United States
Department of
Agriculture

Economic
Research
Service

Agricultural
Economic Report
Number 482

Solar- and Wind-Powered Irrigation Systems

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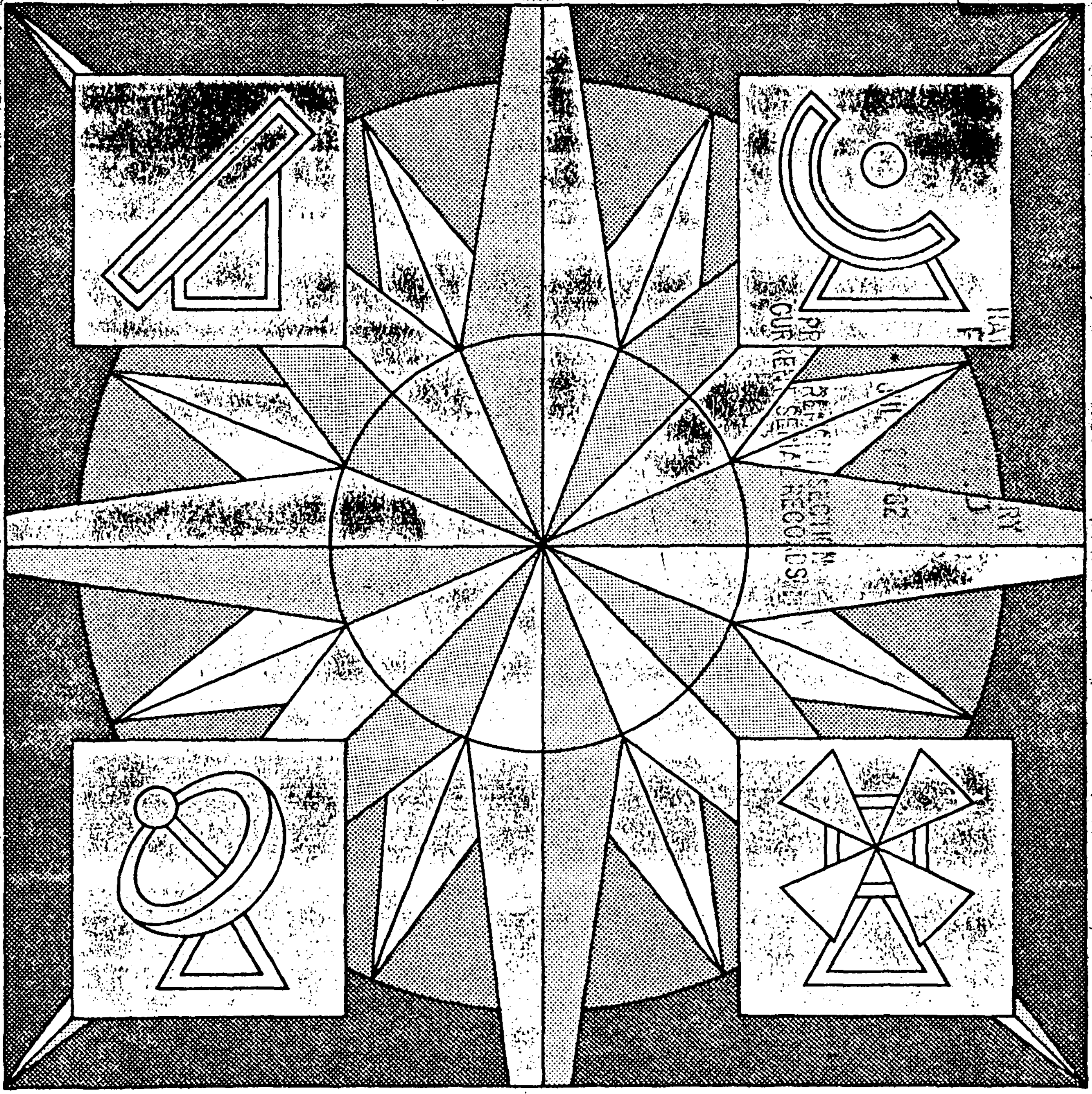

SOLAR- AND WIND-POWERED IRRIGATION SYSTEMS.

Robert V. Enochian. National Economics Division, Economic Research Service, U.S. Department of Agriculture. Agricultural Economic Report No. 482

Abstract

Five different direct solar and wind energy systems are technically feasible for powering irrigation pumps. However, with projected rates of fossil fuel costs, only two may produce significant unsubsidized energy for irrigation pumping before the turn of the century. These are photovoltaic systems with nonconcentrating collectors (providing that projected costs of manufacturing solar cells prove correct); and wind systems, especially in remote areas where adequate wind is available.

Keywords: Energy, solar energy, photovoltaics, wind energy, irrigation pumping.

Washington, D.C. 20250 February 1982

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Summary

Onsite solar energy systems are technically feasible for pumping water to irrigate farm crops. However, out of five direct solar and wind-powered irrigation systems studied, only two may be economically feasible before the turn of the century.

The two systems that appear capable of economically producing significant energy by 2000 are:

- Photovoltaic (solar cell) systems using nonconcentrating collectors, provided that projected costs of fossil fuel and projected costs of manufacturing solar cells prove to be correct; and

- Wind-powered systems. Wind systems may already be feasible in remote areas where electric utility power is unavailable, where the transport of fossil fuel is difficult and costly, and where adequate wind is available.

It is important to find technically and economically feasible ways of using solar energy for irrigation pumping for two primary reasons:

- Irrigation pumping uses large quantities of energy currently provided by nonrenewable fossil fuels; and

- Solar energy is particularly compatible with irrigation. The maximum need for irrigation occurs at times, and in locations, of maximum solar radiation (insolation), such as during summers in the Southwestern United States. Conversely, less water evaporates from crops and land during periods of lower insolation—when solar energy would be less available for powering irrigation systems.

The five solar irrigation systems reviewed in this report include solar thermal systems which use either (1) concentrating or (2) nonconcentrating collectors to convert direct solar energy into mechanical energy and then, in some configurations, to electrical energy; systems that use photovoltaic (solar) cells to convert solar energy directly into electricity using (3) concentrating or (4) nonconcentrating collectors; and (5) wind energy systems which produce either mechanical or electrical energy for powering irrigation pumps.

Solar- and Wind-Powered Irrigation Systems

Robert V. Enochian*

Introduction

Irrigating the world's farmland takes a large amount of energy. Irrigation operations in the United States use about 20 percent of all the energy used by farms for direct production operations. Conserving this use of energy and replacing fossil fuels used for irrigation with renewable sources of energy can have worldwide benefits by improving trade balances, by reducing inflationary pressures, and, especially, by lowering the costs of producing farm crops.

This report reviews the technical and economic feasibility of the two basic systems of using direct solar energy for irrigation pumping (with two variations of each), along with the use of wind energy for irrigation. It also presents a brief review of the utilization of energy for irrigation pumping and the practices that can be adopted by pump irrigators to conserve energy used for this important production operation.

The two direct solar systems with their variations are solar thermal and photovoltaic (solar cell) systems with concentrating and nonconcentrating collectors. All of the systems are found to be technically feasible; however, only two seem to have the potential of economically producing significant quantities of energy before the turn of the century. These two are the photovoltaic system with nonconcentrating collectors and wind systems, especially in remote areas.

This review will be useful to pump irrigators for identifying those solar systems which might have the greatest feasibility the soonest. It will also provide policymakers, research administrators, and research workers with information that will help them decide which solar irrigation technologies might be the most deserving of future research support.

Energy Requirements for Irrigation

The number of irrigated acres worldwide rose from 1 million in 1900 to about 561 million in 1976, and is expected to continue rising (*32*).[1] In the United States, more than 35 million acres of farmland were irrigated in 1974 with 69 million acre-feet of onfarm pumped water from both ground water (wells) and surface water (lakes and rivers) sources. Land irrigated with pumped water accounts for just over 10 percent of the Nation's harvested acres. However, in 1969, irrigated farmland accounted for 25 percent of all farm commodity sales (*78*). The 17 westernmost States contained over 80 percent of the land irrigated with pumped water in 1974; with over 50 percent of the pump irrigated land concentrated in Texas, Nebraska, and California (*31*). See figure 1 for a display of these 17 States.

The combined direct energy from all sources used for pumping this water was estimated to be over 260 trillion British thermal units (Btu's) in 1974, not including the energy lost in generating and transmitting the electricity that was used (*78*). This represents about 20 percent of all energy used by farms in the United States for direct production operations. In Texas and California, an estimated 40 percent of all energy used for direct production operations goes for irrigation pumping (*23*, *92*). These calculations exclude the indirect energy used in the manufacture of farm fertilizers, pesticides, and farm machinery.[2]

The energy required for irrigation pumping depends on the number of acres irrigated, the amount of water applied per acre, the height the water is lifted, and the method used to distribute or apply the water (*66*, *78*). In addition to surface (gravity flow or flood) application, which currently represents the largest area irrigated with pumped water, various types of pressurized (sprinkler and

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[1] Italicized numbers in parentheses indicate items in References section.

[2] Estimates of energy used for the manufacture of fertilizers and pesticides can be found in (*31*).

drip) irrigation systems are in use. The use of sprinkler systems is increasing rapidly because surface application is not practical on certain types of soil, terrain, or crops, and requires large amounts of labor, which is costly and in short supply (*78*). Although pressurized systems require more energy per unit of water applied than surface irrigation, the overall energy and economic efficiencies of surface irrigation apparently are lost as water lift increases to over 250 feet (*20, 77*). Thus, as the depth of farm wells increases, pressurized systems of irrigation become more cost effective than surface irrigation.[3] The energy intensities for irrigation in each of the Western United States is shown in figure 1. These intensities result from the relationship among pumping depth, proportion that ground water is of total water supplied to agriculture, and method of water application.

In 1974, total U.S. expenditures for energy used for onfarm irrigation systems were estimated at $594 million *(78)*. By 1977, these expenditures had risen to $800 million, with approximately $700 million expended in the 17 westernmost States *(66)*. This increase was due mostly to increased prices for fossil fuels used for generating pumping energy and due partially to shifts to systems requiring higher amounts of energy.

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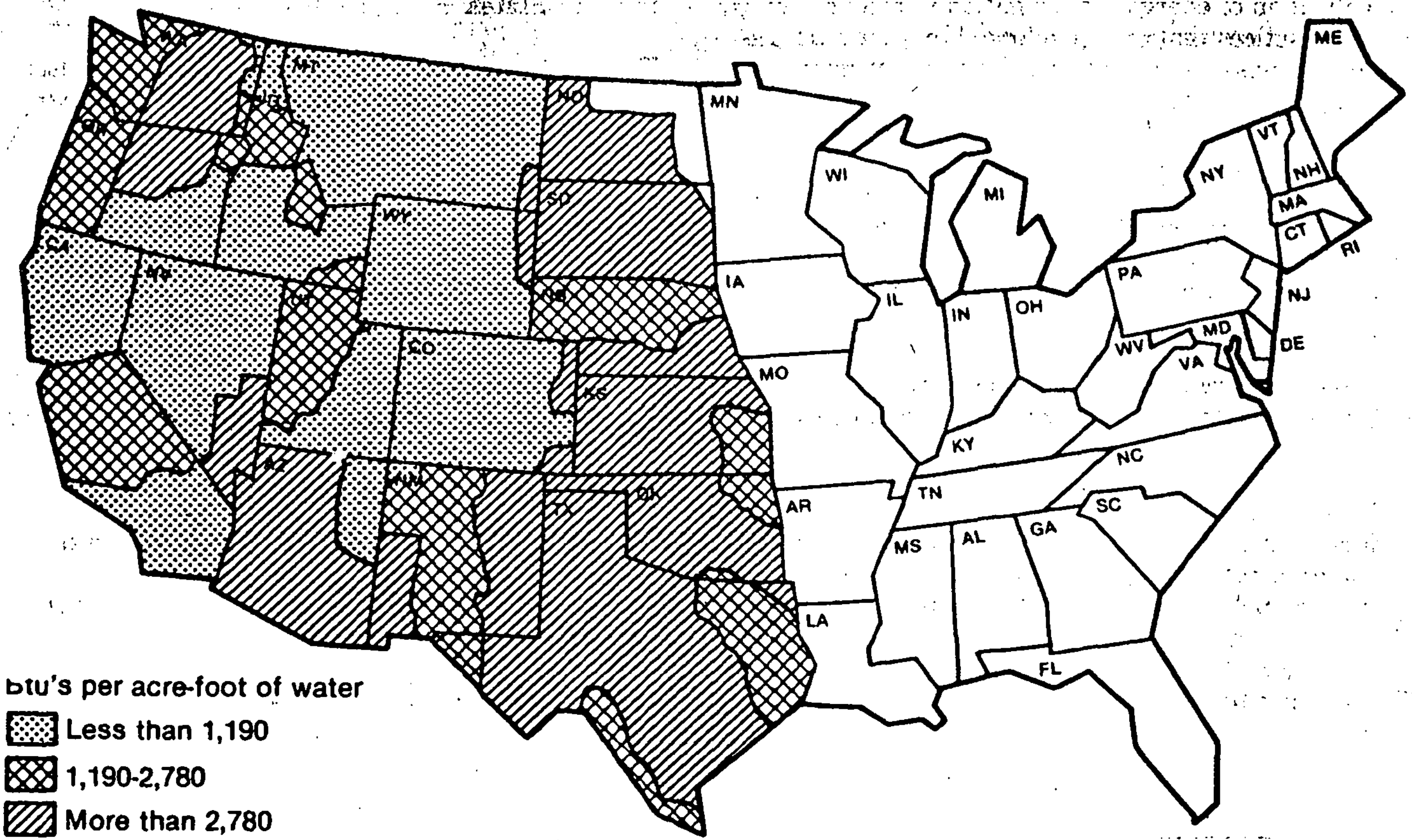
[3] Since the quantity of water applied by sprinkler systems that is pumped from wells over 250 feet in depth is unknown, the possible increase in the cost of energy used for irrigation attributable to the shift to sprinkler systems cannot be estimated.

Figure 1

Irrigation Energy Intensities in the Western United States



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Conserving Water and Energy: Dual Goals

Ground-water tables are declining steadily, and there is an increasing demand for water by industrial users as well as agricultural users. So as fossil fuel supplies become more limited and more costly, farmers who use pump irrigation will attempt to reduce costs by adopting practices that conserve both energy and water.

The amount of water used for irrigation is partly controlled by a crop's consumptive water use, that is, the water required for building plant tissues, for the natural transpiration of the plant, and for the evaporation from soil adjacent to the plant. However, the quantity of irrigation water used also depends on a number of factors controlled by irrigation practices. These include local irrigation customs, water availability, labor availability, seepage and evaporation from canals and ditches, surface runoff, unnecessarily deep percolation of water into the soil, and losses and waste caused by poor management. On lands irrigated by surface distribution, it has been estimated that one to three times the amount of water actually needed to satisfy consumptive use may be lost in the process of delivering and applying water to the land *(13)*.

There are several practices farmers can use to save energy directly and to use water more effectively. For example, more timely adjustment or repair of irrigation pumps could improve pump efficiency. Farmers in some locations could shift pumping loads to times that electricity rates are lowest. In addition, some farmers could change to cropping patterns which require less water, while others could improve irrigation practices to make more efficient use of water. Comprehensive discussions of conservation practices for farmers who use pump irrigation can be found in *(4, 24, 77)*.

Most energy planners agree that conservation of energy is more cost effective than developing new sources of energy *(39)*. Improved selection and maintenance of irrigation facilities can reduce pump-size requirements and improve overall efficiency of the system. Some authorities believe that input energy for irrigation can be reduced by as much as 40 to 50 percent *(23, 25)*. However, at present energy prices, not all of the currently known irrigation system conservation practices are cost effective because of the large capital investment and nonenergy operating costs required to adopt such practices *(23, 77)*. Nevertheless, since the potential for energy savings is so great, research on irrigation systems which can conserve both water and energy is receiving high priority by the agricultural research establishment.

The USDA and State agricultural experiment stations are currently conducting over 100 research projects concerned with more efficient use of irrigation water, and, thereby, more efficient use of energy *(73)*. For example, a new closed-conduit irrigation system has been developed that reduces water requirements while operating at pressures no greater than those required by surface application and costing no more than other sprinkler or drip irrigation systems *(74)*.

Irrigating with Solar and Wind Energy

In both developed and developing countries around the world, attention is being focused on improved systems for using solar and wind power to provide energy for a number of tasks, including the powering of irrigation pumps. A major purpose of the solar irrigation projects that are now either in operation or are planned is to develop performance data that can be used to improve system design.

A Brief History

People used water lifted from wells, lakes, and rivers for irrigating fields long before the discovery and widespread use of fossil fuels for this purpose *(26, 29)*. Initially, the power for lifting water for these first irrigation systems was provided by humans. Later, these primitive systems were powered by bullocks, camels, or donkeys. Many of these human and animal-powered systems are still in widespread use in the developing countries of the world.

Eventually, ways were found to use wind power to do some of the work. Vertical-axis windmills have been used in Persia for grinding grain and lifting water since the first millenium A.D. and, before the widespread use of fossil fuels, windmills were used extensively for lifting water throughout the world *(57)*. In many areas, including North America, wind power continues to be used for lifting water, but only for providing drinking water for livestock or for use by farm households.

Throughout the past four centuries, a number of recorded experiments have used direct solar energy to lift water for irrigation purposes. Perhaps the earliest of these was described by the French engineer, Solomon de Caux, in 1615 *(65)*. Another example was in about 1885, when solar thermal energy was used to power an apparatus at Auteuil, France, which lifted over 300 gallons of water per hour from a depth of 65 feet using 350 square feet of solar collecting area *(17)*. In the United States in 1907, and again in 1911, near Philadelphia, Pa., F. Shuman developed solar steam engines of several horsepower which were used to pump water. And in 1913, near Cairo, Egypt, F. Shuman and C. V. Boys built a large solar-powered system of over 50 horsepower that powered a heat engine and pumped irrigation water from the Nile River *(26)*. References to other recorded early experiments on using solar thermal energy for irrigation pumping can be found in *(26, 48, 65)*.

After World War I there was a gap in research efforts because of the ready availability of cheap, convenient-to-use fossil fuels. However, interest in the use of solar energy for irrigation pumping was revived in the late fifties and early sixties *(65)*. The impending shortages and higher prices for fossil fuels contributed to this renewed interest as did the growing interest in increasing food production by providing irrigation water to remote arid lands, particularly in the developing countries.

Since the renewal of interest, a number of solar irrigation systems have been built or planned, in both the United States and other countries. Many of these are demonstration projects, but in some of the developing countries—especially Africa and Latin America—there are already solar thermal-powered pumping systems providing small villages with water for drinking and irrigating.

Systems Under Consideration

The solar projects built since the sixties or now being planned have emphasized flat-plate, or focusing, tracking collectors for collecting solar energy. Solar ponds and cylindrical transparent collectors also are receiving consideration. All of these collectors heat a transfer fluid which then heats a working fluid to power a heat engine which generates either mechanical power or electricity to power a pump. Photovoltaic and thermovoltaic systems are also receiving considerable research attention. These convert solar radiant energy directly into electricity which is then used to drive an electric motor connected to a water pump.

Agricultural biomass is an energy source derived indirectly from the sun which can also be used for irrigation pumping *(84, 94)*. The biomass approach uses plant or animal residues to produce methane gas, or grain and sugar crops to produce alcohol, which can then be combusted in an internal combustion engine to power a water pump. Texas A & M University has initiated work on biomass as a possible source of energy for irrigation pumping *(22)*; but because of the relatively minor attention biomass has received for this purpose to date, it is not considered in this report. Furthermore, since gas or alcohol produced from biomass is easily stored and transported, the use of biomass does not have to be confined to a specific site as does the initial mechanical energy produced by the solar thermal or wind systems dealt with in this report.

Other solar energy systems for powering irrigation facilities are possible both for onsite generation of power and centralized generation systems from which the power would be distributed through a public utility grid. Centralized power generation systems, which can provide energy for irrigation pumping, are outside the scope of this study. With regard to other possible onsite systems, such as photochemical conversion or wind-powered hydrogen production, no references were found during this review to the use of such systems for powering irrigation facilities.[4]

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[4] For a comprehensive overview of solar energy systems that have the potential for providing significant quantities of energy by the year 2000, refer to *(91)*. It describes research and development programs and implementation scenarios for six technically feasible solar energy technologies for heating and cooling, providing high temperature heat, and producing mechanical and electric power or clean fuels.

Solar Thermal Irrigation Systems

In recent years, several systems for converting solar thermal energy to mechanical and then, in some systems, to electrical energy for pumping water have been found to be technically feasible. The basic difference in these systems is in the design of the solar collector—some concentrate or focus the sunlight and some do not.

The remainder of this section describes the basic design of solar thermal systems that have been used in irrigation pumping experiments and evaluates the engineering and economic aspects of these systems.

System Design

The basic configuration of the solar thermal energy systems used for pumping water, as well as for other purposes, is similar. Specific components may vary but, in general, the systems consist of a solar collector which heats a fluid, called a transfer fluid. This transfer fluid circulates through a closed system with its flow controlled by temperature sensors and valves. When heated to the appropriate temperature, it enters a heat exchanger and heats another fluid, called the working fluid, which is contained in another closed system. When the working fluid is heated, it vaporizes into a gas which is under pressure. The expanding gas drives a turbine coupled directly to a water pump or to an electric generator for powering the pump. The gas is then condensed and returned to the heat exchanger/vaporizer to complete the cycle.

In order to operate such a system during periods of low solar radiation (insolation) or at night, either a thermal storage tank, an auxiliary boiler, or both can be introduced, usually between the solar collector and the heat exchanger/vaporizer. Other means of providing irrigation water to crops for short periods of low or nonexistent insolation are to store the pumped water in a reservoir instead of pumping it directly for irrigation, or to store electricity produced by the system in batteries.[5]

A schematic of a solar-powered system for pumping irrigation water using mechanical energy for powering the pump is shown in figure 2. An electric generator could be introduced between the turbine and the pump shown in this schematic for providing electricity to drive the pump. An advantage of such a modification is that electric power provides greater flexibility in utilizing the system for other purposes when it is not needed for irrigation. In addition, surplus electricity can be channeled into the local electric power grid and sold to the electric utility company. This practice is generally more efficient than energy storage.

Collector Design

The basic component of a solar thermal energy system is the solar collector. A number of different types of collectors have been designed and tested but design concepts are changing so rapidly that selecting an optimum design is difficult.[6] Factors that need to be taken into consideration are the available space, the availability of direct and indirect sunshine, and the compatibility of the collector output with the other components of the system. There are two general categories of collector design: nonconcentrating and concentrating.

The most common type of nonconcentrating solar collector is the flat plate collector which uses water mixed with antifreeze as the heat transfer medium. Another nonconcentrating collector design is the solar pond. This is a shallow pond dug in the earth, lined with black plastic, partly filled with concentrated saltwater, and then topped with a layer of fresh water. The concentrated saltwater collects the sun's heat and acts as the heat transfer fluid. The top layer of water acts as an insulator to keep the heat from escaping from the concentrated saltwater layer. Research is underway to reduce the problem of the two layers mixing, especially when there is air turbulence. These nonconcentrating collectors provide fairly low temperatures and, therefore, their use in operating heat engines (turbines) is limited.

Systems which concentrate the sun's rays are the most effective users of heat energy because they

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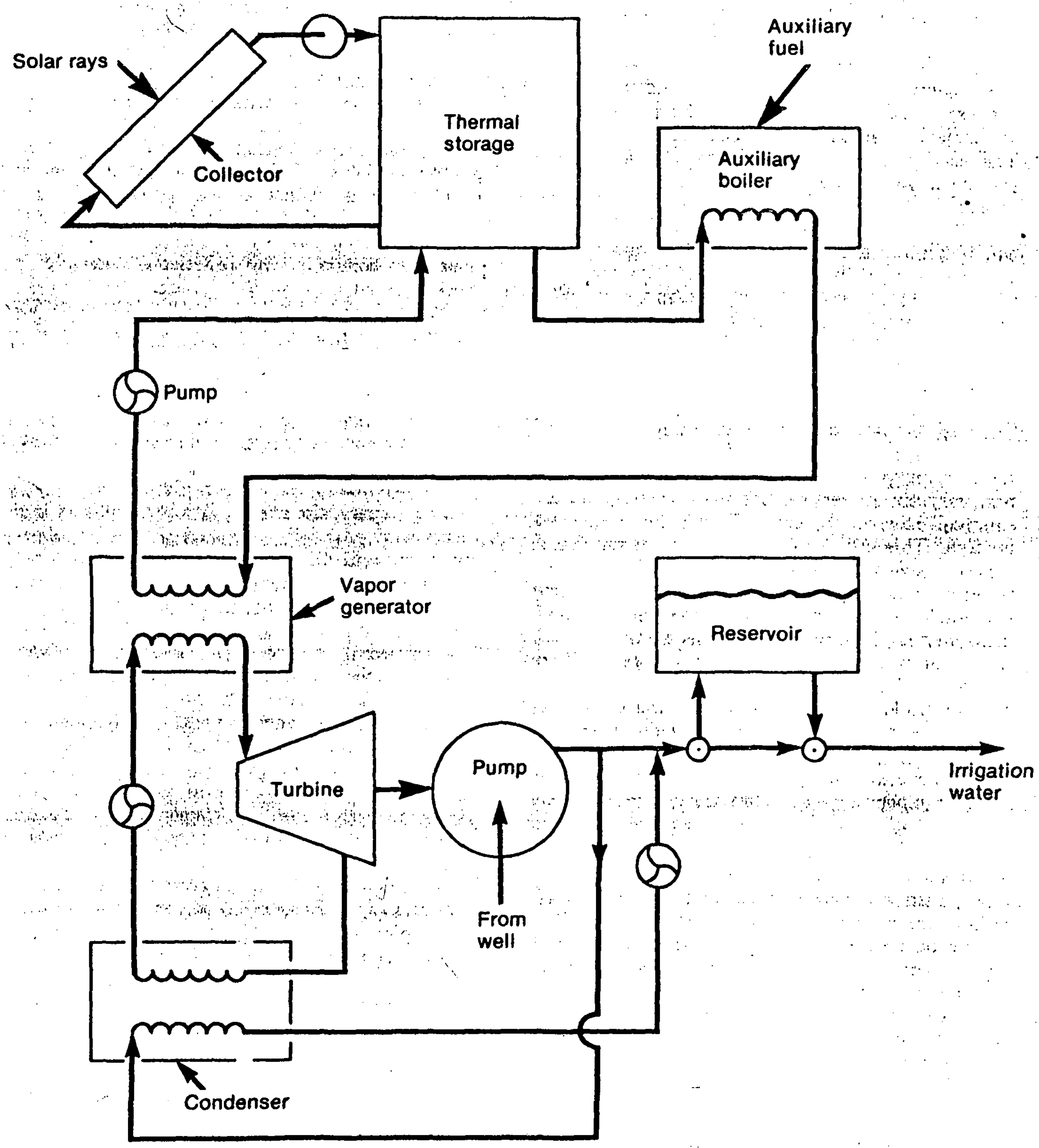
[5] A comprehensive discussion of various means of storing energy generated by solar systems is contained in *(67)*.

[6] A comprehensive discussion of a wide array of collector designs and heat engines is contained in *(67)*. A brief description of collector designs is contained in *(86)*.

Figure 2

Schematic of Solar-Powered Irrigation Pumping System



Source: (81)

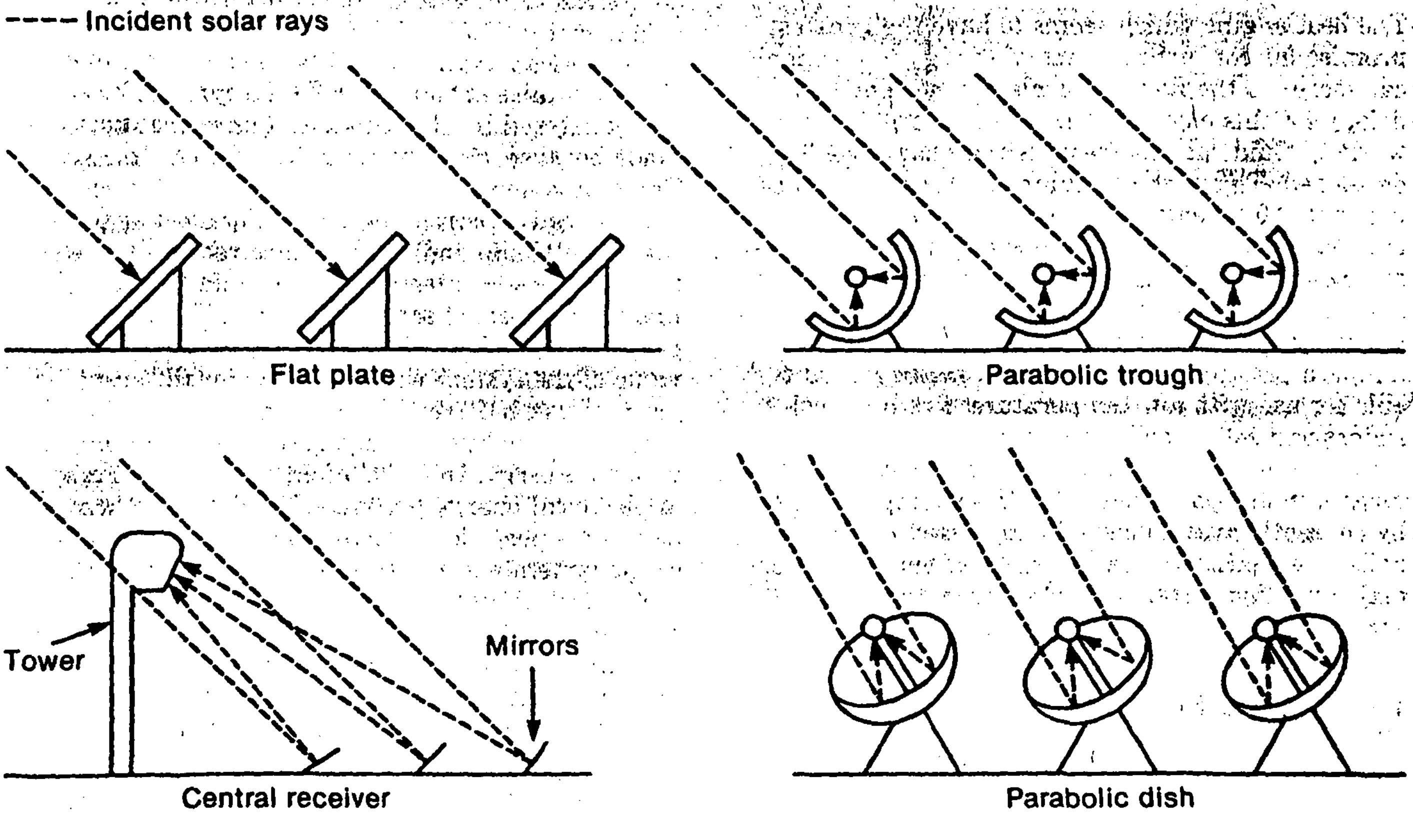
lso track the sun for optimum performance (fig.). They have received the greatest attention in olar-powered irrigation experiments, especially in he United States. Some engineering problems xist with these systems and high investment costs make them impractical for powering irrigation ystems at the present time. The widespread use of these systems will depend upon substantial anticipated cost reductions resulting from economies of arge-scale manufacture of components and from the resolution of engineering problems that will improve system efficiency.

There are a number of variations but the three common concentrating collector designs are the parabolic trough, the parabolic dish, and the central receiver which is mounted on a tower and receives reflected sunlight from a field of mirrors. All of these concentrating collectors have reflector surfaces which focus the incident solar rays onto a receiver which contains the transfer fluid. The transfer fluid is usually water containing antifreeze, or some type of oil.

A variation of the parabolic trough does not track, and consists of a cylinder made of a transparent synthetic material with a thin aluminum reflector on the bottom half. A metal tube, situated on the longitudinal axis, carries the transfer fluid. Another type of concentrating collector is the Fresnel lens, which has a short focal length yet large diameter, such as those used in searchlights and automobile headlights.

Figure 3

Types of Solar Collectors Most Commonly Used in Irrigation-Related Experiments



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Heat Engines

Thermal energy concentrated by solar collectors must be converted into mechanical energy for powering an irrigation pump directly or for powering an electric generator to drive the pump. A number of devices for converting thermal energy into mechanical energy are available and can be utilized for solar thermal systems.

The basic differences in these devices are the type of working fluid used (organic, water, or gas) and the temperature at which they operate. Theoretically, the higher the operating temperature, the higher the thermodynamic efficiency of heat engines. However, in selecting a heat engine, consideration must be given to the overall efficiency and cost of producing energy. Collector costs for a lower temperature cycle may be lower and, in actual operation, efficiency does not necessarily increase proportionately with increasing temperature *(67)*.

The heat engine which seems to have the greatest promise for converting thermal energy to mechanical energy is the Rankine-cycle engine. The technology for this engine, which uses an organic working fluid such as freon, is reasonably well-developed. This type of engine has been used since the early 19th century for powering everything from steamboats to electric power plants using nuclear energy and is most commonly used for generating stationary power *(67)*. With current technology, the Rankine-cycle engine can operate at temperatures up to 1,100°F, thus, making it suitable for use with low-temperature, flat plate collectors and solar ponds as well as with concentrating solar collectors that produce higher temperatures. Limitations above 1,100°F are imposed only by currently available steel alloys used in most boilers and other components. All of the solar thermal irrigation systems referred to in the current literature use the Rankine-cycle heat engine.

Experimental Systems

Some solar thermal systems are in use for pumping water, model systems have been developed for evaluation, and demonstration projects are being operated or are under construction, especially in the Southwestern United States.

SOFRETES Systems. Several solar thermal prototype systems are already pumping water in a number of Latin American and African nations and more are under construction in these countries. These sytems were designed and installed primarily by a French firm, Societe Francaise d'Etudes Thermiques et d'Energie Solaire (SOFRETES). The systems use flat plate collectors and organic fluid, Rankine-cycle heat engines and have generating capacities ranging from 1 to 50 kilowatts *(79)*. One of these systems, installed in the Mexican town of San Luis de la Paz, produces about 25 kilowatts of electrical energy and pumps about 330,250 gallons of fresh water daily *(14, 15)*. A proposal for a larger system that can pump 1.7 million gallons of irrigation water per day from the Senegal River in Africa has been prepared by SOFRETES and the Thermo-Electron Corporation of Waltham, Mass. *(83)*. Funding for this proposal is to come from the Government of Senegal, from the French Government's foreign aid agency, Fonds d'Aide a la Cooperation (FAC), and from the U.S. Agency for International Development (USAID).

The economics of the SOFRETES systems have been analyzed but firm conclusions cannot be made because of the many unknowns *(14, 15, 83)*. These unknowns include such things as future interest rates, petroleum and utility electric power costs, useful life and maintenance requirements for these relatively untested systems, and future manufacturing costs of solar equipment. For the proposed Senegal River installation, the net present value of the system was estimated for different years of use, different discount rates, and different average annual percentage rates of change in the value of energy. In 1979, when the projected cost of electrical energy produced by diesel fuel was 58.0 cents per kilowatthour, the net present value of the system was equal to or greater than the estimated actual cost only when the years of system use were 20 or more, the discount rate was 10 percent or less, and the projected annual rate of increase in energy costs was more than 10 percent *(83)*. In any case, most of the installed SOFRETES systems are currently supported by government subsidies in one form or another, as are most systems used for generating electricity in the countries in which SOFRETES systems are being installed.

Ormat Turbines Ltd. Systems. Another solar thermal water pumping system, developed by an Israeli firm, Ormat Turbines Ltd., couples an organic fluid, Rankine-cycle engine with a cylindrical concentrating collector, half of which is a transparent synthetic material and the other half an aluminum reflector. This system is used to produce electricity, which then operates a standard well pump *(68)*. Ormat has proposed a joint venture with the Lawrence Livermore Laboratory in Livermore, Calif., to evaluate and further develop this system *(69)*. The end result of this project is to be an operating 50-kilowatt system to demonstrate the feasibility of using solar energy to pump irrigation water in California. Cost estimates for this system are incomplete *(69)*.

Lawrence Livermore Laboratory Systems. The Lawrence Livermore Laboratory, supported by the U.S. Department of Energy (DOE), has modeled and evaluated the feasibility of a 150-kilowatt irrigation pumping plant using shallow solar ponds as collectors coupled with an organic fluid, Rankine-cycle heat engine *(71)*. The purpose of this model was to test the concept that savings in collector costs might more than offset the lower efficiency of converting thermal to mechanical energy with low-temperature collector arrays. Calculations of energy output were made using data from engineering studies for the Rankine-cycle engine and weather data from meteorological records for Inyokern, Calif., April through October 1962.

Once the physical plant was specified and the system's components were costed, computer simulation was used to arrive at costs of generating energy based on assumed system life and depreciation, interest, and tax rates. These costs were then compared with the costs of purchased electric power and of other solar irrigation systems. The authors concluded that shallow solar ponds, coupled with the organic fluid, Rankine-cycle engine were the lowest cost solar thermal power system proposed up to the time of the study (April 1978). However, such a system can only show an economic advantage over purchased electric power if the cost of power were to inflate more than 8 percent faster than the components needed for the solar system. At a 17-percent differential inflation rate, investment in this type of system would return 10 percent, based on the assumptions used. If such extreme conditions occur, the economic and social problems associated with them would, in the authors' words, "complicate the rate-of-return analysis." Nevertheless, a similar system is already in operation in Israel where there are plans to install many such systems *(42)*. The economics of these systems under Israeli conditions were not specified.

Texas Tech University Systems. In 1976, Texas Tech University, operating under a grant from the National Science Foundation through the Agricultural Research Service of the U.S. Department of Agriculture, modeled and evaluated solar energy systems for operating feedmills and irrigation facilities *(80, 81)*. After evaluating a variety of possible solar collector configurations and power cycle and energy storage options, the authors concluded that the central receiver collector system (fig. 3) was more capital cost effective than other collector types for both electric power and process heat generation, and selected it for evaluation in the study. The power cycle chosen was the Rankine steam cycle. Storage of the fluid heated by the solar collector to keep the system operational during periods of low insolation was determined to be more cost effective than either storage of pumped water in a reservoir or no storage (fig. 2).

An economic analysis of a 100-kilowatt solar-powered irrigation system using the most cost effective configuration, as specified above, indicated that the system would be economically feasible only if the cost of fossil fuel escalates at an annual rate in excess of 18 percent. This result was generally true for both the High Plains Region of Texas and the Pinal County Region of Arizona. According to the authors *(81)*, it is reasonable to assume that maximum annual fuel cost increases will not be above 10 percent for prolonged periods, leading them to the conclusion that the onsite use of solar energy for irrigation pumping is not economically feasible at the present time.[7]

The authors attribute the poor economic feasibility of the system to two factors and suggest solutions.

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[7] USDA and DOE project annual fuel cost increases of 4 to 8 percent above the rate of inflation for the near future.

One factor is that an onsite solar irrigation system in the areas considered would have a low utilization factor because it would only be used about 100 days per year. The other factor is that the system is relatively inefficient because of its small size. The authors suggest that both problems can be rectified by building large-scale solar power plants tied into the local utility grid. They also suggest that if the onsite system concept is pursued, an effort should be made to lower capital costs by improving cycle efficiency, by lowering component costs, and by utilizing the system for other purposes, including selling power to the utility company when it is not being used for pumping irrigation water.

Arizona State University Studies. A study of the feasibility of utilizing solar energy for irrigation pumping conducted at Arizona State University concluded that solar energy will be cost competitive with alternative energy sources if these sources increase in price at a rate greater than interest rates and the solar power plant is fully utilized *(47)*.

Another Arizona State University study concluded that the cost competitiveness of onsite solar irrigation systems can be improved by changing pumping schedules, using the solar system only to provide the base energy supply, supplemented by auxiliary sources, and by developing other uses for the energy output during periods that the system is not being used for pumping *(45)*. Even with these improvements, however, the final conclusion was that lower investment and lower operating and maintenance costs are required to make solar energy (for onsite irrigation pumping) competitive with alternative energy sources.

NML/Battelle System. In April 1977, the Northwestern Mutual Life Insurance Company (NML) and Battelle Memorial Institute began operating what was described as the world's largest solar-powered irrigation system at NML's Gila River ranch, southwest of Phoenix, Ariz. The system was developed and installed over a 2-year period by Battelle. Design and optimization of the system involved computer modeling to select the optimum combination of components. It consisted of 5,500 square feet of parabolic tracking solar collectors, an organic fluid, Rankine-cycle heat engine, and a 50-horsepower pump capable of delivering up to 10,000 gallons of irrigation water per minute at peak operation. The system made no provision for energy storage, thus was capable of operating only on cloudless days. At night, and during hailstorms, the collectors automatically stowed in an inverted position to protect the surface against weather damage and to minimize the effects of condensation, which reduces collector efficiency. A full description of the system and performance characteristics is contained in *(7, 16, 53)*.

The NML/Battelle system was operated and evaluated during the 1977 season, at the end of which it was concluded that solar energy is not yet an economical answer to rising electricity costs. The research team suggested that solar energy may have a chance of being competitive (with other means of producing mechanical power) by 1985 if research and development are continued and result in reducing total system investment significantly—perhaps to one-quarter of the then-current costs *(6, 7)*.

On the basis of operating experience during the 1977 season, the NML/Battelle system was modified to achieve more mature capabilities and to further evaluate operating and maintenance requirements during the 1978 season. These tasks were performed by Battelle under contract with the DOE, formerly ERDA, operating through Sandia Laboratories, Albuquerque, N. Mex. According to the report of 1978 results, the modified system was operated for 188 hours and pumped 32.8 million gallons of water during which significant information was gathered on performance, component life, and maintenance requirements. Several new operating and maintenance problems were encountered, with the result that satisfactory progress towards unattended system operation was not made *(6)*. Economic considerations aside, it was concluded that more testing and development will be required before the system is considered acceptable. The facility was to be maintained in a temporary shutdown condition for 6 to 12 months to facilitate the initiation of any follow-on program or demonstration in connection with additional work *(6)*. Operation of the system was supported by the DOE through mid-1980 at which time Sandia Laboratories concluded it had all the data it needed to fully evaluate the system. NML has sold its Gila River ranch and the new owner has discontinued operation of the system because the maintenance costs do not justify its continued operation *(8)*.

Sandia Laboratories Projects. Early in 1976, Sandia Laboratories proposed development of a small solar-powered system to pump water. The project was funded by the State of New Mexico and by DOE and is described in *(11)*. Subsequently, Sandia Laboratories formulated a comprehensive solar irrigation program plan for DOE which was published in November 1976 and revised in 1978 *(12)*. This plan contains four major activities:

- To upgrade and operate the NML/Battelle facility for the purpose of collecting additional operational and maintenance information. As indicated, Sandia contracted with Battelle to carry out this work.
- To construct and operate a 25-horsepower (19 kilowatt) shallow-well experiment in New Mexico in cooperation with New Mexico State University *(11)*.
- To conduct systems studies and economic analyses of onsite solar irrigation systems.
- To monitor the design, construction, and operation of a 150-kilowatt deep-well experiment in Arizona, in cooperation with Arizona State University.

The last three of these activities are described below.

Construction of the Sandia/New Mexico shallow-well experiment began in 1976 at the Torrance County Land and Livestock Company farm in the Estancia Valley near Willard, N. Mex. The system was similar in design to the NML/Battelle solar irrigation system at Gila Bend with selection of components based more on availability and cost than on performance optimization *(2)*. The system employed tracking parabolic-trough concentrating collectors (6,720 square feet), an organic fluid, Rankine-cycle engine, and both thermal and pumped water storage which enabled the system to provide irrigation water around the clock during the season. Details of design consideration can be found in *(2, 9, 10)*.

The system was operated for several seasons to obtain data on operations and maintenance as well as to carry out irrigation experiments. Numerous problems were encountered with the collector field, the heat storage system, and, especially, the Rankine-cycle heat engine. The problems identified with the collector field and heat storage system were either remedied or have had remedial solutions proposed. Due to the complexities of the heat engine it was difficult to analyze problems, and a number of modifications did not result in appropriate solutions *(1, 10)*. The engine system used for converting thermal energy to mechanical energy was not designed for the extreme temperature cycling (ranging from ambient nighttime temperatures to operating temperatures of up to 450°F) encountered in solar thermal irrigation systems *(8)*.

Engineering considerations aside, the Sandia/New Mexico researchers concluded that widespread applications of solar thermal systems cannot be expected because of the excessive initial investment. The 25-horsepower installation at Willard cost approximately $200,000 and, even with large cost decreases through mass production, the cost of an installed system would be expected to exceed $100,000 *(1)*. Justifying such an investment would require year-round utilization of the facility *(1, 8)*. This could be accomplished by using the system for other purposes during the off-season (multiple use), or for operations that are conducted on a year-round basis (such as feedmill operations), or by selling unneeded electric power to the local utility by plugging into their grid. Federal Energy Regulatory Commission rules issued under the Public Utility Regulatory Policies Act of 1978 that went into effect in March 1981, say that small power producers must be allowed to sell surplus power to their local electric utility *(36)*. The basis these regulations set for the price the utility must pay for this power is the "avoided cost" that the utility would have to spend to generate an equal amount of power *(36)*. Because of the high costs of constructing new electric power-generating facilities, these avoided costs could be higher than the price the utility receives for the electricity it sells from old facilities. The effect of these regulations on the construction of onsite solar electrical systems cannot be foreseen at this time.

The Willard installation was turned over to the State of New Mexico and is currently not in use. Because of the major problems with the heat engine, plans are being made to eliminate use of the heat engine and pump and to use only the thermal part of the system to produce process heat for the production of alcohol from cull potatoes *(8)*.

Another major activity in the solar irrigation program of Sandia Laboratories was to conduct systems studies and economic analyses of onsite solar irrigation systems. In 1977, a preliminary analysis was conducted of the economic feasibility of stand-alone solar irrigation systems for certain applications, in selected locations, using a system configuration similar to the Sandia/New Mexico solar irrigation experiment *(10, 49)*.

Locations selected for analysis were based on data in the 1969 Census of Agriculture and on the irrigation weight ranking of the Western States. Sites selected included southern Arizona, the San Joaquin Valley of California, northwestern Nebraska, central New Mexico, southeastern Oregon, and the southern High Plains of Texas. Crops considered were the principal crops produced in each location. Initial capital costs were generated by an optimization procedure. Prices for equipment were based on industry estimates, with system components sized to meet crop water demand for each location. Economic feasibility was determined by comparing the life cycle cost of the solar system to that of conventional systems. The economic parameters used to calculate life cycle costs were as follows:

	Percent
Loan rate	9
Downpayment	20
Market discount rate	10
Effective income tax rate	50
Depreciation rate	5
General inflation rate	6
Fuel escalation rate	10
Investment tax credit	10
Maintenance expenses (% of investment)	2
Property tax rate	0

Two sets of calculations were made, both which assumed that the initial costs of all inputs, except the collectors, were the same. Two initial costs were assumed for the collectors which, starting with 1978, were assumed to be either \$10 or \$5 per square foot.[8]

When it was assumed that the solar irrigation system would be used only for irrigation pumping, the life cycle cost of the solar system was always higher than that of a conventional electric water pumping system throughout the period from 1980 to 1990, even with the lower collector cost assumption. However, because of the differential in the escalation rate for general inflation and fuel costs, the life cycle cost for the solar system dropped more rapidly than for the conventional system.

The 1990 projections show that the life cycle cost for the solar irrigation system, using the lower collector cost assumption, ranged from a low of 1.5 times that for the conventional electrical system in southern Arizona, where the price of electricity is highest of all areas considered, to a high of 4.5 times in southeastern Oregon which has low-cost hydroelectric power. In Arizona, where it is less expensive to pump water using natural gas rather than electricity, solar compares less favorably with natural gas than with electricity. This is also true for the southern High Plains of Texas and central New Mexico. In northwestern Nebraska, where both electricity and diesel are used for pumping water, life cycle costs are about the same for systems using these two fuels. However, the analysis shows that by 1990 the life cycle cost of the solar irrigation system using the lower collector cost assumption would be about 3.5 times higher.

On the basis of their analysis of the economics of a stand-alone solar irrigation system used only for irrigation, the authors conclude that the conventional energy alternatives are the least costly *(49)*. However, the study also analyzes the impact of several methods of improving the feasibility of solar energy. These methods include finding alternative uses for energy produced by the solar system when

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[8] Both costs are based on the assumption that these levels can be achieved with large-scale production and improved manufacturing efficiencies. In 1978, the price for parabolic-trough concentrating collectors of the type used for the Willard facility was in the range of \$15 to \$20 per square foot *(64)*.

it is not needed for irrigation purposes; government incentives, such as a tax deduction for the cost of the energy that would have been purchased if a solar system had not been installed; and the use of a hybrid system which combines solar energy with a conventional system. Other ways of increasing the use of an onfarm power plant are to reduce peak energy demand for irrigation and extend the period of use by modifying irrigation and cropping practices *(46)*.

The analysis of the stand-alone system conducted by Sandia *(49)* shows that in southern Arizona, with 100-percent utilization of the energy from the solar irrigation system and assuming a 1978 starting price of $5 per square foot of collector area, the life cycle cost of the solar irrigation system would be comparable to that for an electric-powered system sometime between 1985 and 1990. For the same location and assumptions and allowing an income tax deduction for the cost of electricity saved by using a solar irrigation system, the life cycle cost of the solar system would break even by 1985. By combining the 100-percent utilization and the tax deduction advantages, the life cycle cost for the southern Arizona location would be lower for the solar option as early as 1980, even with a $10-per-square-foot starting price for the collectors. The savings for the hybrid system—solar plus electric—in southern Arizona would be an estimated 10 percent of the cost of an all-electric system. Whether or not the assumptions used can be considered realistic is not known. Their use, however, results in a more favorable economic picture than for other analyses which do not use such advantageous assumptions.

A final major activity of the Sandia Laboratories Solar Irrigation Program is a 150-kilowatt deep-well experiment near Coolidge, Ariz. *(12)*. The experiment was designed to involve industry in the solution of solar irrigation; to determine by study contracts the best system to be built for the experiment; and to construct and operate the best system to obtain true performance and cost data *(10)*.

DOE requested proposals from industry in October 1976 for a study into system design, to be followed by construction of the system. The three top proposals received which were given further consideration were:

(1) A distributed collector field employing parabolic tracking collectors, a thermal storage system, and a Rankine-cycle heat engine similar in design to the Willard, New Mex., experiment, submitted by the Acurex Corporation;

(2) A two-axis tracking parabolic dish concentrating collector field using a Brayton-cycle (gas turbine) engine, submitted by Honeywell; and

(3) A central tower system with heliostats (tracking mirrors) and a central cavity receiver which would furnish thermal energy to a steam turbine heat engine, submitted by Black and Veatch Consulting Engineers.

All three designs were judged technically good and ranking them proved difficult. Some considerations were how well the system met proposal requirements, maintenance requirements, risk involved in meeting projected operating conditions, ease with which a farmer could operate them, and life cycle costs for both present and predicted systems. From a performance standpoint, the Acurex proposal was ranked highest and DOE awarded the company the contract for construction and operation of the system *(10)*. A full description of the system's analysis, the preliminary design, and system production cost estimates are contained in the Acurex design study *(3)*.

The system was constructed on the Dalton Cole and Son farm near Coolidge, Ariz. A farmer-owned electrical cooperative located near the site is cooperating with the project by allowing the system to put generated electricity into its grid and later removing an equivalent amount without any loss or cost to the experiment *(10)*. Due to budgetary constraints, only half of the planned 48,960-square-foot collector field was originally built. This meant that the water pumps could operate only half the time. The other half of the collector field was added in fiscal 1981. Nevertheless, even before completion, the system was operated on a daily basis, and operation and maintenance data were collected for evaluation *(8)*. For a comprehensive outline of the tests and evaluation of this system during 1981 see *(85)*.

DOE Progress Report. The characteristics of the NML/Battelle installation at Gila Bend, Ariz., the shallow-well experiment at Willard, N. Mex., and the 150-kilowatt experiment at Coolidge, Ariz., as well as a photovoltaic irrigation experiment at Mead, Nebr., discussed later in this report, are summarized in a 1978 DOE progress report prepared by the Aerospace Corporation *(89)*. This report also contains economic and market analyses of solar thermal irrigation systems based on various scenarios. All scenarios are based on projected 1985 economic conditions, many of which seem overly favorable to the solar option. Even for the most favorable scenario, however, the analysis shows that the economics of solar thermal systems are not favorable. In addition, the authors point out other factors which might inhibit adoption of solar irrigation systems. Economics and market penetration in the future are expected to be more favorable, based on two assumptions: (1) continuing high petroleum prices and (2) rather optimistic reductions in the costs of manufacturing and installing solar collectors *(89)*.

Aside from continuing the evaluation of the Coolidge experiment, and a plan to request proposals for testing a 20-kilowatt solar thermal electrical generating system side by side with a 20-kilowatt photovoltaic system in Tunisia, for comparative evaluation under comparable conditions, DOE has decided to redirect its solar thermal energy program *(8)*. Current plans are to concentrate on trying to make solar thermal heat competitive with other sources of process heat for such purposes as industrial water heating. When this has been achieved, consideration will again be given to adding systems for generating mechanical and electrical energy for powering irrigation facilities *(8)*.

Conclusions

Whether or not future developments in converting solar thermal energy into mechanical or electrical energy will reduce costs sufficiently to make this source of energy competitive with present sources is uncertain. It seems certain, however, that at least three developments will continue to improve the competitive position of solar thermal energy for powering irrigation facilities. These developments are a continuing rapid escalation in the prices of fossil fuels; adoption of the many technological advances that can be foreseen for improving the efficiency of solar thermal power systems; and the execution of recently adopted legislation that requires utility companies to purchase surplus electrical energy from onsite solar-electric systems at a price that is equal to the utility's avoided costs of producing an equivalent amount of power. Nevertheless, some observers believe that the capital investment required for converting solar thermal energy into mechanical or electrical energy will remain high per unit of energy output, while the efficiency of conversion remains low, thus making its widespread use during this century doubtful *(76)*.

Photovoltaic Energy Irrigation Systems

Another method of utilizing solar energy to pump irrigation water is to convert the energy directly into electricity through a device called a photovoltaic, or solar, cell. Although the basic patents for solar cells were established in the early forties, the first breakthrough in their manufacture came at Bell Laboratories in 1954 *(59)*. In the following two decades, photovoltaic cells, arranged in panels and wired together, became the standard source of electric power for space satellites. A limited market for solar cells also developed where conventionally generated power was particularly expensive, such as in remote locations where electricity was needed to operate a radio transmitter or to record weather data *(60)*.

Photovoltaic-generated electricity could become a feasible option for other uses sometime during this century, provided DOE's projections of the cost of manufacturing solar cells proves to be valid. This would be especially true for applications in which the system could be utilized for long hours over a year, such as for pumping water to irrigate vegetable crops. DOE's cost projections, however, depend on developments leading to improved efficiency of solar cells and breakthroughs in the development of efficient cells made from lower cost materials than those made by the current single-crystal silicon wafer technology. The probability of these developments occurring seems uncertain at this time. A factor contributing to this uncertainty is the Government's current budget-cutting operations. This could result in a reduction in the research and development programs that are necessary to achieve the projected breakthroughs that would reduce solar cell costs sufficiently to make photovoltaic electricity a feasible option for powering irrigation systems and many other uses during this century.

The remainder of this section describes the way photovoltaic cells operate, discusses the potential for photovoltaic generation of electricity, and reviews the results and conclusions of various photovoltaic irrigation systems.

Solar Cell Design

Solar cells usually employ thin wafers of single-crystal silicon as part of their electric circuitry. When sunlight strikes the cell, electrons of silicon atoms are freed from their chemical bond within the silicon crystal. The freed electrons are mobile, as are the "holes" that they leave. These freed electrons, which are negatively charged, and holes, which are positively charged, will eventually recombine unless they are separated into different regions of the crystal.

In photovoltaic devices, the separation of freed electrons and holes is accomplished by a positive-negative (p-n) junction which divides the crystal into p-type and n-type regions. The junction is produced in semiconductor crystals through extremely careful control of chemical purity during crystal growth, followed by deliberate introduction of a very small quantity of selected impurity, called "dopant," which, through diffusion, becomes established at the location that constitutes the p-n junction. As the freed electrons and holes come near the p-n junction, the electrons will be pushed by the electric field that exists in the vicinity of the junction into the n-region and the holes will be pushed into the p-region. Conductors connected to the top and bottom surfaces of the cell allow connection to an external circuit through which the cell's electric current flows. The current will flow so long as sunlight strikes the cell and generates the electron-hole pairs. Since solar photovoltaic arrays generate direct current, power inverters are necessary to convert to alternating current to be compatible with present electrical systems. Comprehensive discussions of the operation of a photovoltaic cell, with illustrations, are contained in *(47, 56)*.

The Potential for Solar Cells

As indicated, the use of solar cells for providing electric power has been limited to the space program and for specialized uses in remote locations. The cost of solar cells dropped steadily from about \$200 per peak watt[9] during the height of the space program, to about \$10 in 1978 and is expected to continue to drop *(58, 59)*. At this price, solar cells are cost effective for specialized uses in remote locations which otherwise would have to rely on heavy-duty batteries with their high maintenance and replacement costs *(59)*.

Before widespread use of photovoltaics becomes practical, however, their costs will have to drop dramatically. Further cost reductions are expected by efficiencies that can be achieved through large-scale manufacture; by the development of new, low-cost photovoltaic materials; by the use of improved devices for concentrating sunlight onto the cells for improving their performance; and by improving cell conversion efficiency. Conversion efficiencies have already been increased from about 4 percent in 1975 to 11 percent in 1978 and are expected to reach 16 percent by 1986 *(5)*. These estimates are for cells made from silicon wafers, but possible breakthroughs are also expected for cells made with lower cost materials such as gallium arsenide, cadmium sulfide, or amorphous silicon, and thin-film devices which can be produced at much lower cost than single crystal devices *(5, 70)*.

The use of sunlight concentrators for improving solar cell conversion efficiencies results in higher temperatures which, in turn, degrade power output. This can be counteracted by providing liquid or air cooling for cells with concentrators. However, this results in increased costs and consumption of some of the power produced *(55)*. A model has been developed for assessing the economic tradeoffs between conversion efficiencies and concentration ratios, as well as for other major parameters *(75)*.

In 1980, DOE sponsored a meeting to review the photovoltaic program for technology and systems

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[9] Peak watt is the amount of power produced in direct sunlight at 25°C. With indirect or diffused sunlight the power output would be less. Power output is also degraded with increasing temperatures.

development. This review followed nine semiannual reviews conducted since the photovoltaic program began in 1975, and focused on residential photovoltaic applications. The objectives and status of the DOE's photovoltaic research program, and the outlook for achieving these objectives, were also discussed and are presented in the proceedings of the meeting *(88)*. Since collector technology has universal application, these objectives, and the outlook for their achievement, will be of interest to those considering photovoltaics for other applications, including irrigation.

The overall goal of DOE's photovoltaics program is to reduce system costs to a competitive level in both distributed and centralized grid-connected applications. Program activities are directed toward the development and testing of technologies and infrastructures that will yield technically, economically, and socially acceptable energy-producing systems. The basic objective of the collector research program is to develop low-cost reliable materials, devices, and collectors to meet the program's key module price goals.

As late as 1980, DOE's price goals for solar cells were to reduce costs to $1.00 to $2.00 per peak watt (in 1975 dollars) by 1982, to 50 cents by 1986 *(5, 30)*, and to 15 to 40 cents by 1990 *(88)*. According to DOE, widespread use of photovoltaics will depend on cost reductions to 20 cents per peak watt by the nineties *(30)*. In mid-1981, the actual prices quoted by manufacturers of solar cells ranged from $6.00 to $16.00 per peak watt. The postulated improvements that would reduce cell costs dramatically enough to result in electricity costs competitive with those produced by other means are uncertain at this time. However, proponents of photovoltaics are optimistic about achieving these cost reductions, especially if a greater commitment is made to research and development by the Government *(58, 59)*. On the other hand, some observers are not as confident that the technological breakthroughs necessary for widespread use of photovoltaics will ever materialize *(56)*.

The attractive features of photovoltaics and the possibilities of technological breakthroughs have resulted in continuing research and development efforts by both private industry and by DOE-funded projects. Still to be resolved is whether distributed (onsite) or aggregated (centralized) systems for producing electricity with photovoltaics is most advantageous. Economies of scale are not as great for photovoltaic systems as for conventional electric power systems because of the modular characteristic of photovoltaic systems. Environmental considerations for photovoltaic systems will be of reduced importance, however, thus providing greater flexibility on where such systems may be located. On the other hand, unless it is demonstrated in actual use that photovoltaic devices have an unusually high reliability and low maintenance requirements, small dispersed systems may result in special maintenance problems and maintenance diseconomies *(43)*.

Experimental Systems

To evaluate the operational and maintenance requirements as well as the economics of distributed photovoltaic systems, a number of modeled studies and experimental demonstrations have been made or are in progress. Those relating to the operation of irrigation facilities are described in this section.

Foreign Systems. In 1978, Newkirk prepared an annotated bibliography of experiments on the use of photovoltaics for powering water pumps *(65)*. Seven publications were reviewed describing experiments in the Soviet Union; 2 describing experiments in France; 1 in Germany; 3 in the United States; and 1 which contained 31 abstracts from worldwide literature on the use of solar energy for irrigation, some of which used photovoltaics.

With the exception of the experiments in the United States, the experiments reviewed were for small-scale installations ranging from about 300 watts to 1 kilowatt in size. The objectives of these experiments were to test system designs, demonstrate technical feasibility, evaluate sunlight concentrators, evaluate economic feasibility, and determine the direction of future developments.

The conclusion of one of the Soviet experiments was that despite the present-day extreme cost of photoelectric converters, the use of independent solar plants based on such devices proved to be more favorable, under appropriate conditions, than the employment of internal combustion engines *(65)*. In

France, the conclusion of one of the experiments was that when compared with a thermal steam engine, photovoltaics showed a definite advantage. Also, that the expected drop in prices and improvements of solar panels would make megawatt-size stations economical for large-scale irrigation and for full electrification of remote areas *(65)*.

A 1977 comparative study of power costs for irrigation pumping with solar cells (1 kilowatt) versus diesel pumps showed that solar cells should become competitive in 5 to 6 years, assuming that ERDA (DOE) projections of solar cell costs hold true *(5)*. The same study indicates that using solar cells for generating electricity appears to be especially promising in those developing countries without cheap fuel sources. In Upper Volta, for example, the only domestic fuel source is firewood, and electricity costs 19 cents per kilowatthour. India, on the other hand, has large deposits of coal and the cost of power generation is relatively low (about 5 cents per kilowatthour in many areas).

Mead, Nebr., Systems. In the United States, modeled and experimental irrigation systems using solar photovoltaics have been considerably larger in size than those in other countries. The first step towards realization of a large-scale photovoltaic system was made during the summer of 1977 by the construction of an experimental unit capable of generating approximately 25 kilowatts of peak power. The work was sponsored by the DOE and carried out by the Massachusetts Institute of Technology/Lincoln Laboratory and the University of Nebraska/Agricultural Engineering Department *(52)*. The site selected for the experiment was near Mead, Nebr., where the major irrigated crop, corn, requires an average of 14.2 inches of water per season. Using 75-percent water application efficiency, this amount of water would require 19.2 gallons of diesel fuel per acre to lift the water from the average ground-water reservoir of 100 feet depth, plus additional fuel for distributing the water through gated pipe or sprinkler systems. The saved cost of this fuel could be credited to the investment cost of a photovoltaic system.

The experiment was designed to operate a 7.5-kilowatt pump for 12 hours a day. During the July-August irrigation season, it irrigated 80 acres of corn. Following the irrigation season, the system is used from October through March to dry the 330 tons of corn harvested from the 80-acre test field. The system consists of three major elements: the photovoltaic array, battery storage, and power inverting and control elements. Approximately 100,000 nonconcentrating solar cells are connected together on 28 panels to form the 25-kilowatt array. The system is used to acquire data and to evaluate design, performance, and maintenance characteristics. A comprehensive description of the system is contained in *(52)*.

Using data obtained from the Mead, Nebr., photovoltaic irrigation experiment, DOE projections on costs of solar cells and optimistic and conservative scenarios, an economic analysis was undertaken to estimate when photovoltaic systems might become profitable in Nebraska, West Texas, Arizona, and the Central Valley of California *(40, 51, 52)*. These areas differ widely in their water sources, pumping depths, irrigation season lengths, and in the magnitude of incident insolation during the year. The analysis calculates the profitability of adopting the photovoltaic system in each year from 1977 to 2000 on the basis of several combinations of assumptions. The analysis assumes year-round utilization of the system at different values for the energy, depending on use. Four sets of parameters are used for the analysis. Under the optimistic scenario, the discount rate is 5 percent (the subsidized rate charged by the Farmers Home Administration for 40-year real estate loans), the fuel inflation rate is 4 percent, the year 2000 solar-cell-array target cost is $100 per peak kilowatt (DOE's 1986 target cost is $500 per peak kilowatt), and system support costs are $550 per peak kilowatt. With this scenario, the use of photovoltaics becomes profitable by 1983 in the Southwest (Arizona, Texas, and California) and by 1986 in Nebraska where the year-round insolation is less and the irrigation season is shorter than in the Southwest. Under the conservative scenario, where the discount rate is 8 percent (the rate charged by the Farmers Home Administration for 12-year equipment loans), the fuel escalation rate is 2 percent, the year 2000 solar-cell-array target cost is $300 per peak kilowatt, and system support costs are $1,050 per peak kilowatt, the use of photovoltaics doesn't become profitable until 1990 in the Southwest and after the year 2000 in Nebraska *(40, 51, 52)*. Extending the analysis to include the effects on farmers' income taxes, as well as possible Government incentives (tax credits), showed that the year of profitable adoption would be somewhat earlier. The analysis also showed that because of the expected continued decline in solar cell costs, the optimal year of investment in photovoltaic systems would be considerably later than the initially viable year. The analysis concludes that small tax credits can have great leverage in accelerating adoption of solar photovoltaic systems, but this is not necessarily recommended as a public policy option *(40, 51)*.

BDM Study. In 1978, the BDM Corporation prepared a market identification and analysis of photovoltaic systems for the DOE *(18)*. This study concludes that the seasonal requirement for pumping energy, coupled with the low unit cost of conventional electrical energy, limits the application of photovoltaics for irrigation pumping before the nineties. The key factors that would result in greater economic attractiveness include the ability to use the system for other applications during the irrigation off-season, the reduction in capital cost to the user, and technical innovations that would reduce the need for battery storage. Early market penetration will depend largely on Government incentives and price reductions of solar cells *(18)*.

Texas Tech System. In 1979, Texas Tech University, under contract with DOE, designed a model 2,000-kilowatt photovoltaic concentrating system applied to deep-well irrigation in the Trans-Pecos region of Texas *(50)*. The operational concept of the system design is to displace daytime utility power with solar-generated electric power. According to the operation and evaluation plans of the experiment, once the system has been constructed and is in operation, it will be used to collect data for analyzing the reliability and maintainability of the system for the purpose of improving it as well as providing information that would be applicable for designing and operating other similar systems. No time frame was given as to when the system would be constructed.

NASA/Lewis System. The NASA/Lewis Research Center in Cleveland, Ohio, under contract with DOE, has constructed and is evaluating an experimental photovoltaic system for pumping water on the Schuchuli Indian Reservation near Gunsite, Arizona. This system pumps 900 gallons of water per hour for 5 hours a day using a 2-horsepower motor *(72)*. Several other Indian reservations in the Southwest are using similar systems developed by other organizations. NASA/Lewis is also collaborating with USAID to install small photovoltaic systems in several developing countries, some for pumping water. These countries include Upper Volta, Gabon, Guyana, and Ecuador *(72)*. Electric power rates in these countries are among the highest in the world. As indicated above, a test project is also planned for Tunisia for evaluating a photovoltaic system side by side with a solar thermal-generating system *(8)*.

Sandia Laboratories Study. In 1980, Sandia National Laboratories issued a three-volume report, prepared by the BDM Corporation for the DOE, summarizing the findings and conclusions of a contract study to identify and characterize agricultural energy demands that can effectively use photovoltaic systems, and to conceptualize and evaluate system designs for selected agricultural applications *(54)*. About 50 agricultural operations that use significant amounts of energy were identified and screened for potential photovoltaic applications on the basis of technical and cost feasibility, market size, and project compatability. Those that were unpromising were dropped from further consideration, while those that were promising were analyzed to select the best four for conceptual design.

According to the report, irrigation did not appear to be generally attractive because of the limited annual operating cycle for most crops and the very high energy demands. However, year-round irrigation, such as vegetable crop irrigation in Southern California, Arizona, and Texas may be very attractive, particularly since the demand for irrigation is highest during periods of high insolation *(54)*. Vegetable crop irrigation was, therefore, one of the four applications chosen for conceptual design. The other three chosen applications related to livestock operations *(54)*.

The conceptual design of the irrigation system was sized to supply a sufficient annual amount of water to a 200-acre vegetable farm in Phoenix, Ariz., with Santa Maria, Calif., as an alternate location. Two conceptual photovoltaic collector designs were analyzed: one was an array of 2-axis tracking, concentrating (Fresnel lens) collectors, and the other was an array of nontracking, nonconcentrating (flat plate) collectors. Tradeoff analyses were performed to select each of the other key system options. The selected system design supplies direct current (DC) power to a variable speed pump to accommodate the variable power output from the array which has no electrical storage and no utility backup or feedback. Performance and cost estimates were made of these conceptualized systems. The cost estimates are based on a 1986 time frame and range from about 9.0 cents per kilowatthour for the flat plate system to about 13.0 cents per kilowatthour for the Fresnel lens system. This compares with the annualized cost of electricity from the grid of 8.0 cents per kilowatthour, making the flat plate system nearly competitive *(54)*. Even though the cost of electricity from the concentrator system is estimated to be higher than the nonconcentrating, the study points out that future improvements in technology will probably enhance the economics of concentrator systems.

Conclusions

A general conclusion that can be drawn from all of the photovoltaic experiments and studies to date is that the large-scale use of solar thermal energy systems will depend on cost reductions brought about largely through solving engineering problems and from the economies of large-scale manufacture of components. In contrast, the widespread use of photovoltaics will depend more on developments leading to improved efficiency of solar cells and breakthroughs in the development of efficient cells made from lower cost materials than single-crystal individual silicon wafers. The probability of these developments occurring seems uncertain at this time.

Wind Energy Irrigation Systems

In some regions, wind will probably have a greater potential for irrigation pumping than either solar thermal or photovoltaics. Wind turbines are more efficient because they can power irrigation pumps with direct mechanical power. Because of the substantial investment tax incentives that have been made available to encourage the use of solar energy, irrigators in the higher tax brackets and those in areas of extremely high costs for conventional energy, such as some of the developing countries, will find wind to be an especially attractive alternative energy source.

This section discusses the use of wind as an alternative energy source, the advantages and disadvantages of both horizontal-axis and vertical-axis wind machines, and the results and conclusions of wind-powered irrigation experiments.

The Wind as an Energy Source

Interest in developing large-scale schemes for using wind energy has always been tempered by the availability of abundant and cheap petroleum, the promise of inexpensive and trouble-free nuclear power and, between 1930 and 1950, the widespread availability of federally subsidized, centrally generated electric power to farms by USDA's Rural Electrification Administration *(33, 57)*. However, the problems and public concern associated with the use of nuclear power and the rapid increase in petroleum prices in recent years, have led to renewed interest in wind energy.

The amount of energy available from wind is enormous, but the technological problems of extracting this energy at a reasonable cost and the unpredictable nature of wind, limits its application at the present time. Current research and development programs for utilizing wind energy are attempting to overcome these limitations. However, because of the nature of the wind and the developments that have already been made, some experts feel that only incremental improvements can be expected *(57)*.

The application of scientific study to windmill design began early. In 1759, John Smeaton read a paper before the Royal Society on the aerodynamics of windmill blades. In 1891, the world's first wind tunnel was designed and built for research on windmills at Askov, Denmark. In the late twenties and early thirties, extensive experimental and analytical work was done at Gottingen, Germany. In the early forties, the largest wind machine that has ever operated—the Smith-Putnam 1,250-kilowatt wind turbine—was erected on a mountain called Grandpa's Knob in southern Vermont. The machine was operated intermittently as a test unit for the 100 production units that were expected to follow. However, before the production units were built, the test unit was dismantled because projected costs were found to be greater than the cost of energy from other sources *(57)*.

The type of wind machine most widely used in the world today, the American multivane fan water pumper, was developed in the Midwest in the mid-19th century by artisans, mechanics, farmers, and small-scale manufacturers—all with little scientific knowledge. The recent resurgence of interest in wind energy is proceeding through both the scientific and artisan communities *(57)*.

Windmill Design

Over the years many designs and materials have been used for windmill construction and many of these are currently used for providing energy for small-scale operations *(61)*. The U.S. Government is focusing attention on large-scale power generating windmills of the horizontal-axis, two-bladed propeller type, and several test windmills, ranging from 100 kilowatts to 2.5 megawatts, have been constructed or planned *(63)*. These are Government financed in the hope that after research, development, and engineering show the way, these wind generators can be manufactured on a large scale at a cost that will make the energy they produce competitive with other sources of electricity *(57, 63)*.

The Federal Government's wind energy program is broadly based.[10] In addition to the large-scale power generating program being developed with NASA, DOE is also active in programs with vertical-axis machines; innovative designs and small wind machines (under 100 kilowatts); characterization of wind patterns and development of techniques for wind machine siting; and the legal, social, and environmental aspects of wind energy generation *(63, 87)*.

Most current wind-powered irrigation pumping experiments in the United States are using the Darrieus design. The curved blades of this vertical-axis design have resulted in the nickname "egg beaters." The vertical-axis machines have two primary advantages over those of horizontal-axis design. First, the generator and gearbox can be located at ground level instead of at the top of a tower as with the propeller-type, horizontal-axis machines. This reduces structural requirements and provides easier access for maintenance. In addition, since vertical-axis machines need not turn as wind direction changes, yaw control is not needed. Another possible advantage may be a reduced need for pitch control devices to protect the machines against high winds because of the vertical-axis design's natural aerodynamic stall characteristics.

Disadvantages of the vertical-axis design include an aerodynamic efficiency about 10 percent less than horizontal-axis machines, limited ability of the rotor to self-start (thereby requiring an electric starter), and generally lower rotation speeds, which require a higher drive train torque capacity. As a result, a Darrieus machine is able to produce only about 50 percent of the annual energy of a propeller-type, horizontal-axis machine of the same power rating *(57, 68)*.

Sandia Laboratories, Albuquerque, N. Mex., is developing the vertical-axis Darrieus design for DOE. This work has progressed to a point that indicates that even though this design may be less efficient from an engineering viewpoint, it could eventually prove to be cost-competitive with horizontal-axis designs. However, at this time research and development on the horizontal-axis designs is more advanced than on the vertical-axis machines *(63)*.

Experimental Systems

To evaluate the operational and maintenance requirements as well as the economics of wind-powered irrigation systems, a number of modeled studies and experimental demonstrations have been made or are in progress.

DOE's Research Program. The DOE's wind energy research program includes funding of USDA for research to develop farm and rural use of small wind-energy systems. This program's objectives are to identify and test applications of these systems, assess the performance of available small wind turbines for these applications, identify small machine development needs, and develop and evaluate advanced small wind turbines. Projects include the development of rural and remote applications of wind-generated energy, apple storage and cooling, direct hydraulic dissipation of heat, dairy milk cooling, water heating, and pumping for irrigation *(87)*.

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[10] A comprehensive annotated bibliography of wind energy information sources which contains references to all aspects of the Government's research program is available from DOE *(90)*.

USDA Studies. In 1977, the USDA contracted with Development Planning and Research Associates, Inc., for a study to assess the potential of wind energy applications for various selected agricultural enterprises in 23 States to determine what combination of wind characteristics, wind turbine generator parameters, enterprise load characteristics, and alternative energy costs are required to make the installation of a wind turbine generating system (WTGS) economically feasible. The study report contains estimates of the number, size, and rated power of wind turbine generating systems best suited for various U.S. farm applications, including irrigation pumping.

The economic feasibility of wind turbine generating systems was examined for six different scenarios considering combinations of high and low WTGS capital costs and energy costs equivalent to 4.0, 6.0, and 8.0 cents per kilowatthour. Other general assumptions of this study *(27)* were the following:

- Purchased electricity from utilities would be a constant backup to wind-generated electricity without payment of penalty for power company losses of revenue nor credit for excess wind energy generated.
- No storage of wind-generated electricity.
- No adjustments of wind speed data for either recorded anemometer heights or WTGS tower height.
- 10-percent discount rate.
- 20-year use life of WTGS with no salvage value.
- Annual operating and maintenance cost of 3 percent of the turnkey wind generator capital cost.

With high capital costs and low prices for alternative fuels (4.0 cents per kilowatthour equivalent for electricity, natural gas, fuel oil, gasoline, and diesel), a WTGS was not economically feasible given economic conditions in 1977. Nor was it feasible with low capital costs and high prices for alternative fuels (8.0 cents per kilowatthour equivalent). Some feasible applications were found only when optimistically low WTGS manufacturing and distribution costs and prices for alternative sources of energy of 6.0 cents per kilowatthour or greater were assumed. The authors state that "these conditions are unlikely to occur in the near future" *(27)*.

The USDA and the West Texas State University Alternative Energy Institute are testing a 56-horsepower (40 kilowatt) vertical-axis, Darrieus wind turbine for wind-assisted irrigation pumping. The turbine is mechanically coupled to a vertical turbine pump through a commercially available combination gear drive. The wind turbine supplies mechanical power to the pump whenever the wind speed exceeds a minimum cut-in level, thus reducing the load on an electric motor that supplies the remainder of the power required for constant output pumping. During the test, the wind turbine supplied 65 percent of the energy used to pump water, thus reducing electricity costs *(21)*. The study report did not contain a comprehensive economic analysis.

In another study, the USDA investigated the application of wind energy systems, without energy storage, for irrigation in the Great Plains *(37)*. A simulation model of four modes of well yields was developed to compare: maximum pumping rates as a function of drawdown in a typical well; monthly well yields using a 2,690-square-foot swept area wind system for each mode in three different locations; and the percentage of fossil fuel replaceable by wind energy. It was concluded that wind-powered systems could supply at least half of the Great Plains irrigation demand using the present mix of irrigation systems. However, because the wind resource is not constant, modes without auxiliary energy would require two wells to yield water amounts similar to one well with auxiliary power that pumps continuously *(37)*. The study did not contain an economic analysis.

In 1979, a workshop on wind energy applications in agriculture was conducted at Iowa State University. One paper included in the workshop proceedings *(41)* discusses an experiment being conducted at Manhattan, Kan., by USDA and Kansas State University *(38)*. The system is designed for pumping from tailwater pits (a pit for catching irrigation runoff) and other surface water sources, with a Darrieus vertical-axis wind turbine mechanically coupled to a vertical turbine pump.

Lifting and distributing surface water accounts for nearly 6 percent of the energy used for irrigation pumping on farms in the Great Plains *(78)*. Successful development of a wind-powered system of the type being developed at Manhattan, Kans., could replace some or all of this energy. It could also encourage utilization of tailwaters where electricity is not now available, thus conserving both water and energy *(38)*. A number of design parameters have been investigated and engineering improvements made for this system, but a comprehensive economic analysis has not been made.

Texas Systems. In 1977, the State of Texas Governor's Energy Advisory Council had a wind-powered irrigation system modeled and analyzed for two types of pumps: positive displacement and airlift *(34 35, 62)*. The general system parameters were for a wind rotor which could pump 200 gallons per minute from a well 200 feet deep. The rotor design (20 kilowatts at a wind speed of 22 miles per hour) and operation were analyzed using a computer program which gave the optimized power coefficient. The efficiencies for three modes of operation (constant power coefficient, constant revolutions per minute (rpm), and constant torque) were compared and the problems of matching torque-rpm characteristics of loads (water pumps) to those of the wind rotor were analyzed. It was concluded that even with the variability in wind power, it is technically feasible for pumping irrigation water. A cost-benefit analysis was then made comparing the wind systems to conventional irrigation systems. The general conclusion was that even though the initial costs (investment) for utilizing wind energy are considerably greater than for using fossil fuels, wind energy is a viable alternative for pumping irrigation water, and the research and development work needed should be started while fossil fuels are still readily available *(34)*.

New Mexico State University Study. In 1980, New Mexico State University conducted an economic analysis of wind energy for irrigation pumping *(44)*. Four types of wind-powered irrigation systems were evaluated. These were wind-assisted combustion engines (diesel, natural gas, LPG, and gasoline); wind-assisted electric systems with and without sale of surplus electricity; and stand-alone reservoir systems. These systems were considered for three different price scenarios and seven different geographic locations throughout the United States, representing different wind availabilities, lengths of irrigation season, and water requirements.

The study concluded that the most economically feasible wind systems were the stand-alone reservoir systems, followed closely by the wind-assisted electric systems in which surplus electricity was sold. The other systems were a distant third. The regions showing the greatest potential for economic utilization of wind power were the High Plains of Kansas, Texas, Oklahoma, New Mexico, and south central Nebraska. The authors conclude that by taking advantage of the substantial investment tax incentives that are available, irrigators who are in the 50-percent tax bracket would find wind turbines to be an attractive investment at the present time *(44)*. Those irrigators in lower tax brackets may need to wait further technological and economic advances in wind turbine manufacture before an investment would be economical.

India Study. A study of the economics of wind energy use for irrigation in India concluded that energy from windmills designed specifically to operate in the low wind velocities that prevail in India during the main irrigation season would provide an economical means of irrigating small farms from open wells *(82)*. This conclusion was made after comparing costs of utilizing wind energy with those for bullock-powered water lifts, utility electric power, and diesel-powered pumps. Widespread use of such windmills, however, might require government assistance primarily in the form of low-interest loans. It is also expected that the economics of wind energy can be improved if the government supports research and development efforts to optimize the design of windmills for operating in low wind speeds and to actively promote their use *(82)*.

Conclusions

The experiments described in this section indicate that under some conditions, some configurations of wind-powered irrigation systems may be feasible alternatives to using fossil fuels. Research and development may help to further enhance the feasibility of wind-powered irrigation systems.

Presently, the situation under which wind is most likely to be a feasible option is in a location where utility electricity is unavailable and fossil fuels are extremely expensive, where there are adequate wind availabilities, and where the wind turbine can be utilized for long hours throughout the year. In some locations with adequate wind availabilities, such as the High Plains of the Southwest, conditions may already be suitable to make wind-powered irrigation systems feasible. This is most likely for irrigators who have the possibility of utilizing wind turbines for long hours over a year and those in the higher income tax brackets who could benefit most from the substantial investment tax incentives that are available.

Conclusions and Recommendations

Studies and experimental projects of solar-powered irrigation systems to date indicate that many technical and economic problems exist which preclude the immediate widespread application of these systems. Some systems, particularly those that utilize non-concentrating photovoltaic collectors and some wind-powered systems are closer to being cost effective than any of the solar-thermal systems or the photovoltaic systems with concentrating collectors. All systems, however, require further research and development to improve their technical efficiency and cost effectiveness before they can be competitive with systems using conventional sources of energy.

Since irrigation pumping uses such large quantities of energy in the production of food and fiber, finding technically and economically feasible ways in which to use solar and other renewable energy sources for operating irrigation facilities should receive high priority. Another reason that such research should receive high priority, particularly the use of direct solar energy, is the compatibility of irrigation with solar energy. The maximum need for irrigation occurs at times and in locations of maximum insolation, such as during summers in the Southwestern United States and all year in most of the Southern Hemisphere. Conversely, evaporation losses from crops and land decrease during periods of lower insolation—when solar energy would be less available for powering irrigation systems *(65)*.

Widespread use of solar-powered irrigation systems will require substantial long-term funding of research and development and the selective subsidization of investments in appropriate technologies. The funding of research and granting of subsidies ultimately will be based on political, technical, and economic considerations. Policymakers will need information on the comparative cost effectiveness of solar-powered irrigation systems, as well as information on other systems that use solar energy and that conserve energy from conventional sources.

The cost effectiveness of using onsite solar-powered irrigation systems should be compared with alternative irrigation methods that are now in the planning or experimental stages. These alternative methods include the use of methane gas or alcohol produced from agricultural residues or from cereal and sugar crops.

The feasibility of onsite solar irrigation systems also should be compared with that for centralized generation of solar electricity in which the electricity is distributed through a utility network.

The decision to make an investment in an onsite solar system for irrigation pumping must be based on the costs of energy from that system compared with the cost of purchased energy *(45)*. The latter is based on several factors, one of which is the amortization of old (as well as new) generating plant investment costs. These old investments were made when the cost of capital was much lower than at present. Thus, comparison of energy costs from a new solar plant and from an older, conventional power plant reflects the situation actually confronting farmers, with costs usually favoring the conventional source. On the other hand, for utility companies facing the decision of investing in new alternative generating plants, the solar option may be more feasible.

The development of onsite solar irrigation systems for providing mechanical or electrical energy should be pursued only if their projected economic benefits and their possible environmental advantages are considered to be more favorable than other systems. Otherwise, their development will divert resources away from systems with a greater probability of early success in achieving the goal of greater energy self-sufficiency.

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☆U.S. GOVERNMENT PRINTING OFFICE: 1982-360-932:ERS-1038