "2001 Survey of World Energy Resources." Available at http://www.worldenergy.org/wec-geis/publications/reports/ser/overview.asp.