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Technical and Economic Assessment of Solar Powered Pumping for Remote Areas

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115 and Livermore, California 94550 for the United States Department of Energy under Contract DE-AC04-76DP00789.

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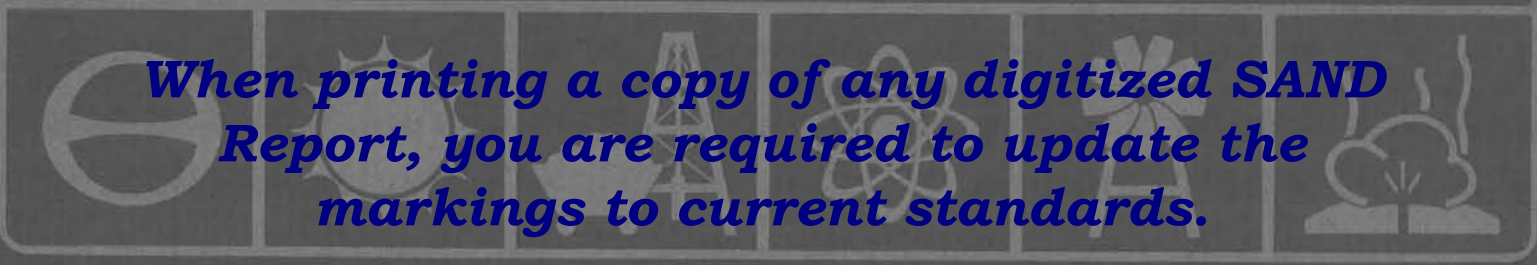

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TECHNICAL AND ECONOMIC ASSESSMENT OF SOLAR POWERED WATER PUMPING FOR REMOTE AREAS

FINAL REPORT

Prepared for
SANDIA LABORATORIES
LIVERMORE, CALIFORNIA

By

BECHTEL NATIONAL, INC.
RESEARCH AND ENGINEERING
San Francisco, California

DECEMBER 1978

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ABSTRACT

This study reviewed the technology of solar powered water pumping. An overview of the technology and its economics is provided, based on a review and assessment of the open literature. It is shown that pumped water is used most extensively for irrigation, and that new irrigation methods, such as the center pivot system, have significantly increased the water pumping power demand in recent years. The coincidence of the peak irrigation season and peak seasonal insolation makes solar energy a good candidate to supplement or displace depletable energy sources currently used for water pumping. Solar powered water pumping demonstration systems with capacities to 50 kWe have been built, utilizing solar thermal, photovoltaic and wind powered energy conversion. The prime movers of these systems either drive the pumps directly or indirectly through electric power generation. A comparative evaluation of these and other proposed solar concepts was conducted and resulted in the selection of a reference system comprised of a number of individual parabolic dish collectors with integral Brayton cycle engines. This reference system provided a basis for economic comparisons with a typical conventional electric pumping system. It was determined that the cost of power from the reference solar concept will probably not break even with present-day utility-powered pumping systems until at least the turn of the century.

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Section 1

INTRODUCTION

1.1 BACKGROUND

The availability of adequate water supply has been one of the main factors in determining the geographical location, the development, and at times the survival of civilizations throughout history. The waters of the Tigris and Euphrates Rivers supported the Mesopotamian civilization; the ancient Egyptians thrived because of the Nile; the Ganges and Yangtse Rivers were instrumental in the development of the early Hindu and Chinese civilizations. Water lifting and transportation is one of the most ancient technologies, starting with the primitive water wheels powered by human labor or beasts of burden. It is probable that windmills, driving shallow well pumps, represent one of the earliest methods of solar energy conversion. The development of more sophisticated power conversion and deep well drilling and pumping equipment opened the way for supplying water to communities and agricultural land away from surface water sources.

Today, pumped water is supplied in many areas of the world for irrigation, human and animal consumption, and industrial purposes. When water is required in remote areas, the energy to pump this water must be transported in the form of electricity or fossil fuels over long distances and at high costs. Where this is the case, the use of solar energy to substitute or supplement these energy sources may be economically attractive in the future as fuel and electricity costs increase.

In principle, the use of solar energy for water pumping may be advantageous for the following reasons:

- Insolation is generally high in arid and semi-arid areas; therefore, there is a good match between energy supply and water demand.
- Solar energy is available at the site; thus, the need for costly, long-distance transportation of energy to remote areas can be minimized.
- In many applications, water is only needed in the daytime hours, or, even if the demand is continuous, water pumped into storage reservoirs during the day may be used to meet the night time needs. The technical problems and the high cost of thermal or electric energy storage to maintain the continuity of service overnight may be eliminated, or at least minimized.
- Some of the solar power concepts are technically simple and the equipment is rugged. This enhances the possibility of remote, unattended operation, and minimizes maintenance requirements. Maintenance and operation would not necessarily require highly skilled technicians.
- The sun is an inexhaustible source of energy, and its use for water pumping would reduce the United States and world use of the rapidly depleting fossil fuels.

Recognizing these potential advantages, the United States government and private companies, as well as several foreign countries, have recently designed and built several commercial and experimental solar powered water pumping systems. As a result of an intensified search for new energy sources during the past few years, this attention to solar power technology has steadily increased. Several improved concepts for solar energy collection and conversion have been advanced. It is therefore timely to undertake a review of present and future water pumping requirements, together with the available solar technology, to identify the role which solar power may play in providing the needed energy for such a service.

1.2 PROJECT OBJECTIVES AND TECHNICAL APPROACH

The objective of this study was to assess the general technical and economic feasibility of solar powered water pumping for extensive use in remote areas in the United States and in foreign countries. In accomplishing this objective, the approach taken was to:

- Examine the potential market for solar powered water pumping.
- Identify the technical requirements of potential applications.
- Identify and evaluate solar power concepts which may meet these requirements.
- Select an appropriate solar system for economic evaluations.
- Compare the cost of power from the selected solar system against a representative conventionally powered pumping system.

The study has concentrated on those solar concepts that are either already well developed or can be expected to achieve technological readiness within the next 5-10 years. Open literature available up to the end of 1977 was used as principal source of data. Parts of this report also utilized the findings of a parallel Bechtel in-house study related to solar power applications for remote area water pumping.

It is recognized that solar and conventional water pumping systems have many common features and components. Under closer scrutiny, it becomes apparent that significant differences between these two types of systems may be reduced to those related to the methods of providing torque to pump shafts or electricity to the drive motors. Conventional systems may use internal combustion engines or utility supplied electricity. In solar powered pumping installations, shaft torque or electricity is obtained by converting the solar energy in heat engines, photovoltaic arrays or by wind turbines. Consequently, the technical evaluations and economic comparisons of this study concentrated on the power aspects of the water pumping systems. The sources of water and the distribution systems were considered only to the extent that they determined the power requirements.

The economics of solar power differ significantly from conventional energy sources. While the cost of power in conventional (specifically fossil-fired) systems has a significant fuel cost component, in solar systems the amortization of the initial investment is the most significant cost component. Accordingly, the life cycle cost approach, developed specifically to permit meaningful comparisons of the economics of very diversified energy systems, was used in this study to analyze the economic potential of solar powered water pumping. The analysis assumed that a substantial demand has already created an adequate equipment manufacturing base to supply the necessary components for a significant share of the annual pumping system sales.

It is noted that the volume of solar power related publications is increasing at an extremely rapid pace. Accordingly, it will be necessary to review and update this report prior to any committment to a future project to assure that the most up-to-date information is considered in any decision making process.

Section 2

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

2.1 GENERAL

This study pertains to the application of solar energy to power water pumps in areas away from population centers and main routes of transportation. The pumped water may be used near the source for irrigation or in mining operations, or it may be piped some distance to supply water to a community. The remote installations often require unattended operation.

The principal incentives for considering solar power for remote area water pumping derive from the following:

- The cost of conventional fuel is becoming prohibitively high in many remote communities and the supplies are becoming unreliabile
- The power requirements for water pumping often cause undesirable peak demands on the electrical grid.
- Seasonal demands for irrigation generally coincide with seasonal peak insolation, giving an excellent match of energy supply and demand.
- The water sources are often dispersed. The ubiquitous availability of solar energy lends itself well to on-site energy supply to dispersed small installations.

2.2 MARKET POTENTIAL

Remote area water pumping may be used to feed municipal water supplies, to serve industrial and mining installations, to supply water for farms and livestock operations or for irrigation of crop lands and pastures. The single largest volume of application among these is irrigation. In 1974 there were some 35 million acres under irrigation in the United States, and between 1.5 and 2 million acres of new land is brought under irrigation annually. The continuing increase in the demand for farm-grown food products, and the significantly better yield from irrigated land, will provide the incentives for large increases of the irrigated acreage in the foreseeble future. Many new and upgraded irrigation systems are using the so called center pivot system. It was estimated by the industry that as many as 15,000 to 20,000 center pivots were sold in the U.S. during the 1975-1976 period. Under nominal conditions, one of these center pivot units requires about 150 kWe for pumping water from wells and to provide the necessary system pressure, flow and auxiliary power for rotating the unit. Given a technically proven and economical solar system, one could expect that a growing share of these installations would be driven by solar power plants. The introduction of solar powered pumping may be accelerated in regions such as the northwest portion of Nebraska where the already existing irrigation systems compete for power with homes and industrial clients of the utilities during the summer months, and strain the peak load generating capacity of the local utilities.

2.3 CONVENTIONAL WATER PUMPING SYSTEMS

Designs of conventional pumping systems vary with the prevailing conditions at the site. Temporary or even semi-permanent systems are often assembled from components salvaged from other installations. The only requirement for such "cheap and dirty" pumps is that they deliver the required amount of water with adequate pressure. A rationally designed system for prolonged use must satisfy the head/flow requirements in the most economical manner.

The pumps used are mostly of the deep well turbine type. For shallow well applications, either horizontal or vertical shaft centrifugal or axial flow pumps are used, depending on suction conditions and intake configurations. Single or multiple stage units are selected, depending on the head requirements. Wide variations of water source conditions, distribution system requirements and pump efficiencies determine the power rating and operating range requirements for the prime mover.

The main consideration in selecting the prime mover is the availability and prevailing cost of energy at the site. For example, while electric pump drives are used to pump water for 44.5 % of the irrigated land in the U.S., in the Pacific Coast region, where electric energy costs are comparatively low, electricity is used almost exclusively. Other considerations include reliability, convenience of operation and initial investment costs.

The conventional water pumping system selected in this study for the purpose of economic comparisons with a reference solar powered system consists of electric motor-driven pumps which are powered from a rural utility grid. It was assumed that the pumps supply one of the increasingly more popular center pivot irrigators. The power required to drive the pumps and the center pivot unit was assumed to be 150 kWe.

2.4 EXISTING AND PROPOSED SOLAR POWERED WATER PUMPING SYSTEMS

The potential for using solar power in water pumping applications has been recognized for some time. The French SOFRETES consortium is marketing solar powered water pumping systems and has a number of them already operating in countries on three continents. These systems use relatively inefficient, water-cooled flat plate collectors, and Freon 11 or butane Rankine cycle heat engines. Unit capacities range from 1 to 50 kWe. In the U.S., other types of systems have recently been installed, mainly for demonstration purposes. They include several solar collection and energy conversion technologies.

Two of these demonstration systems use parabolic trough collectors and Rankine cycle heat engines. Water or heat transfer oils, such as Caloria supplied by the Exxon Corporation, are used to transfer the thermal energy from the collectors to a boiler where the heat is used to vaporize a Rankine cycle working fluid such as Freon or toluene. The output of the solar power unit is torque applied either to a pump shaft or to an electric generator. The system power ratings range from 25 kWe to 50 kWe.

Another installation, located in Nebraska, is designed to deliver 25 kWe using photovoltaic cells. Also, at least one recent installation uses a vertical shaft Darreius wind machine. There are, of course, a large number of old, multivane wind mills still in operation. In an ongoing Department of Energy (DOE) program, competing preliminary designs were recently developed for a 150 kWe deep well irrigation facility, variously employing; a heliostat and central receiver system, a parabolic dish collector system, and parabolic trough collector system.

Some existing U.S. installations also include energy storage provisions to extend the daily pumping time or to assure continuity of service during cloudy periods.

2.5 SELECTION OF A REFERENCE SOLAR POWERED WATER PUMPING SYSTEM

To establish a rational basis for selecting a reference solar power system, several factors, considered most important to long-term viability, were identified. These are:

- Stand-alone vs. hybrid operation
- System reliability
- System efficiency
- System operation and maintenance
- System safety and environmental impact

- Economics

An inventory of the available options for each subsystem of a solar powered water pumping system was prepared to identify viable combinations of these subsystem options and working fluid alternatives. It was found that the existing U.S. installations and designs proposed for the near future cover most of the plausible combinations (see Section 2.4). In particular, both the parabolic trough-Rankine cycle system and the parabolic dish-Brayton cycle system appear to be strong contenders for near term applications. While the former is more technologically developed, the latter appears to hold a competitive position if research and development continues to ascertain its technology. For the purpose of this study, a 150 kWe parabolic dish Brayton cycle system was arbitrarily chosen as a reference for economic comparison with the selected conventional water pumping system.

The reference solar system consists of fifteen two-axis tracking parabolic dish collectors, each equipped with a Brayton cycle heat engine-generator of 10 kWe nominal capacity. Each collector is also equipped with a receiver to convert the concentrated solar energy into thermal energy for use in the power cycle. A centralized power conditioning subsystem is provided with the system. The specified capacity of 150 kWe is adequate to power the water pumps for one center pivot irrigator, which is identical to the one specified for the selected conventional water pumping system (Section 2.3). It is assumed in this system that when solar energy is not available, the pumps of the irrigation system are powered from the utility grid.

2.6 ECONOMIC COMPARISONS

The levelized cost of capital recovery over the life of the solar powered plant is used as the basis of economic comparisons with the conventionally powered plant. In the solar plant, the major part of the cost of energy is the amortization of the initial investment. Operating and maintenance costs are less significant contributors. In the conventional plant, electric energy cost is the major factor. It has been projected that energy costs will escalate at a higher rate than the cost of other materials and services. To span the range of probable escalation of the cost of energy, rates of up to 10% above an estimated general inflation rate of 7% were assumed. As shown in Figure 2-1, if the generating plant of the reference solar powered water pumping system costs $1,174,000, and operates in conjunction with utility supplied power, economic breakeven with the conventional system would be reached within the design life of 30 years unless the escalation rate was about 6% above a general inflation of 7% annually. If this type of solar systems is to achieve a more competitive status, major improvements in performance and cost must be achieved. Due to the lack of meaningful data on the collector and engine costs, this economic analysis must be regarded as very preliminary with the results subject to futher verification.

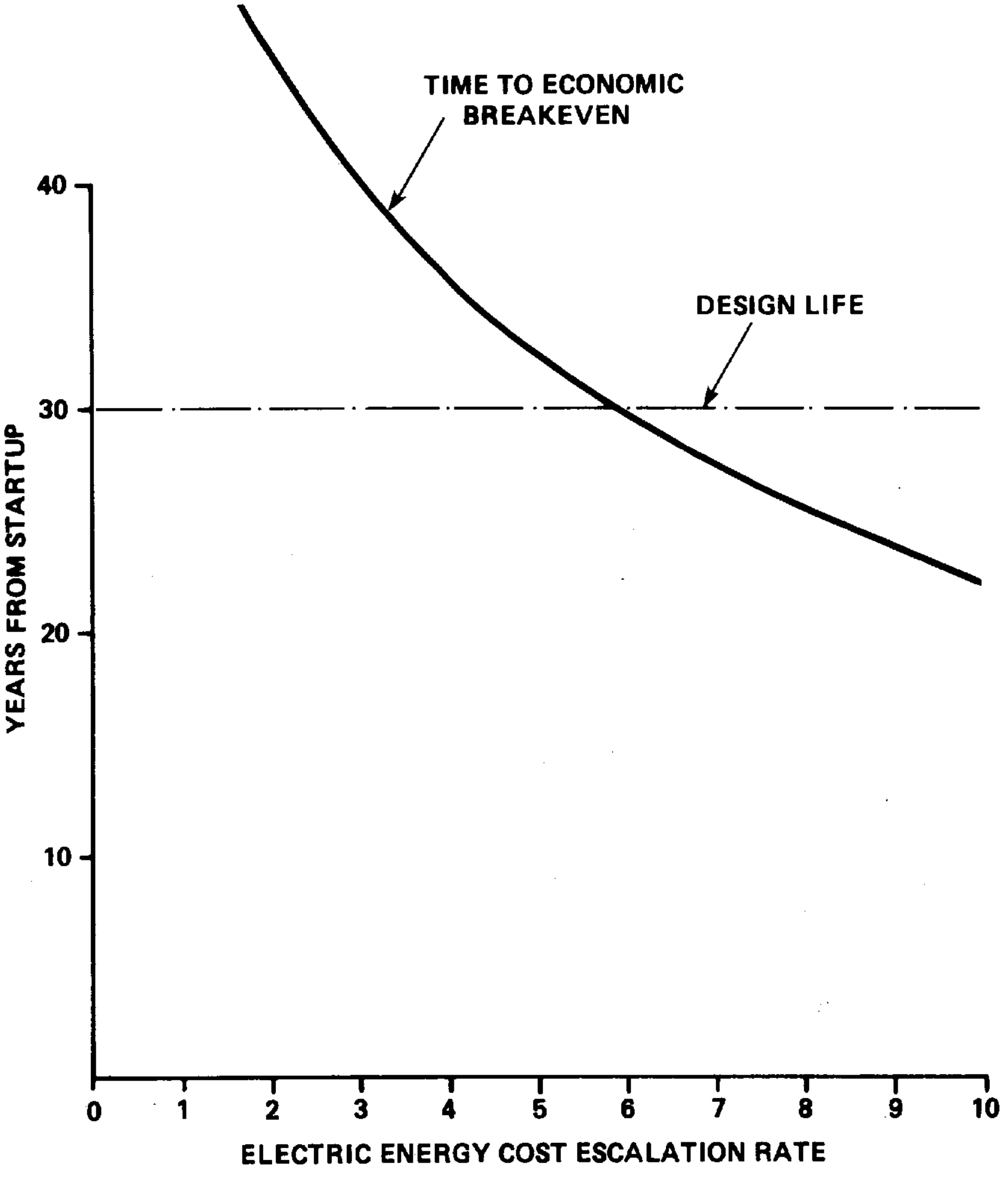


Figure 2–1 SOLAR VS CONVENTIONAL WATER PUMPING COST BREAKEVEN TIMES

2.7 TECHNICAL UNCERTAINTIES

Several areas of technical uncertainty were identified with regard to the reference solar system. The more significant of these are the following:

- The concept requires the development of an efficient receiver for air-cooled service.
- Although Brayton engines are available in the range of required operating conditions, complete solar power system modules must be tested to verify integrated operating characteristics.
- Improved methods for the mass production of low cost, high quality dish collectors and mount drives are needed.
- The dynamic characteristics of a number of low capacity generating systems operating in parallel with large inductive loads must be determined.
- The performance capabilities of a viable reference design need to be tested over a range of typical site conditions.
- Development of low cost, highly efficient regenerators is needed.

2.8 CONCLUSIONS AND RECOMMENDATIONS

2.8.1 Conclusions

The results of this study indicate that water pumping could eventually become a valid application of solar power both in the United States and abroad. Significant market potential is evident in the field of irrigation where the rapid increase of irrigated acreage requires many new pumping installations. Retrofitting existing irrigation facilities represents additional sales potential. Power shortages, already developing in certain areas of the U.S. where the power requirement for irrigation is placing a severe burden on local utilities, provide a strong incentive for considering solar energy for water pumping. However, at this time the high cost of this solar application represents a serious drawback.

Solar water pumping technology development is pursued vigorously in the U.S. as well as in foreign countries. Design, construction and operational data were obtained from commercial and demonstration installations employing solar thermal, photovoltaic and wind power conversion techniques. At this time, however, there is no clear indication as to which of these technologies will eventually be best suited for water pumping applications. It is probable that the broad range of site specific conditions, service requirements and system economics will result in several generic types of solar systems. Under present financing conditions, tax structures and expected conventional power cost escalations, solar powered water pumping will not be economically viable in this century except in locations where power costs are already much higher than the national average. To accelerate market penetration, it will be necessary to be economically competitive. This may be achieved by reducing the cost of solar collection equipment and by instituting additional market incentives.

2.8.2 Recommendations

Based on the findings of this study it is recommended that:

- The efforts to develop the technical and institutional bases for using solar power in remote area water pumping applications be continued.
- Follow-on engineering studies be undertaken to develop one or more generic conceptual designs of solar powered pumping systems best suited to meet the power requirements of such applications.
- The most effective modes of fully utilizing the output of solar power plants where the water pumping requirements are seasonal be identified, and the economics, utility interfaces and institutional barriers associated with such plants be evaluated.
- Requirements for a representative stand-alone solar powered water pumping system be identified, and a conceptual design, including water or energy storage provisions, be developed for subsequent technical and economic evaluations.

Section 3

MARKET POTENTIAL FOR SOLAR POWERED WATER PUMPING

The results of the review of potential markets for solar powered water pumping are reported in this section. The characteristics of the pumped water demand and the sources of water are also described, since both of these considerations affect the requirements placed on a potential solar powered water pumping system.

3.1 AGRICULTURAL WATER USES

The incentive for considering solar energy for water pumping is perhaps best illustrated by the fact that in 1974 some 260 trillion Btu were used to pump water in the U.S. for irrigation alone. In addition, the availability of solar energy at the widely scattered wells and other sources of water offers the potential for local solar energy conversion and utilization. The single greatest use of pumped water in the United States is irrigation of farm and pasture land (Ref. 3-1). The annual increase of irrigated acreage is also quite significant.

3.1.1 Irrigation Water Use in the United States

A comprehensive summary of the irrigation water uses in the U. S. during 1974 was presented in a paper by Gordon Slogget (Ref. 3-1), prepared for the 1977 ERDA Solar Irrigation Workshop. The study covers the eleven regions of the U.S.A. shown in Figure 3-1.

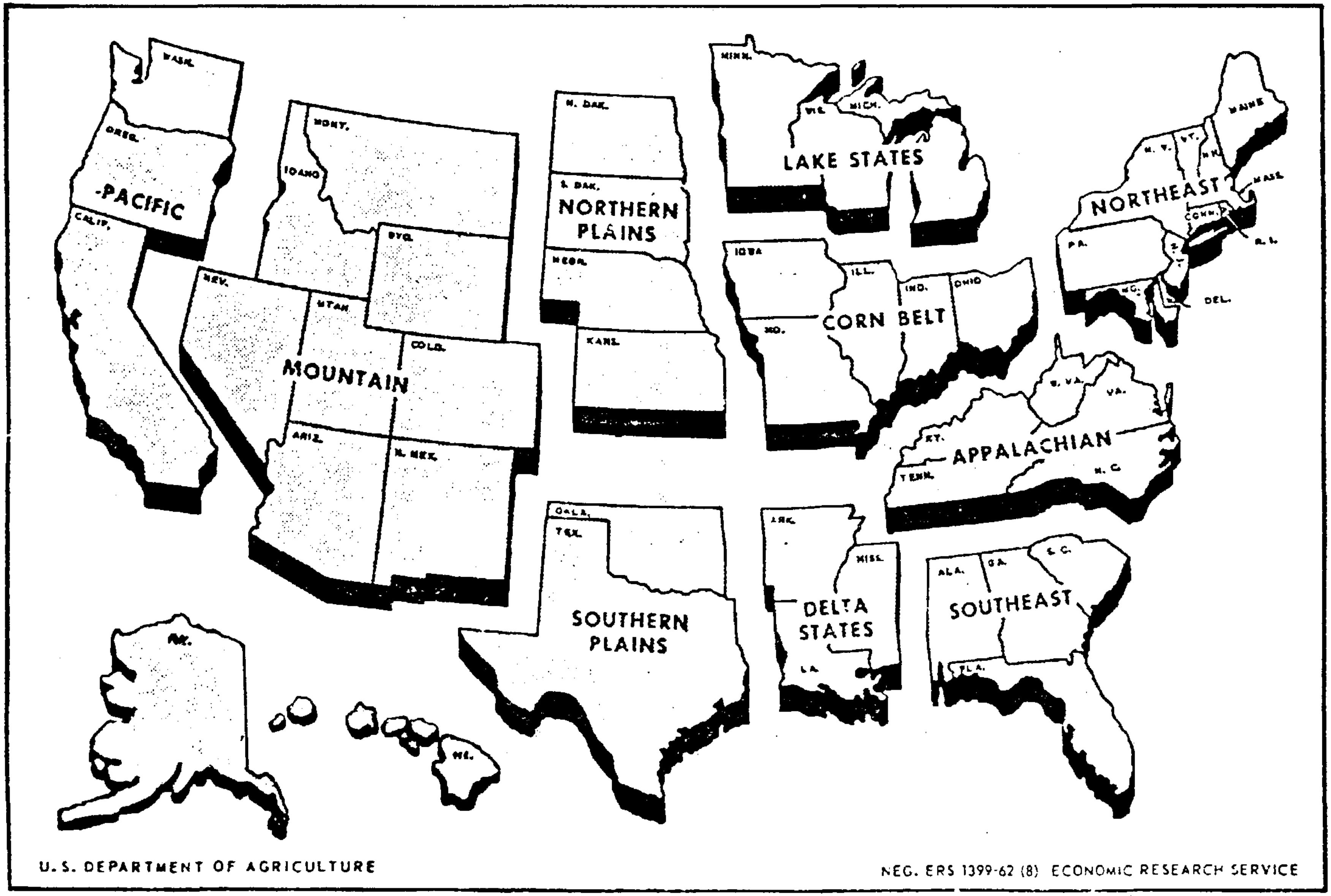


Figure 3-1 FARM PRODUCTION REGIONS

In terms of acreage, the six regions west of the Mississippi River contain about 96% of the total of some 35 million irrigated acres (Table 3-1). The cost of irrigation water pumping in 1974 was nearly $500 million, averaging about $17 per acre-year.

In terms of energy sources, electricity and natural gas are the most prominent. About 44.5% of the irrigated land used electric power and 30.4% used natural gas driven pumping. Diesel, LPG fuel and gasoline, in descending order, accounted for the remaining 25.1%. Significantly, electricity accounted for 55.9% of the expenditure for irrigation energy, costing $20.42 per acre-year.

An important consideration for irrigation pumping is the type of water distribution, since its energy requirements are additive to any lift required to feed the distribution system. In 1974, the largest U.S. acreage (71%) used surface distribution. Sprinklers and center pivot systems accounted for 17 and 10 percent respectively. So called "large guns" irrigated about 2%. Average lift and distribution requirements to supply the various systems are as follows:

Large guns	381	ft of equivalent lift
Center pivot	231	"
Sprinklers	161	"
Surface distribution	12	"

The annual irrigation requirements are generally under 1 acre-foot east of the Mississippi, and rise progressively to the west.

TABLE 3-1

ACRES IRRIGATED WITH PUMPED WATER BY SOURCE OF WATER FOR THE UNITED STATES, 1974

Regions	Groundwater Only	Surface Water Pumped	Both	Total
	1,000 acre			
Northeast	137	155		292
Lake States	253	158		411
Corn Belt	274	96		370
North Plains	6,380	684	186	7,250
Appalachian	17	175		192
Southeast	1,058	980	3	2,041
Delta States	1,966	722		2,688
South Plains	7,770	1,491	256	9,517
Mountain	3,431	881	1,284	5,596
Pacific	4,638	2,004		6,642
Alaska	3	4		7
Hawaii	70	6		76
Total	24,997	7,356		35,082

Arizona requires about 5.5 acre-feet, and in the State of Washington the requirement is 3.8 acre-feet.

Demand for irrigation water varies according to the growing cycle for various crops. In general, the summer months from June through August are the high demand periods. August universally represents peak demand. Irrigation is usually required for 105-165 days (Ref. 3-2).

Since 1974, pumped water irrigation has been affected by the following events:

- Energy costs have escalated at rates exceeding the average inflation rate.
- Irrigated acreage has increased.
- The water tables have been receding due to extensive pumping and chronic shortage of precipitation particularly in the regions west of the Mississippi.
- High energy consuming irrigation systems such as the center pivot system have been used more extensively.
- The availability of natural gas has decreased, threatening the cheapest and the second largest source of energy for irrigation.

The following observations apply to potential solar applications for irrigation water pumping:

- Peak demand for irrigation water very closely coincides with peak solar energy availability.
- Regions with the highest irrigated acreage receive the largest yearly insolation.
- Where an electric grid is not available and the pumping requirements are satisfied by stationary, on site,

fossil-fired (internal combustion) engines, local stand-alone solar systems could be employed.

- The benefit of solar energy to displace other energy sources can be maximized by incorporating water storage capacity, particularly elevated storage, if possible, to provide both flow and head during diurnal outages and cloudy periods.

3.1.2 Sources of Irrigation Water

According to Reference 3-1, ground water is used on 74% of the irrigated land in the U.S., 21% is irrigated with pumped surface water and 5% is served from both ground water and surface water.

Ground water well depths vary widely with the local terrain and hydrology. In the regions with the largest irrigated acreage and largest per-acre consumption, water must be lifted 100-350 ft to the surface. In general, surface water requires less than a 60 ft lift. In a few states, however, where irrigated land is on high plateaus, served from rivers and reservoirs in the valleys (such as South Dakota, Washington, Oregon), even surface waters must be lifted 150-250 ft. Typically the wells have a capacity of 700 gpm or less. For example, in the high plains of Texas, 73% of the wells deliver less than 700 gpm (Ref. 3-2). The average well irrigates about 84 acres in that region.

3.1.3 Other Agricultural Water Uses

Other major agricultural users of water are dairies, cattle feed lots and produce growing. Dairy operations require about 20-30 gallons of water per day per head for watering, feed preparation and operation of the dairy. Feed lot operations require 20-25 gallons per head per day. For both of these operations, the water requirements are essentially continuous. Water for these users is derived from wells and surface water sources. Most of the systems use piping distribution with pressures in the order of 150 ft. A significant percentage of the pumps are electrically driven. Range cattle watering requires in the order of 15-20 gallons per day per head. Deep wells supplying the water are the most common sources. Some of the produce grown on irrigated land requires water for washing in preparation for shipment to markets. Demand for water in such operations can be satisfied by irrigation water pumping systems.

3.2 COMMUNITY AND INDUSTRY WATER SUPPLIES

Remote communities of modest population (100-1,000 residents) are often associated with farming areas and mining operations. Farming community water demands usually have a base load supplying the commercial establishments and the permanent population. The demand varies seasonally to satisfy the domestic water needs of migrant or other temporary labor. Mining communities normally have a more stable population all year around. Demand on the water supply varies somewhat on a seasonal basis, using more water during the summer months. Community water systems more often use well water, and pumps are predominantly electric motor driven. The water is distributed under pressure (in the order of 100-150 ft of head). Local canneries, in or near farming communities, use the community water supply if adequate quantity is available. A typical operation described in Reference 3-3 uses 200,000 gallons per day for washing cans in a California cannery which operates year round. Ore leaching or washing operations near the mines represent high demand for water. A uranium milling operation, described in Reference 3-3, requires 300,000 gallons of water per day. Surface water or wells provide the needed supplies, determined mainly by local conditions. Some of the mining operations use high pressure sprays requiring high pump discharge heads.

3.3 POTENTIAL FOREIGN APPLICATIONS

Numerous projects have been initiated in the past decade to introduce more sophisticated farming techniques to improve the world food supply by bringing additional acreage under productive farming and by improving the productivity of already farmed acreage through the use of artificial fertilizers and by irrigation. Solar powered pumping may become an important means for providing the irrigation water in remote interior parts of Africa and the Indian Subcontinent, where energy costs are high and where local sources of fossil fuels are limited. Solar powered water pumping may also be used to supply potable and domestic water for remote communities in these regions. Water pumping systems developed by the French SOFRETES Group are aimed at satisfying such remote markets.

Section 4

TECHNOLOGY OVERVIEW

In current practice, water pumping systems are assembled from standard equipment selected to meet the water flow, head and distribution requirements of the user. There is great variation from system to system. In this section, several typical conventional and solar powered water pumping systems are described. An overview of the potentially applicable solar energy conversion and energy storage alternatives is also presented.

4.1 TYPICAL CONVENTIONAL WATER PUMPING SYSTEMS

The major components of a pumped irrigation system include:

- Sources of water - reservoirs, rivers and wells
- Pumps - centrifugal, axial flow and turbine types
- Prime movers - electric motors, diesel engines and spark ignition engines
- Water distribution systems - furrows, pipes and sprinklers of different types

Domestic and industrial water supply systems consist of similar components, except that they may have purification and chemical addition systems to make the water safe for human consumption. The water sources and the distribution system requirements are the prime factors affecting the system power requirements. Pump types are selected to satisfy the head, flow and suction lift conditions. Energy source availability and economics dictate the choice of prime movers. In the following sections, three typical conventional pumping systems are described to indicate the range of requirements imposed by the water sources and distribution system types.

4.1.1 Surface Water Pumping, Gravity Distribution System

This system is typical for a large share of the irrigation applications. It requires a comparatively low power of 15 kWe for pumping 1,000 gallons per minute as calculated from typical data of Reference 4-1. This type of system would be used for lifting reservoir or river water into distribution canals. Two or more high volume, low head pumps are usually installed to assure redundancy, to provide flow regulation and occasionally to compensate for variation in suction heads. The pumps are individually driven by electric motors, diesel engines (in large units), or by spark ignition engines (in low power applications). The operation is generally demand controlled.

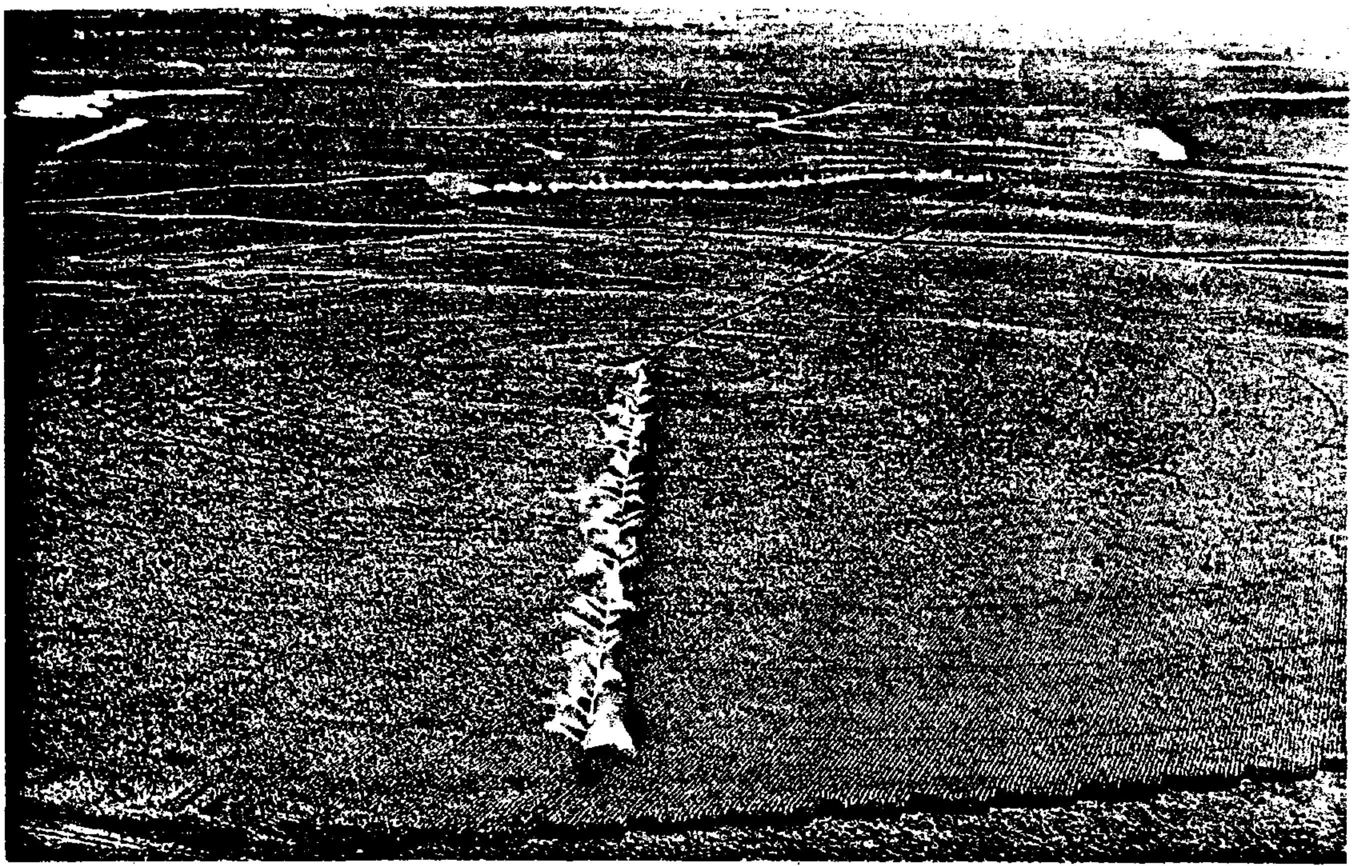
4.1.2 Surface Water Pumping, Pressurized Distribution System

This type of system may be used to lift water from the reservoir level to elevated irrigation canals, and to pump the water against the distribution system pressure. Pumping power ranges from 70 to 150 kWe for 1,000 gpm flow, again calculated using typical data from Reference 4-1. A representative installation along the Columbia River, using the progressively more popular center pivot irrigation method, irrigates 133 acres of land delivering 1/4 to 1/2 inch per day, completing the cycle in 24 hours. Three electrically driven centrifugal pumps require about 50 kWe each. In the Plains States such pumping systems more commonly use natural gas driven engines or diesels.

4.1.3 Deep Well Pumping, Pressurized Distribution System

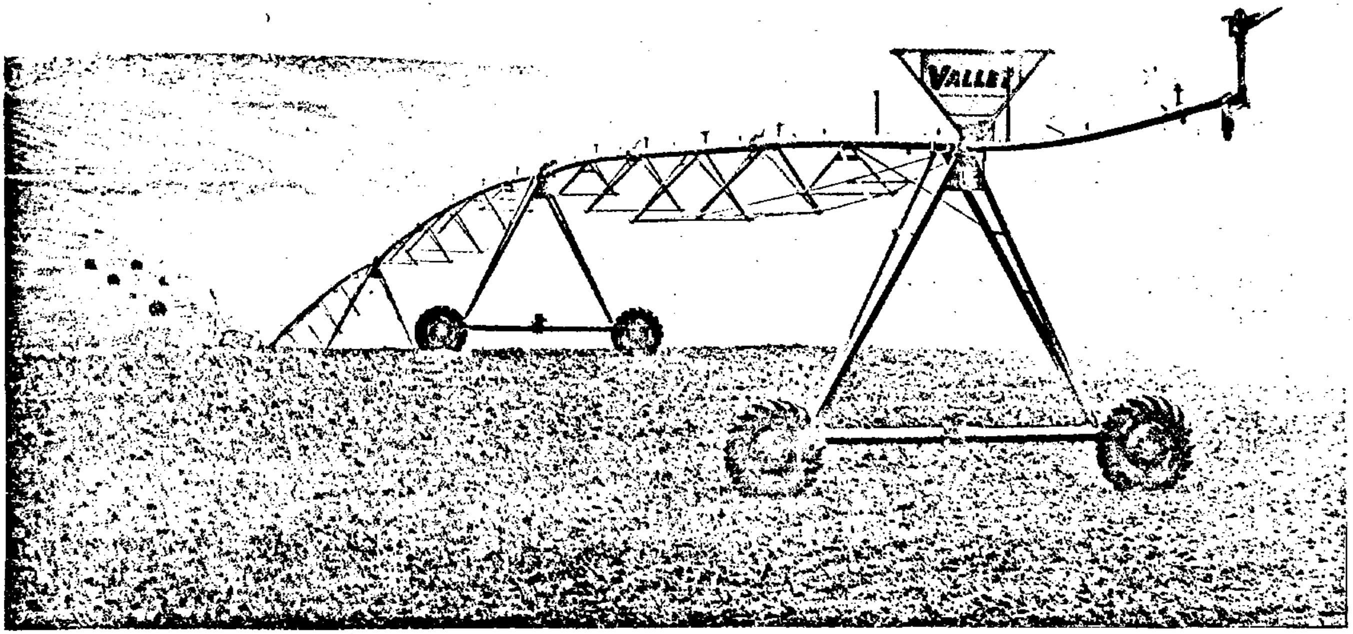
This application is typical for semi-arid areas where subterranean aquifers are used as sources to supply high pressure distribution systems for irrigation, domestic and industrial users. Pumping power requirements per 1,000 gpm range from 100 kWe for shallow wells and domestic supply to 225 kWe for deep wells supplying large gun irrigation systems.

Reference 4-2 describes extensive agricultural applications installed in Nebraska using center pivot irrigation systems (Figures 4-1 and 4-2). Each irrigation unit requires approximately 150 kWe to irrigate a quarter section at a rate of 3/8 inch per day. Deep well turbine pumps are generally used. They are driven mostly by natural gas fueled internal combustion engines. Electric motors are also used. Multiple wells usually supply each sprinkler train.



COURTESY OF RAIN BIRD MFG. CORP. GLENDORA, CA.

Figure 4-1 AERIAL VIEW OF CENTER PIVOT IRRIGATION SYSTEMS IN NEBRASKA



COURTESY OF VALMONT INDUSTRIES, INC. VALLEY, NEBR.

Figure 4-2 GROUND LEVEL VIEW OF AN OPERATING CENTER PIVOT

4.2 SOLAR POWERED WATER PUMPING SYSTEMS

The simplest form of solar powered water pumping, still visible and in limited use, is the windmill pump. It is used to lift modest amounts of well water from shallow wells in remote areas for farm use. In the past two decades, several types of solar powered demonstration pumping units have been built--and more are planned--to test the viability of the use of solar energy for water pumping. The French consortium SOFRETES, in a sales brochure dated September 15, 1976, listed 25 existing solar thermal "commercial installations" they have supplied, and 36 more being installed in Africa, South America and the Philippines. A number of novel pumping concepts have also been proposed by others. Modest size models or demonstration units have been built for some of these.

This section discusses typical solar powered water pumping installations currently operating or scheduled for construction in the near future.

4.2.1 The SOFRETES Systems

References 4-3 through 4-5 describe in detail the line of solar pumping systems offered by SOFRETES. All of these use flat plate collectors, and power delivery ranges from 1 to 50 kWe per single unit. Although these systems have comparatively low thermodynamic efficiencies, their rugged construction and simplicity of operation makes them eminently suitable for remote area operation.

One of their most impressive installations is the the solar pumping station for the city of San Luis de la Paz, Mexico. This 30 kWe unit can supply about 2.4 million gallons of water per day at an average rate of 660 gpm with a combined lift-discharge head of 130 ft. The collector area is 16,140 ft^2. A Freon 11 Rankine cycle drives a 7400 rpm turbine-alternator. An aerial view of the station is shown in Figure 4-3.

4.2.2 Gila River Ranch Pumping System

This 50 hp peak capacity system was developed for low lift pumping by the Battelle Memorial Institute. The installation is located near Phoenix, Arizona, and is intended as a demonstration for units of 100 hp or larger. Water cooled parabolic trough collectors are used to capture the solar energy. In this system, the turbine of the Freon 113 Rankine cycle is directly coupled to the pump shaft. The operating system is shown in Figure 4-4 and is described in Reference 4-6.

4.2.3 New Mexico Solar Experiment

This plant is located near Albuquerque, New Mexico. It is a part of Department of Energy's (DOE) solar irrigation program, covering the shallow well phase, and was completed in 1977. The system uses parabolic trough collectors cooled by a heat transfer

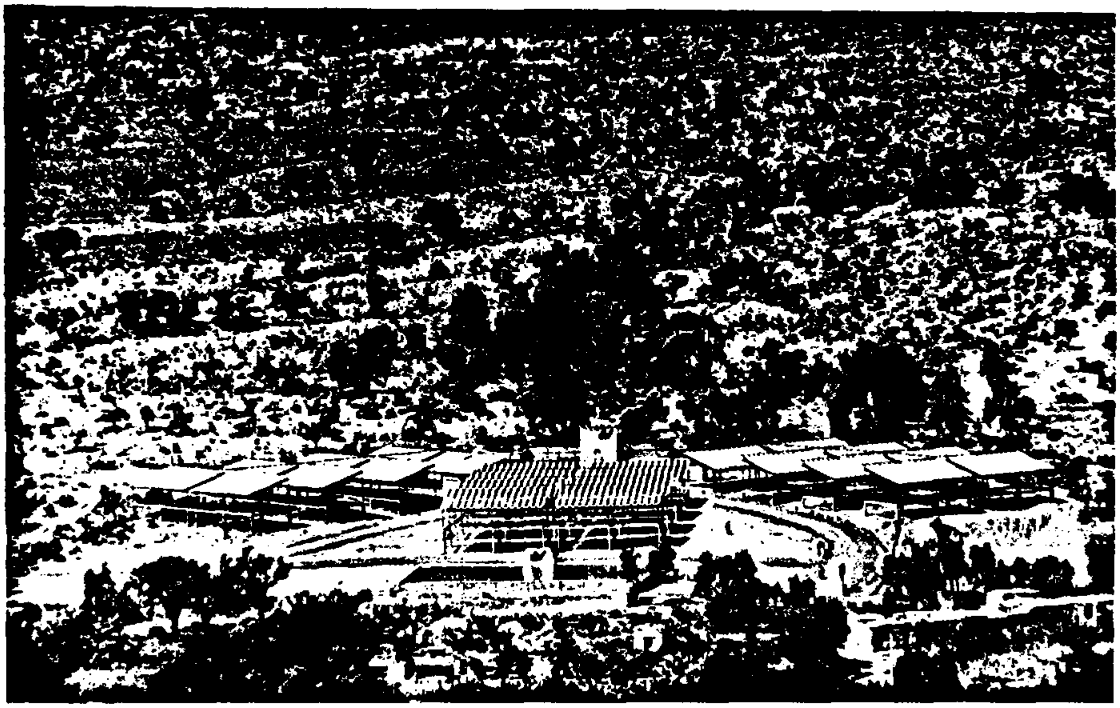


FIGURE 4-3 SOLAR STATION WATER SUPPLY FOR THE CITY OF SAN LUIS DE LA PAZ

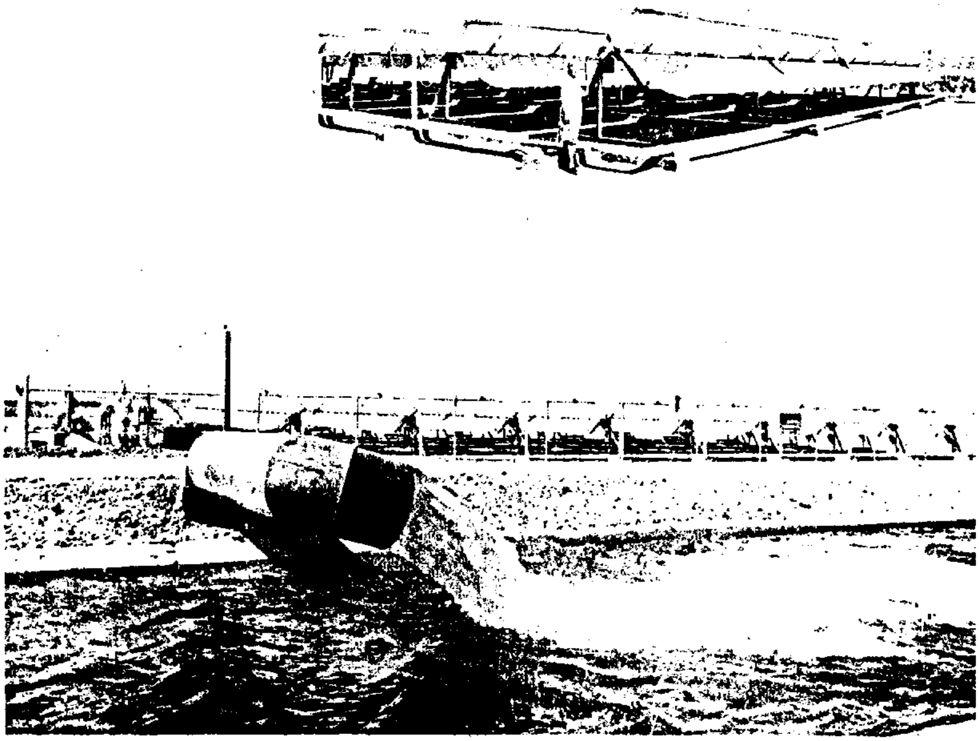


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Figure 4-4 THE GILA RIVER RANCH PUMPING SYSTEM IN OPERATION oil. A Freon 113 Rankine cycle powers a 25 hp turbine which develops the torque needed to directly drive the shallow well pump. The pumped water is discharged to a reservoir for later distribution to the irrigation system, using a diesel engine to drive the distribution pumps. An artist's concept is shown in Figure 4-5. The project is described in several reports, including References 4-7 through 4-9.

4.2.4 Solar Carousel Irrigation Pump

This system, designed by the Sunpower Systems Corporation of Arizona, will be installed on University of Arizona land near Phoenix (Ref. 4-9). The double tracking parabolic trough system is unique in that the entire group of single axis collectors is rotated on the carousel through 180 degrees each day so as to track the sun in two modes, east-west and north-south. A partially exploded view of the future installation is shown in Figure 4-6. The collectors are water-cooled. The collector water is used to generate steam at 230 psig. A positive displacement steam engine capable of delivering 70-75 hp will be used to drive the pump through a standard right angle drive.

4.2.5 Solar Powered Deep Well Irrigation Facility

This facility, resulting from the deep well phase of DOE's solar irrigation program, will be located near Coolidge, Arizona, southeast of Phoenix. Phase I, preliminary design, of the project was completed in August 1977 and construction is

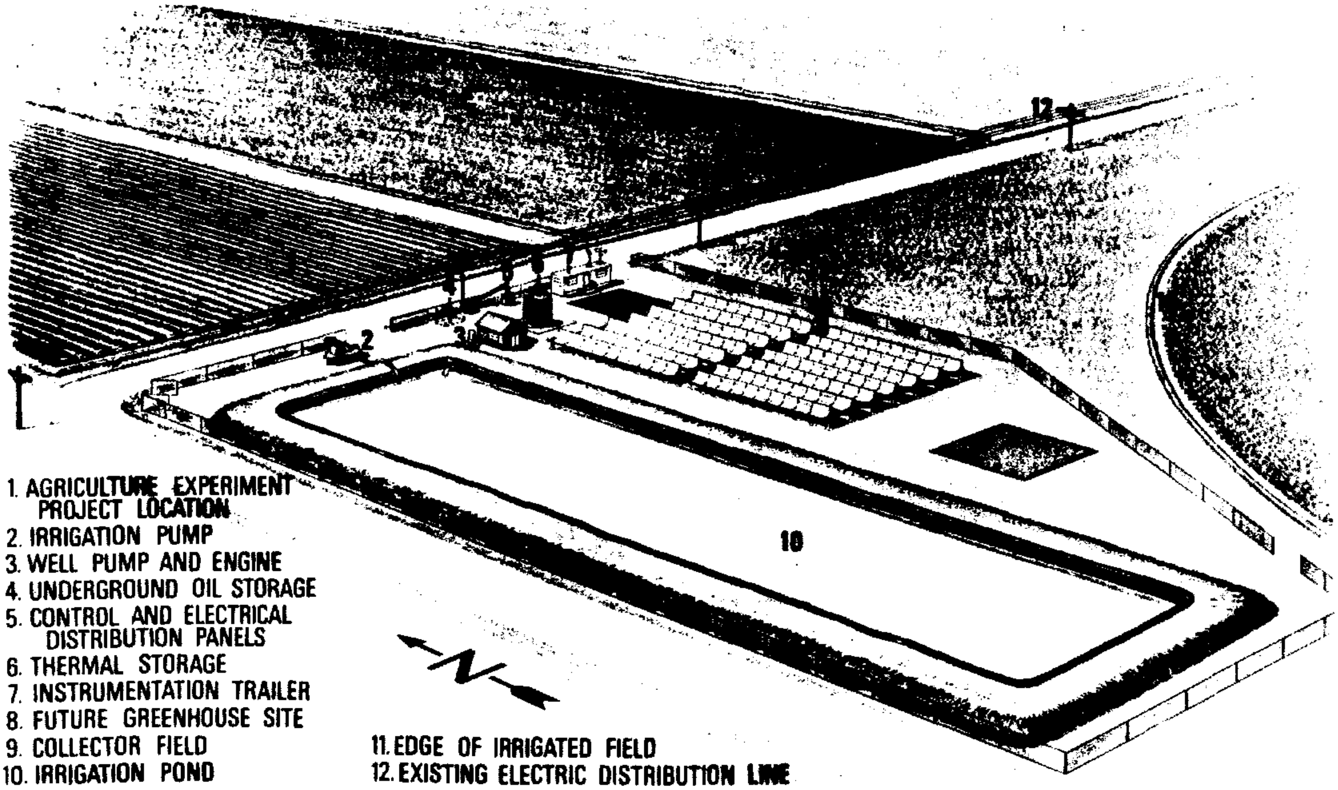

Figure 4-5 ARTIST'S CONCEPTION OF DOE'S NEW MEXICO SOLAR EXPERIMENT

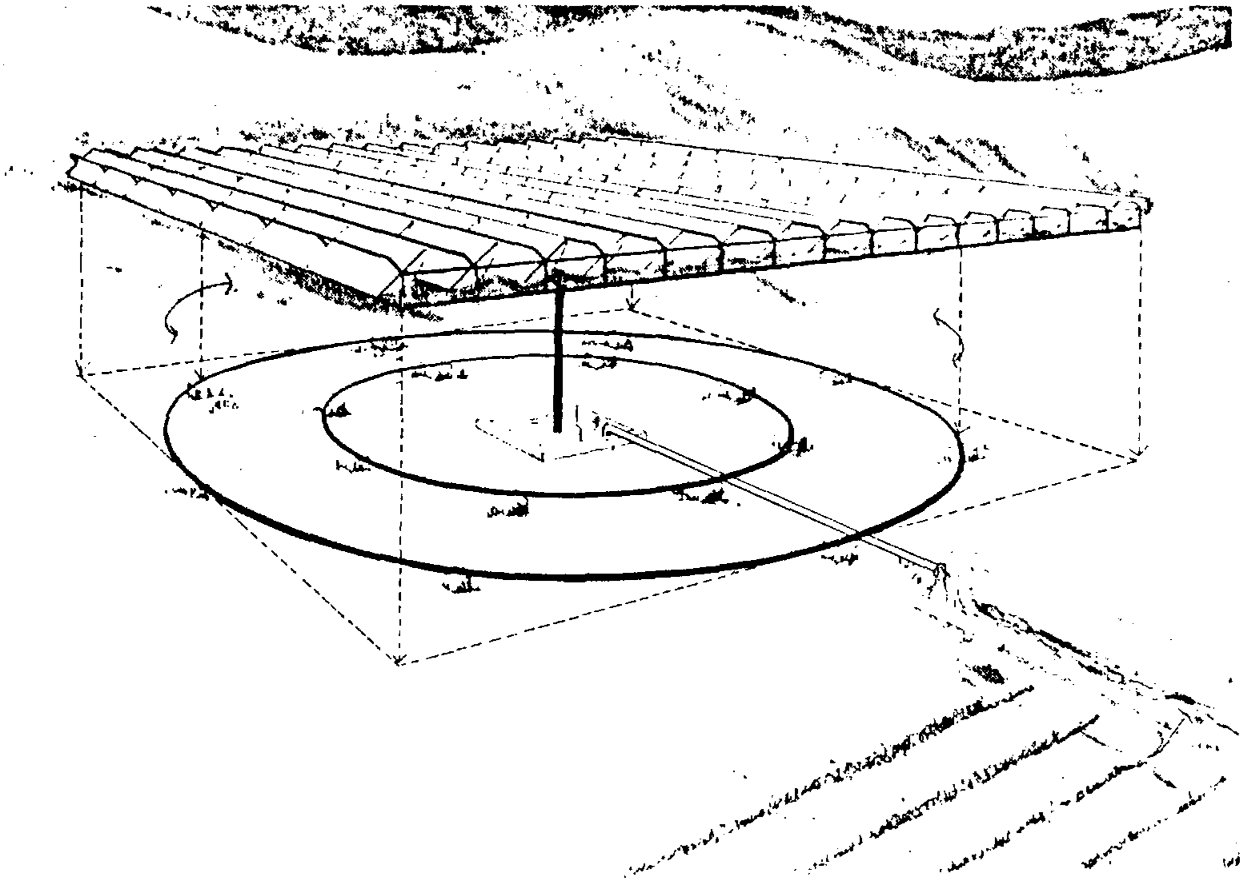

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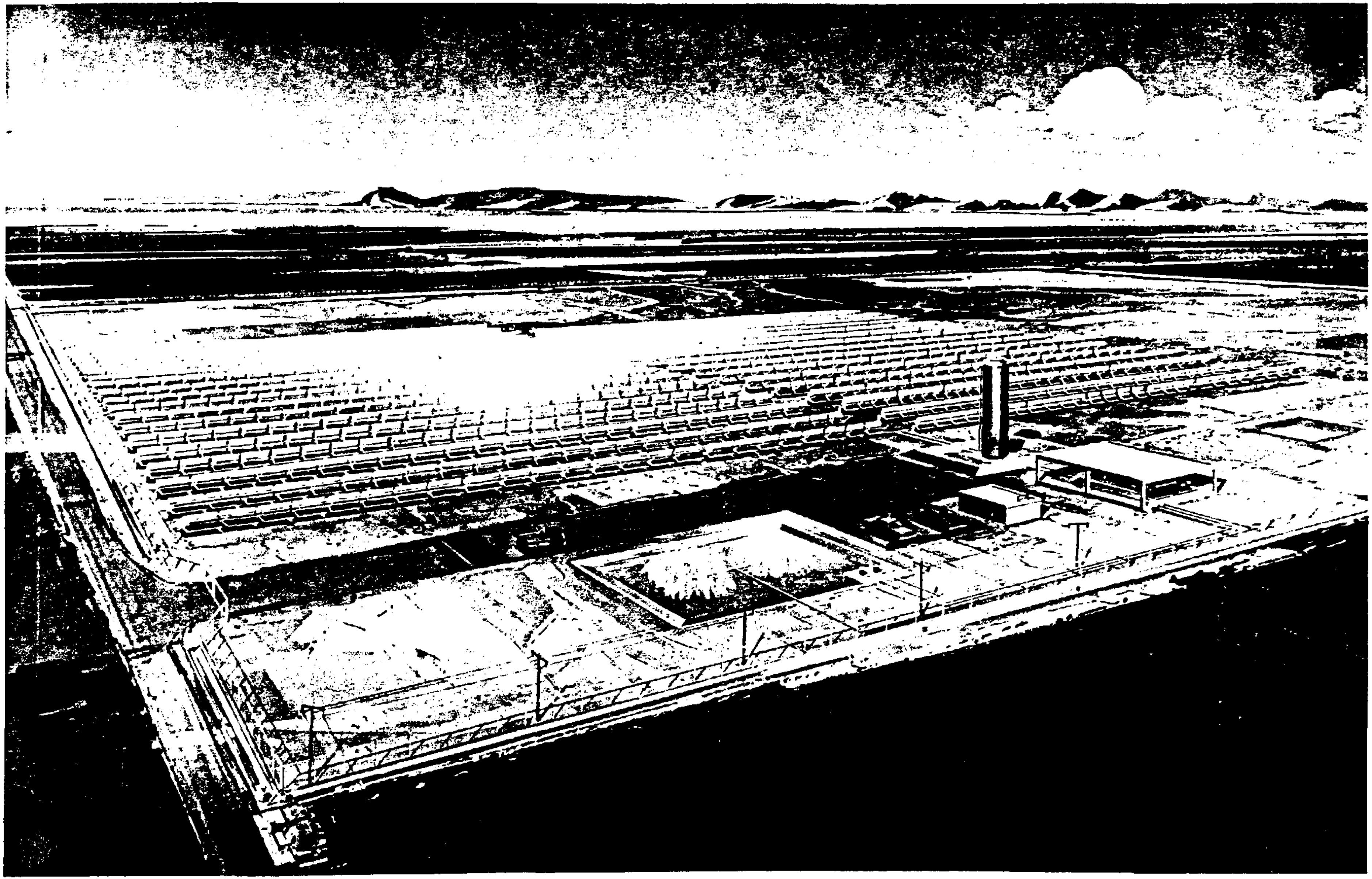
FIGURE 4-6 PARTIALLY EXPLODED VIEW OF THE SUNPOWER CAROUSEL IRRIGATION PLANT scheduled for completion in 1978. When completed, the solar power station will deliver 150 kWe to three existing deep well pumps. In the preliminary design phase, three alternative concepts were developed. These are:

- Single axis tracking parabolic trough collectors with regenerative organic Rankine cycle as designed by the Acurex-Bechtel-Sunstrand Team. An artist's conception of this system is shown in Figure 4-7 (Ref. 4-10).
- Two-axis tracking parabolic dish collectors, with air operated regenerative Brayton cycle heat engine as designed by Honeywell (Ref. 4-11).
- Central receiver solar thermal system concept designed by Black & Veatch, (Ref. 4-12).

The parabolic trough-organic Rankine cycle concept of the Acurex-Bechtel-Sunstrand team was selected by DOE for Phase II detailed design and construction.

4.2.6 Nebraska Irrigation Project

The Lincoln Laboratories of MIT,, under DOE sponsorship, is conducting an experiment with photovoltaic arrays, providing 25 kWe peak power to drive two pumps at Mead, Nebraska. The system pumps 1,000 gpm of water from a surface reservoir to irrigate 80 acres. With battery storage, the system provides power to drive the pumps for 12 hours each day. The dual purpose project supplies power for grain drying after the irrigation season (Ref. 4-13).



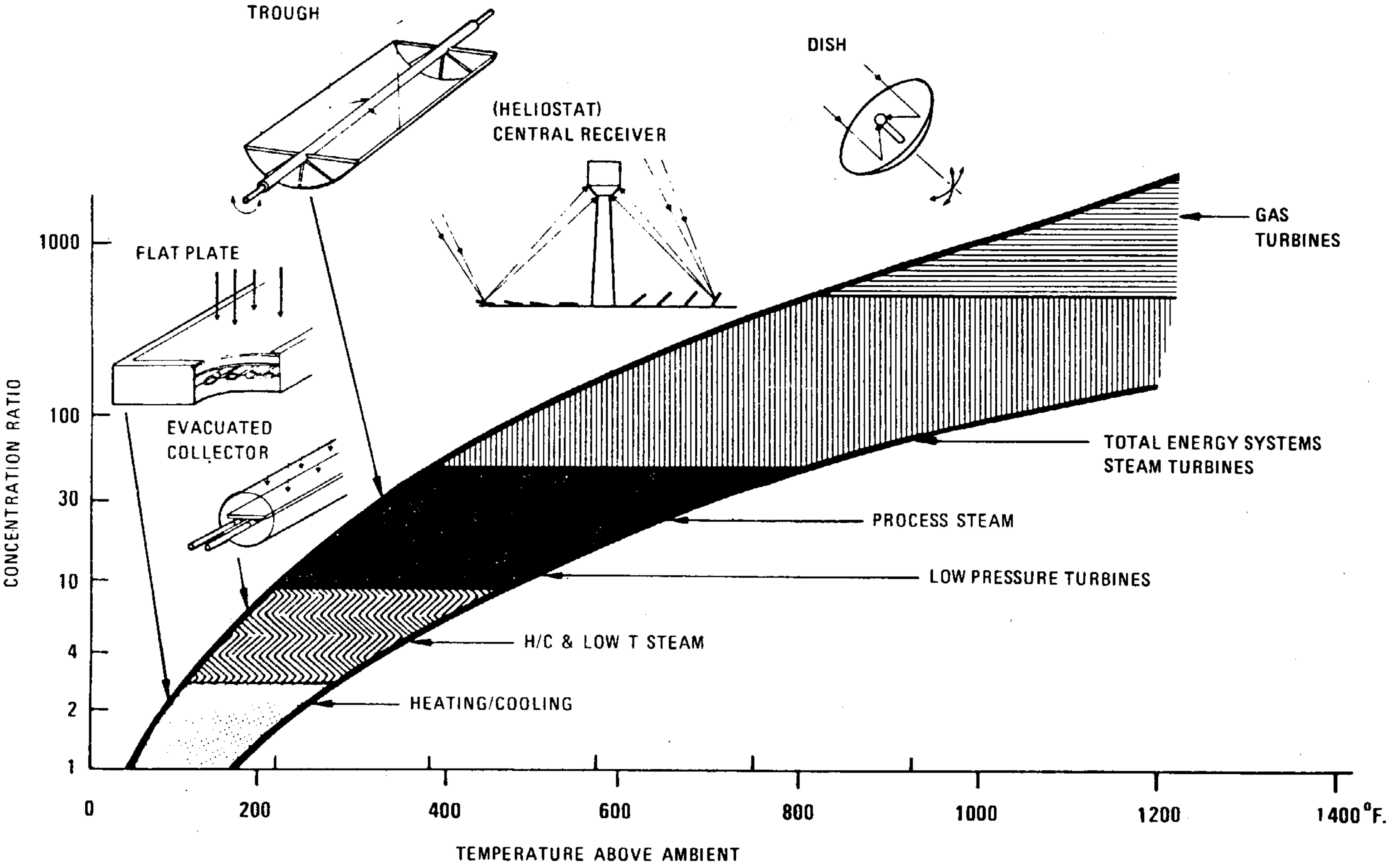
4.2.7 Irrigation Pumping with Wind Energy

Experimental work with irrigation pumping, using modern wind turbines, is in progress under the auspices of the U. S. Department of Agriculture in collaboration with DOE. A 10 hp vertical axis wind turbine (Darrieus type) is operated at Manhattan, Kansas to directly drive a low lift irrigation pump. A 40 hp Darrieus wind turbine is on order to drive a deep well turbine pump at the USDA Agricultural Research Center in Bushland, Texas. At present a 4 hp wind turbine is operating at this site. This unit, coupled to the existing pump drive with an overrunning clutch, is working against a 200 ft lift and a discharge pressure of 42 psi. It is used to augment the capacity of an existing engine (Ref. 4-14).

4.3 SOLAR ENERGY COLLECTION METHODS

4.3.1 Solar Thermal Methods

Solar insolation represents an energy input of about 1800 Btu/ft^2-day. A number of different devices, suitable for solar water pumping applications, have been developed and marketed to collect this energy. Technical details of the various designs are amply described in nomograms and manufacturers literature and will not be given here. Figure 4-8 shows a composite of the main characteristics of various collector types. The projects described in Section 4.2 include the following solar thermal collector types:


TROUGH
(HELIOSTAT)
CENTRAL RECEIVER
DISH
FLAT PLATE
EVACUATED
COLLECTOR
GAS
TURBINES
TOTAL ENERGY SYSTEMS
STEAM TURBINES
PROCESS STEAM
LOW PRESSURE TURBINES
H/C & LOW T STEAM
HEATING/COOLING
CONCENTRATION RATIO
1000
100
30
10
4
2
1
0
200
400
600
800
1000
1200
1400°F.
TEMPERATURE ABOVE AMBIENT

- Flat plate nontracking collectors - typically low temperature, (50-250 F above ambient), low concentration ratios.

- Parabolic trough collectors - typically single-axis tracking, intermediate temperatures (200-800 F above ambient); solar concentration ratios in the range of 20-50.

- Heliostat/central receivers - heliostats have single axis or two-axis tracking, high temperatures (400-1,200 F above ambient), high concentration ratios (100-800).

- Parabolic dish/focal point receivers - two-axis tracking, packaged collector-energy conversion units, high temperatures (>1,500°F), high concentration ratios (>800).

Other collector systems under development with application potential include: the compound parabolic concentrator (CPC) collector, Fresnell lens collectors and evacuated tube type collectors. All of these operate with low concentration ratios, in the lower temperature ranges. Developers and manufacturers of each of these solar collector types are making strong efforts to improve their efficiency by reducing optical and thermal losses. However, the range of temperatures achievable with these collector types is not expected to change appreciably.

Combinations of series and parallel connections of the flat plate or parabolic trough solar collector piping systems are used to achieve the desired power rating. The solar system efficiency is only a weak function of the number of connected collectors in systems which use distributed collectors. With the exception of a few undemonstrated approaches, all solar thermal devices require some type of heat engine to convert the collected energy to shaft torque or electric power to use in pumping applications. Heat engines suitable for solar pumping applications are described in Section 4.4.

The method for transporting the collected energy to the heat engine is by pumping a suitable fluid through the collector receivers. Heat absorption usually occurs in a single phase, sensible heat transfer mode in all receiver concepts except for the central receiver, which may also include boilers and superheaters. Heat transfer fluids for solar service include:

water - suitable for low temperature systems, mainly flat plate collectors

steam/water - up to 950 F, suitable for central receiver concepts

heat transfer oils - up to 600 F, suitable for parabolic trough and central receiver concepts. These oils are marketed under trade names such as Therminol 66, Caloria HT-43, and Dowtherm.

molten salts - 1,050 F or higher, suitable for high temperature central receiver concepts. These salts are marketed under trade names such as Hitec (a eutectic salt mixture).

alkali metals - up to 1,150 F, suitable for high temperature central receivers. Sodium or NaK are candidates.

air and other gases - about 1,500 F, suitable for high concentration such as in parabolic dish or central receiver systems.

Aside from the gases, these heat transfer fluids may also serve as thermal storage fluids intended to ride out temporary cloudy periods without interrupting shaft torque or electric power deliveries. The use of molten salts and alkali metals requires a high degree of technical sophistication and should be considered unlikely candidates for this type of application.

4.3.2 Other Solar Energy Collection Methods

Photovoltaic converters, initially developed to power space vehicles, generate dc current when excited by solar radiation. The current can be used to power direct current motors to drive water pumps. Optionally, ac converters may be used to provide standard voltages for induction motors. Silicon photovoltaic cells are the best developed at this time, although other cell materials are also under investigation. Both flat plate and concentrating type collectors are being developed. The flat plate collectors are usually fixed while the concentrating types may have single axis tracking capability. Arrays of photovoltaic converters are usually connected in series to achieve the needed operating voltage. Parallel connection of such arrays yields the current capacity.

Wind powered pumping installations may use one of the several types of modern wind machines. In current tests, the vertical shaft Darrieus turbines are used to drive water pumps. The vertical shaft turbines have the advantage of being able to drive the pump shaft without the need for angle drive, and they are inherently omnidirectional. A minimum of 12 to 15 mph wind is usually required before useful energy can be extracted.

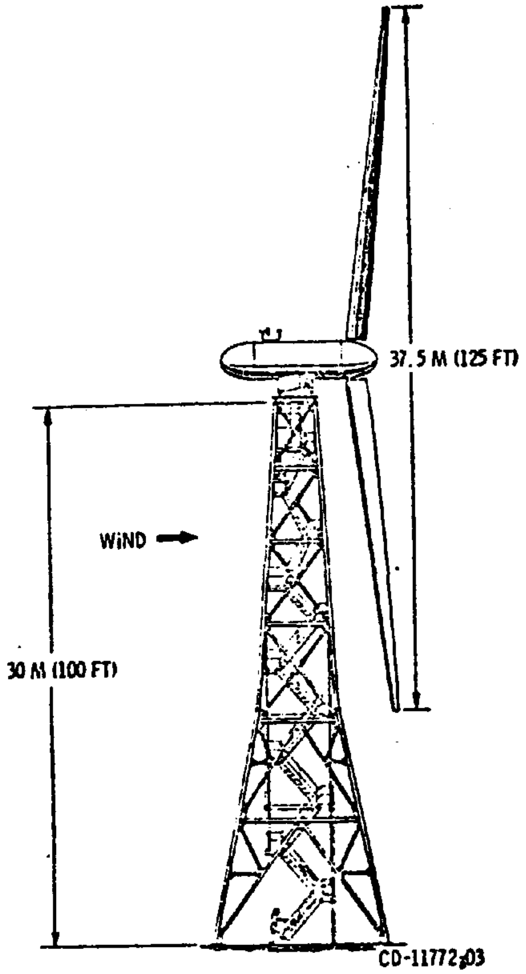
Propeller-type horizontal shaft wind turbines usually have variable pitch blades to provide constant power over a wind velocity range of 15-60 mph. A 100 kWe experimental wind turbine generator of this type at NASA-Lewis Research Center, Plumbrook, Ohio (Figure 4-9) is in the capacity range that would be suitable for water pumping systems (Ref. 4-15). If technically successful, this type of energy source may prove to be economical in areas of relatively steady wind, such as in the Texas high plains.

4.4 THERMAL ENERGY CONVERSION

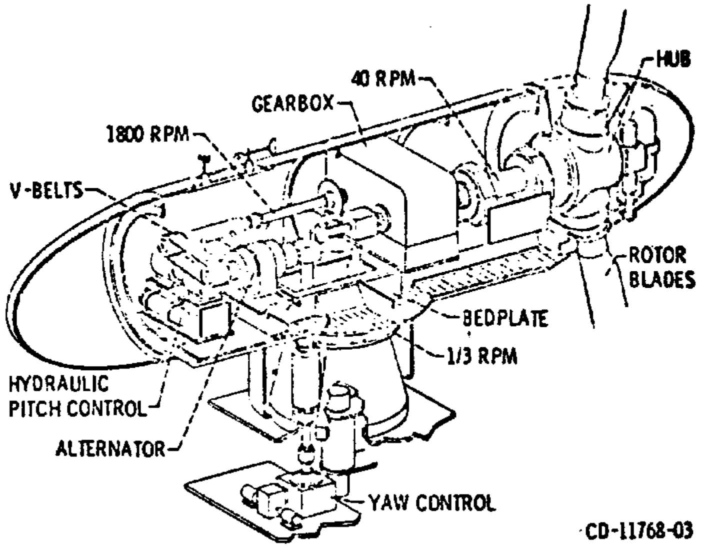
Water pumping applications have the common feature that individual pumps seldom require more than 175 kWe. Thus, apart from potential central electric power generating plants of several megawatt capacity for regional irrigation systems, solar thermal pumping installations would use individual localized energy conversion units of comparatively small capacity. This section contains a description of several heat engine cycles that are potentially applicable for solar powered water pumping service.

4.4.1 Rankine Cycle Engines

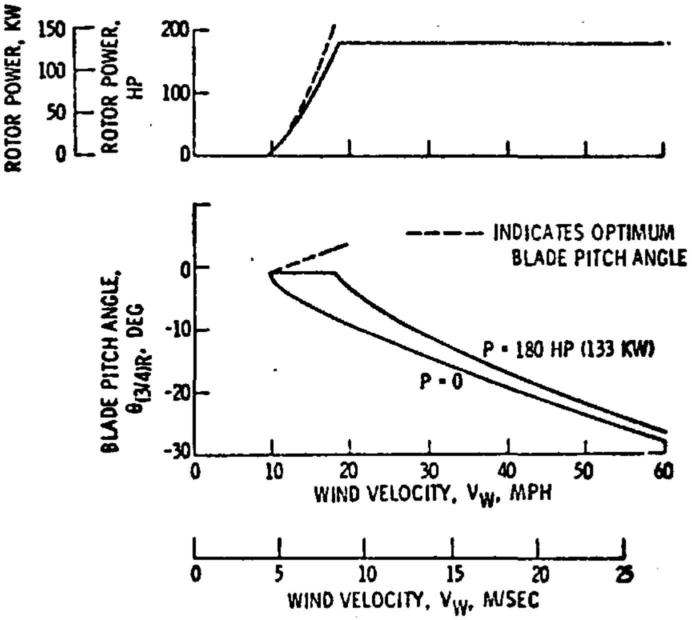
In existing projects, and in some of those planned for implementation in the very near future, Rankine cycle engines are proposed for converting solar thermal energy to shaft torque or to electricity. In this approach, high pressure vapors of the working fluids are expanded in piston-type reciprocating engines,



100-kilowatt experimental wind turbine.



- 100-kilowatt wind turbine drive train assembly and yaw system.



Rotor power and blade angle variation for the 100-kilowatt experimental wind turbine.

Figure 4-9 THE NASA / LEWIS EXPERIMENTAL WIND TURBINE

in turbines or in turbo-expanders. A schematic representation of a turbine-type Organic Rankine Cycle (ORC) is shown in Figure 4-10. Working fluids of the Rankine cycle are selected according to the temperature achievable in the boiler. This temperature is also governed by the type of solar collector used. Figure 4-11 shows the Rankine cycle efficiencies acheivable with steam, toluene and several fluorocarbons in straight condensing cycles. The addition of regenerative feed heating significantly improves the fluorocarbon and toluene cycle efficiencies, as shown in Figure 4-12. Figures 4-11 and 4-12 are taken from Reference 4-16.

The practical temperature limits of Rankine cycle fluids are set by thermodynamic and/or chemical stability considerations. The fluorocarbons, for example, decompose rapidly above 400 F. The thermodymanic efficiency of the toluene cycles peaks at about 600 F. Heat exchange equipment, pumps and most other components for the Rankine cycles are generally available off-the-shelf, often selected from equipment used in refrigeration systems. There is much less choice available in small turbines, specially for fluorocarbon or organic vapor cycles. The 150 kWe deep well pumping system proposed by the Acurex-Bechtel-Sundstrand design team (Ref. 4-10) uses a packaged ORC modified from a unit originally developed by Sundstrand Corporation as a 600 kWe waste heat utilization package. The skid mounted turbine is designed to operate with toluene vapor, has a single stage and rotates at 9,300 rpm. Cycle efficiency of the 150 kWe design is

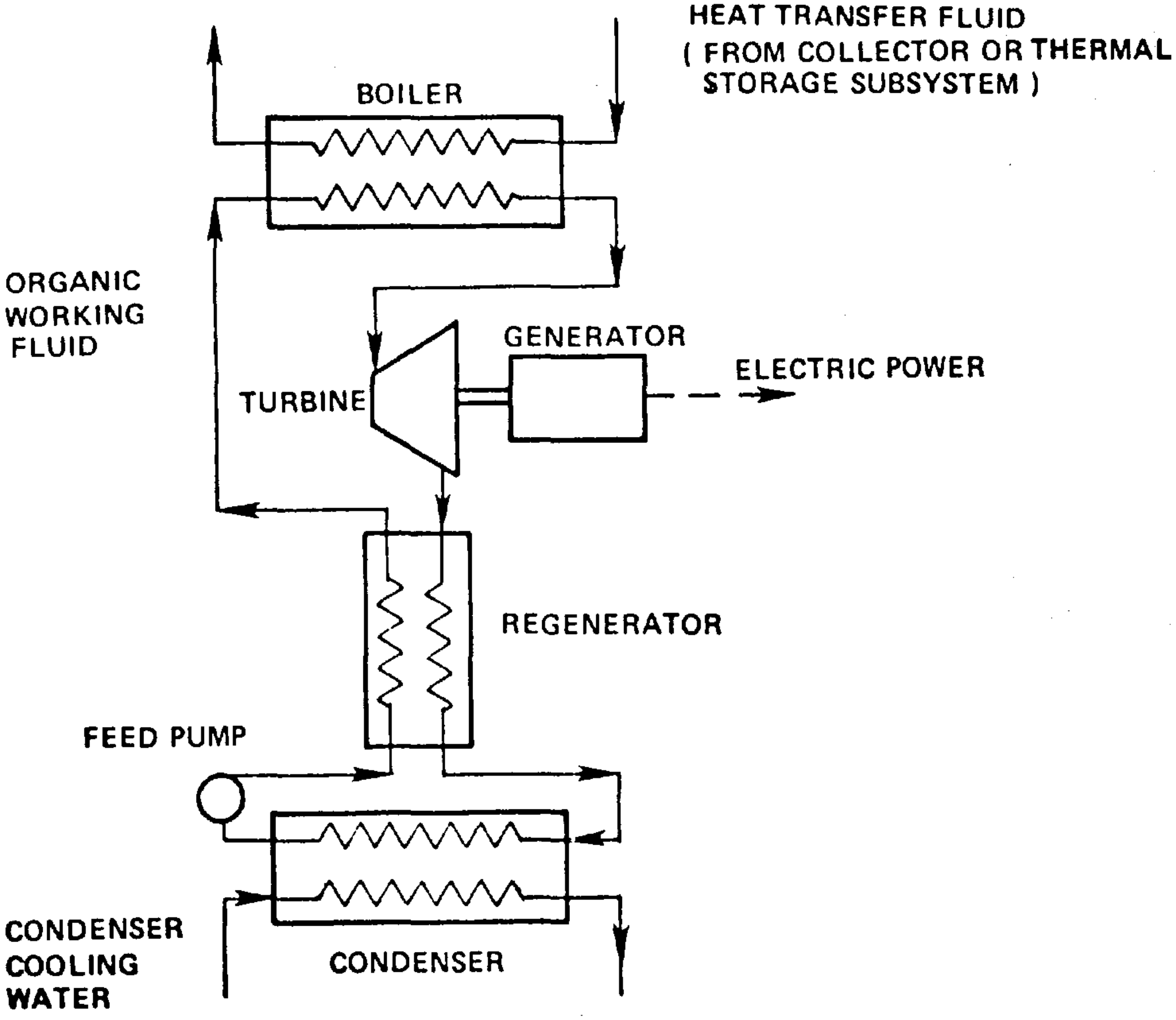


FIGURE 4-10 SCHEMATIC ORGANIC RANKINE CYCLE WITH REGENERATION

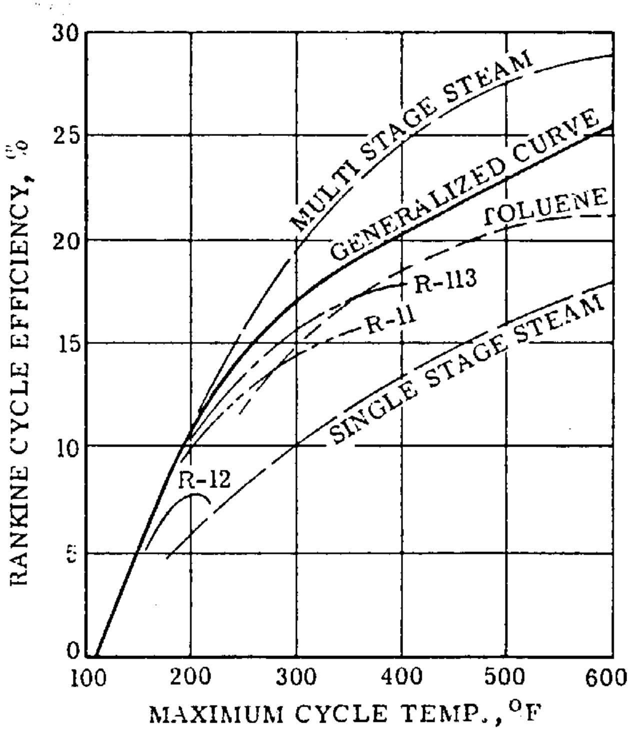


Figure 4 — 11 RANKINE CYCLE EFFICIENCY — NO REGENERATOR USED

ASSUMPTIONS:
1) EXPANDER EFF. 80%
2) PUMP EFF. 50%
3) MECHANICAL EFF. 95%
4) CONDENSING TEMP. 95°F
5) REGENERATOR EFF. 80%
6) PRESSURE LOSSES
 a) 5% HIGH SIDE
 b) 8% LOW SIDE

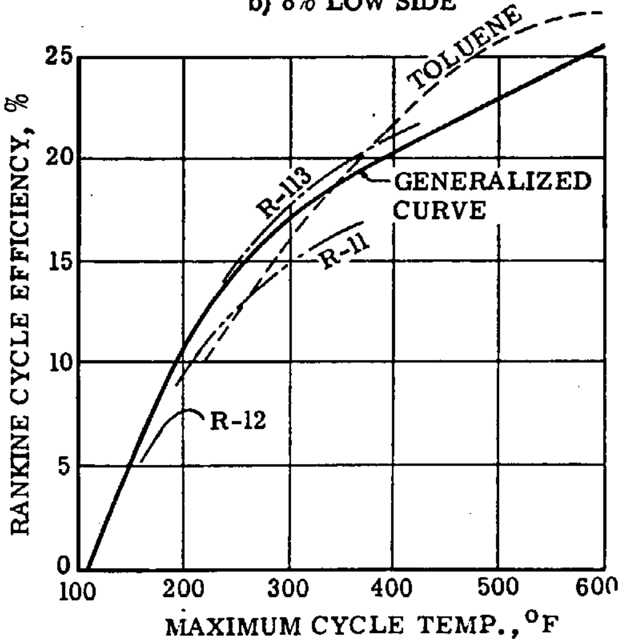


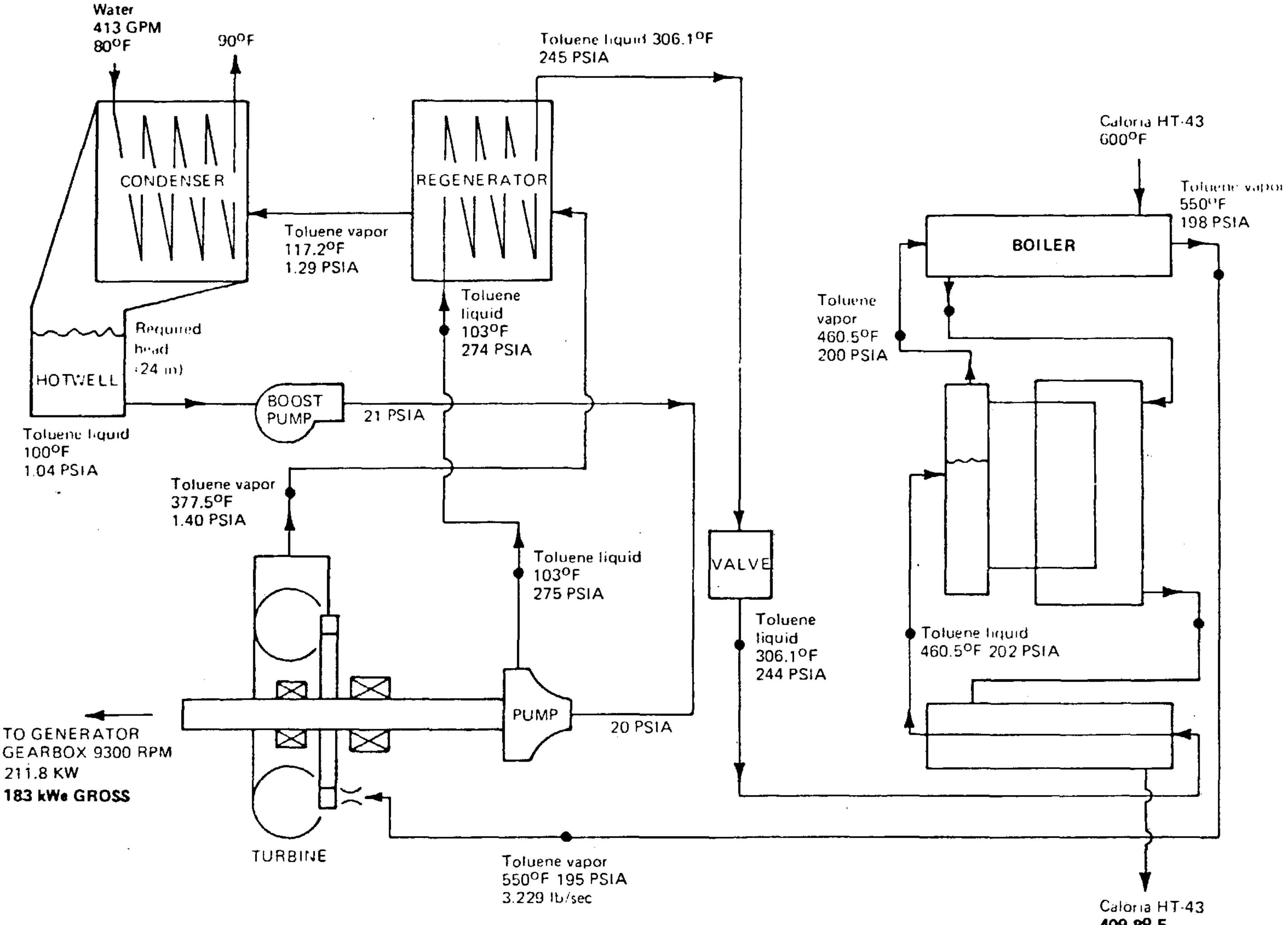
Figure 4 — 12 RANKINE CYCLE EFFICIENCY WITH REGENERATION

approximately 20.5%. A schematic of this cycle, taken from Reference 4-10, is shown in Figure 4-13.

Another Rankine cycle engine, designed for solar powered water pumping, was developed by Barber-Nichols Engineering Company with capacities of 25 and 50 hp. Integrated units of this type operate on a fluorocarbon (R-113) vapor cycle. The rated capacities are attained with an R-113 inlet temperature of 322 F. The turbine speed is 36,300 rpm, and the gear box output shaft rotates at 1,730 rpm. The cycle efficiency is quoted as 15.4% (Ref. 4-17).

The SOFRETES systems use two types of engines. The 1 kW units operate on butane or Freon 11. These are low temperature systems. The engines are 2 cylinder, reciprocating with 1000 cm^3 displacement and rotate at 200 rpm. The water pumps are hydraulically driven. The units rated at 25 kWe or larger use a Freon 11 cycle with a turbo-alternator generating system. The radial flow turbine rotates at 7,400 rpm. The water pumps are electrically driven. Cycle efficiencies of both types are 10% or lower.

A solar powered pumping system designed by Sunpower Systems Corporation uses a conventional dual cylinder reciprocating steam engine running with saturated steam at 230 psig. It delivers 75 hp and can be scaled up to 400 hp.


Water
413 GPM
80°F
90°F
CONDENSER
Toluene liquid 306.1°F
245 PSIA
REGENERATOR
Caloria HT-43
600°F
Toluene vapor
550°F
198 PSIA
BOILER
Toluene vapor
117.2°F
1.29 PSIA
Toluene
liquid
103°F
274 PSIA
Toluene
vapor
460.5°F
200 PSIA
Required
head
(24 in)
HOTWELL
BOOST
PUMP
21 PSIA
Toluene liquid
100°F
1.04 PSIA
Toluene vapor
377.5°F
1.40 PSIA
Toluene liquid
103°F
275 PSIA
VALVE
Toluene
liquid
306.1°F
244 PSIA
Toluene liquid
460.5°F 202 PSIA
TO GENERATOR
GEARBOX 9300 RPM
211.8 KW
183 kWe GROSS
PUMP
20 PSIA
TURBINE
Toluene vapor
550°F 195 PSIA
3.229 lb/sec
Caloria HT-43

4.4.2 Brayton Cycle Engines

Brayton cycle (gas turbine) engines have been proposed by Honeywell, Inc. for the deep well irrigation system at Coolidge, Arizona (Ref.4-11). A schematic diagram of this system is shown in Figure 4-14. Compact assemblies containing the generator, compressor, turbine, recuperator, and other elements of the power cycle have been built by several manufacturers. The particular 15 kWe turbine/generator unit proposed by Honeywell is manufactured by the Solar Division of International Harvester Company. The cycle efficiency is in the order of 25-27%. The efficiency of the Brayton cycle depends strongly on the turbine inlet temperature, dropping off markedly below 1,500 F. Reference 4-18 presents extensive parametric analyses of similar solar thermal Brayton cycles including open recuperative air cycles, open cycles with air, non-recuperative, and closed helium cycles. Brayton cycle engines require highly concentrating solar collectors, usually of the parabolic dish or central receiver types.

4.4.3 Stirling Cycle Engines

As shown in Figure 4-15, dual piston gas engines, operating on the Stirling cycle, have excellent efficiencies at much lower temperatures than Brayton engines. These engines run at comparatively low speeds (in order of 200-1,200 rpm) and, in principle, could be made to be rugged, requiring low maintenance. For best efficiency they need solar concentration ratios of

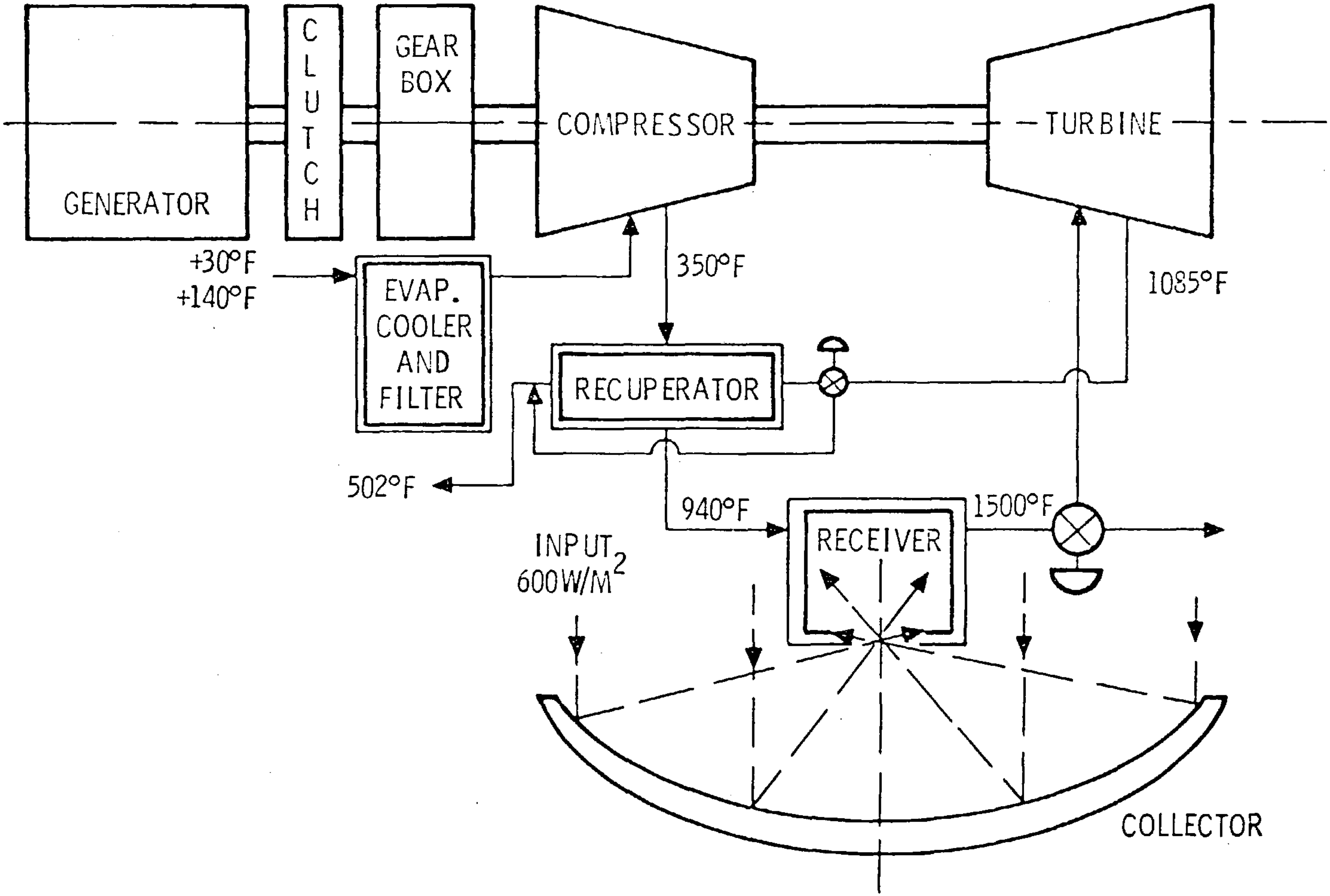


Figure 4-14 DISH / BRAYTON CYCLE SYSTEM

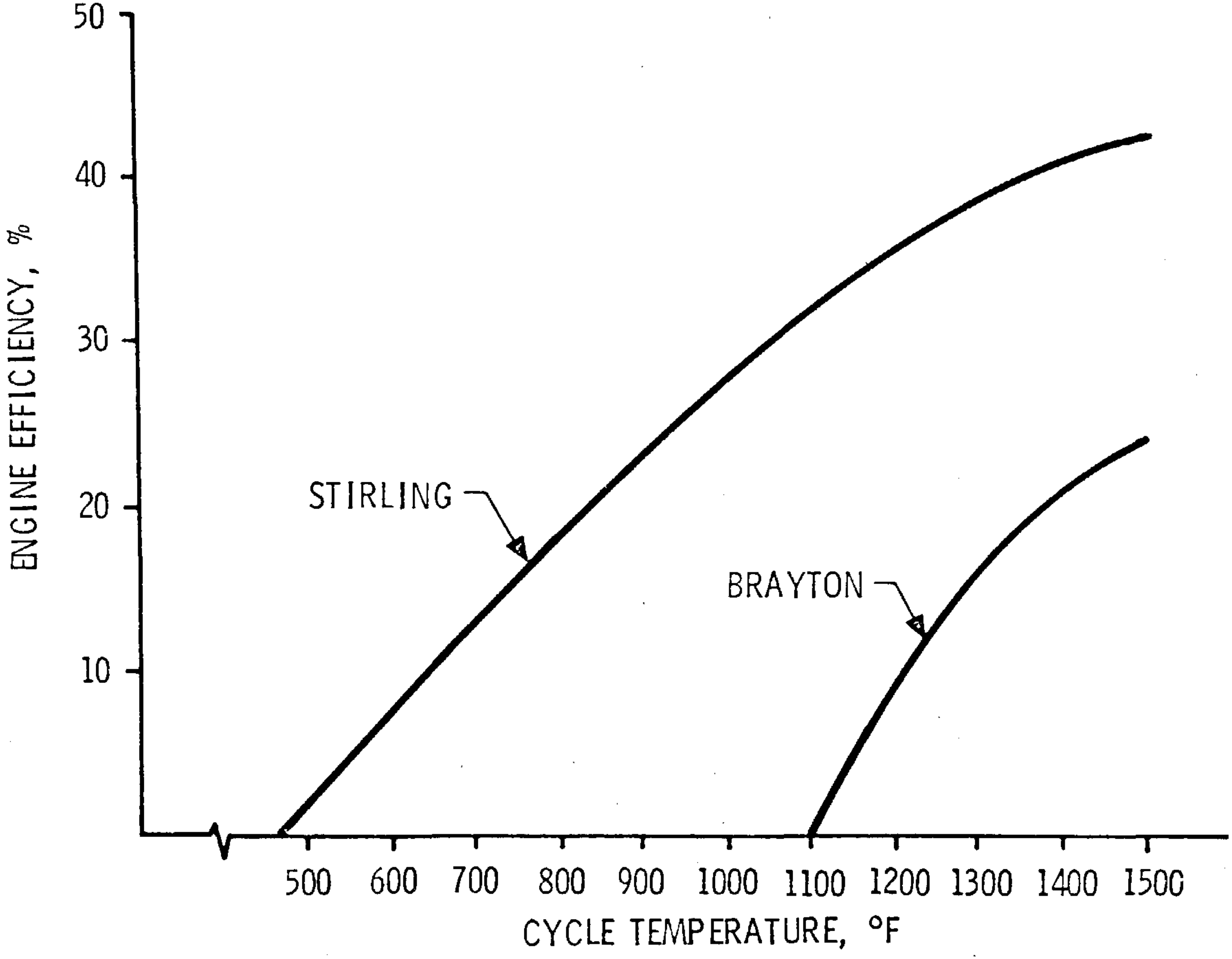


Figure 4-15 ENGINE EFFICIENCY COMPARISON AS A FUNCTION OF TEMPERATURE

1,000-1,500, thus requiring parabolic dish or central receiver solar collectors.

Reference 4-19 reports the results of tests performed by the Jet Propulsion Laboratory on a 1 kWe solar powered free piston Stirling engine. An engine efficiency of 28% is reported at a 1,200 F head temperature. Larger and more advanced engines operating at 1,400 F could provide conversion efficiencies of 42%, thereby making it possible for mature designs of parabolic dish solar collectors of 36 ft diameter to deliver 26 kWe gross output.

Helium and hydrogen are commonly used working fluids in Stirling cycles. Since these gases are difficult to contain at high pressures, developmental efforts have been concentrated on perfecting a sealed engine-alternator unit. The development of engines to 200 hp rating, for automotive use, is being carried forward by Ford Motor Company, United Stirling of Sweden, Mechanical Technology, Inc. and by N.V. Philips Eindhoven Research Laboratories.

A Stirling engine has been proposed for use in a solar total energy system demonstration at Walt Disney World in Florida (Ref. 4-20).

4.5 WATER AND ENERGY STORAGE METHODS

Water or energy storage for solar pumping systems is desirable for the following reasons:

- During the growing season water is often needed around the clock; domestic and industrial water demands are also continuous.
- In a stand-alone plant, stored energy or water is used to provide water during night hours and during long cloudy periods.
- Some of the pumping systems must have the capacity to operate through short cloudy periods to avoid frequent shutdown and re-start procedures.
- It is most economical when pumping from a well due to drawdown.

Storage to extend the operational capability overnight or during long cloudy periods adds to the cost of the system, not only because of the large storage capacity required, but also because of the added solar collector capacity required to charge the storage system while simultaneously providing energy for pumping.

4.5.1 Pumped Water Storage

This is the simplest form of storage in a water pumping system. It is useful for short term, diurnal and seasonal applications. To provide water storage, a reservoir of suitable capacity is needed. During the hours of peak insolation, some of the pumped water is diverted to fill or replenish the water in the reservoir. During the night, and on cloudy days, the reservoir water is used to feed the distribution system. The system can be used with any pumping method. In areas with porous soil, reservoirs in the form of ponds must be lined with clay or plastic to minimize seepage losses. Water stored in elevated reservoirs is also a form of energy storage, since the available static head may be used to provide energy for gravity irrigation.

4.5.2 Thermal Energy Storage

In systems with thermal storage, part or all of the fluids used to transport the thermal energy from the solar collectors is diverted to suitably sized insulated tanks or vaults. During cloudy periods or overnight, the thermal energy stored in the fluid is used to drive the heat engine cycle, thus avoiding the need to shut down and restart the system. Thermal storage is most practical for solar thermal systems operating on a Rankine cycle. Although latent heat systems have been proposed, the technology for sensible heat storage is better developed. Two common sensible heat thermal energy storage configurations are:

- A double tank system with a tank for storing the hot fluid and another tank to hold the cold fluid. Stored energy is extracted by passing the hot fluid through a heat exchanger. The cooled fluid is pumped to the cold fluid tank. The cold tank feeds the working fluid to the solar collectors.
- A thermocline system which uses a single vertical tank. Density gradient causes the warm fluid to concentrate near the top and can be pumped to heat exchangers. The cold fluid is either returned to the solar collectors or to the bottom of the thermocline.

With either configuration, the volume of the often expensive storage fluid may be minimized by the use of rocks or other thermal mass fillers. The thermal storage fluid options are essentially the same as those listed for solar system working fluids in Section 4.3.1. Thermal energy storage is provided for the New Mexico Solar Experiment, described in Section 4.2.3, extending the daily operation to 23 hours. Two of the three competing designs for the 150 kWe Coolidge, Arizona Solar Powered Deep Well Irrigation Facility use hot oil thermal storage (see Section 4.2.5).

4.5.3 Battery Energy Storage

Lead acid batteries provide an available means for storing electric energy in systems with Brayton or Stirling gas turbines, or with photovoltaic and wind turbine systems, particularly if pumped water storage cannot be provided. Thermal storage with Stirling or gas turbine installations is not used at the present since at the higher temperatures usually involved, available storage media do not stand up well, and storage temperature losses would seriously degrade the performance of these engines. Alternately, in order to use thermal storage in photovoltaic or wind turbine systems, the electric power output of these devices would have to be degraded to thermal energy and the already low conversion efficiency would be further burdened.

Use of battery storage requires appropriate inverters and current conditioning equipment for both the charge and discharge modes.

Battery storage is provided for the Nebraska irrigation project described in Section 4.2.6.

4.5.4 Other Energy Storage Methods

Although not used in existing or planned solar pumping installations, there are other storage methods that may find applications in some locations in the future. These include:

- Flywheel storage
- Compressed air storage
- Chemical storage

Both the compressed air and flywheel methods require large volume tankage or sealed underground cavities. Compressed air storage is considered only marginally applicable since its principal proposed application is as a substitute for shaft compressor air in fuel-fired Brayton cycles. Chemical storage processes are in early phases of development.

4.6 SOLAR PUMPING SYSTEM OPTIONS

The principal design alternatives for various subsystems of the solar pumping installations are reviewed in Sections 4.3, 4.4 and 4.5. Table 4-1 provides a matrix representation of these and other available options, with indications of compatibility among them. Table 4-2 summarizes heat transport fluids that are compatible with various solar collector types in workable solar thermal systems. The conventional portions of the pumping

TABLE 4-1 SUBSYSTEM COMPATIBILITY FOR SOLAR POWERED WATER PUMPING

POWER CONVERSION SUBSYSTEMS / SOLAR COLLECTOR AND ENERGY STORAGE SUBSYSTEMS	RANKINE HEAT ENGINE CYCLES				BRAYTON HEAT ENGINE CYCLES (1)			COMBINED CYCLES (2)			STIRLING ENGINES (1)		WIND TURBINES	(1) PHOTO-VOLTAIC
	FREONS	AMMONIA	ORGANICS	STEAM/ WATER	AIR, OPEN	AIR, RECU-PERATED	H_2,He CLOSED	BRAYTON, STEAM	THERMIONIC STEAM	Li VAPOR, STEAM	KINEMATIC DRIVE	FREE PISTON		
SOLAR COLLECTORS														
SHALLOW POND (2)	X(3)	X	X											
FLAT PLATE	X	X	X											
EVACUATED TUBE (2)	X	X	X											
FRESNELL LENS (2)	X	X	X											
COMPOUND PARABOLIC COLLECTOR (2)	X	X	X											
PARABOLIC TROUGH	X		X	X										
CENTRAL RECEIVER				X	X	X	X	X	X	X	X	X		
PARABOLIC DISH				X	X	X	X				X	X		
WIND MACHINES													X	
PHOTOVOLTAIC ARRAYS														X
ENERGY STORAGE														
PUMPED WATER	X	X	X	X	X	X	X	X	X	X	X	X	X	X
THERMAL STORAGE	X		X	X				X	X	X				
BATTERY STORAGE					X	X	X	X	X	X	X	X	X	X
FLYWHEEL (2)	X	X	X	X	X	X	X	X	X	X	X	X	X	X

NOTES
(1) NOT SUITABLE FOR DIRECT MECHANICAL DRIVES OF A PUMP
(2) NOT USED IN EXISTING OR PLANNED SYSTEMS
(3) X INDICATES POTENTIALFOR USE IN A PRACTICAL SOLAR THERMAL WATER PUMPING DESIGN

TABLE 4-2 SOLAR COLLECTOR HEAT TRANSPORT FLUIDS

SOLAR COLLECTOR TYPES	HEAT TRANSPORT FLUIDS					
	WATER	HEAT TRANSFER OILS	ALKALI METALS	MOLTEN SALTS	AIR	H_2, He
SHALLOW POND	X					
FLAT PLATE	X					
EVACUATED TUBE	X	X				
FRESNELL LENS	X	X				
COMPOUND PARABOLIC	X	X				
PARABOLIC TROUGH	X	X				
CENTRAL RECEIVER	X		X	X	X	X
PARABOLIC DISH	X		X	X	X	X

X INDICATES POTENTIAL FOR USE OF FLUID IN PRACTICAL SOLAR THERMAL WATER PUMPING DESIGN systems, the source of water, the pumps and pump motors, and the water distribution system are not included in this compilation since these are assumed to be either already in place or available to meet site specific requirements. The solar pumping system interfaces are either at the pump shaft coupling (mechanical drives) or at the electric motor terminals (electric motor driven systems). If required, cooling water for condensers is taken from the water distribution system.

Although Table 4-1 contains most of the options available for various subsystems, it is apparent that certain combinations of these subsystems are not practical. In addition, the remote operating environment, the characteristics of water pumping applications, or the stage of technological development further reduce the number of workable systems and subsystems.

Among the collector concepts, the solar pond is the least likely option since the temperature levels give poor energy conversion efficiencies. As a class, the combined power cycles are too complex and sophisticated for remote area applications. Among the heat transport fluids for energy collection and storage, alkali metals (sodium, NaK) and molten salts (Hitec, carbonates, Fluorides) require heat tracing, careful inventory mangement and skilled operators. Also, alkali metals present fire and toxic hazards. Both liquid metals and fused salts must be contained in expensive stainless steel piping and vessels. Although attractive efficiencies are attainable by their high temperature capabilities, on balance, these fluids are of questionable value for remote area water pumping applications.

Among the energy storage systems, both compressed air and flywheel concepts are fairly simple in principle, and could be economical. However, as mentioned in Section 4.5.4, compressed air storage would require large volume tankage or sealed underground cavities to store enough energy to drive the pumps overnight. Also, the method is not efficient unless used in conjunction with fired gas turbines. Flywheels for the same operation would also be massive. Chemical energy storage is in early phases of development. These concepts do not appear to be suitable for near term implementation. Pumped water and thermal energy and battery storage concepts, as discussed in Sections 4.5.1 through 4.5.3, are more suitable for solar powered water pumping systems.

4.7 SUITABLE SOLAR POWERED WATER PUMPING SYSTEM OPTIONS

A rigorous evaluation of the solar powered pumping system options is beyond the scope of this study. However, a qualitative comparison of these options was conducted to narrow down the choices. After deleting the obviously marginal solar systems and subsystems, the group of systems characterized in Table 4-3 have been identified as potentially suitable for remote area water pumping. This group includes system types that:

- are incorporated in existing and definitely planned demonstration facilities,

TABLE 4 – 3 POTENTIALLY SUITABLE SOLAR CONCEPTS FOR REMOTE AREA WATER PUMPING APPLICATIONS

SYSTEM TYPE	STATUS	THERMODYNAMIC CYCLES	COLLECTOR FLUIDS	POWER CYCLE FLUIDS	ENERGY STORAGE METHODS
DISTRIBUTED COLLECTORS					
a. FLAT PLATE (SOFRETES)	25*	RANKINE	WATER	BUTANE, FREON 11	NONE
b. PARABOLIC TROUGH	4*, **	RANKINE	WATER, HEAT TRANSFER OILS	STEAM/WATER, FREON 113, TOLUENE	THERMAL
c. PARABOLIC DISH	**	BRAYTON	AIR, OR He	AIR, He	BATTERY
		STIRLING	H_2 OR He	H_2 OR He	BATTERY
CENTRAL RECEIVER	**	RANKINE	STEAM/WATER	STEAM/WATER	THERMAL
		BRAYTON	AIR OR He	AIR OR He	BATTERY
PHOTOVOLTAIC CONVERSION	1*	DIRECT CONVERSION	NONE	NONE	BATTERY
WIND POWER CONVERSION					
a. VERTICAL AXIS, DARRIEUS	2*	DIRECT CONVERSION	NONE	NONE	BATTERY
b. HORIZONTAL AXIS TURBINE GENERATOR	***	DIRECT CONVERSION	NONE	NONE	BATTERY

* NUMBER INSTALLED

** SYSTEM PROPOSED FOR 150 KWe DEEP WELL IRRIGATION DEMONSTRATION PROJECT

*** UNITS ARE OPERATING WHICH WERE NOT SPECIFICALLY DESIGNED FOR WATER PUMPING

- have been proposed in competitive design studies, and,
- that appear to have the capability to function in this service, but have not been included in design studies or demonstration units.

The selection of a reference solar pumping concept from these potential concepts is discussed in Section 5.

Section 5

SELECTION OF A REFERENCE SOLAR POWERED SYSTEM

Water pumping service in remote areas places special requirements on a solar powered system. The value of such systems to owners depends on economical, reliable and trouble-free operation. Early market penetration can only be expected after demonstration of successful operation under conditions typical for commercial water pumping installations. This section outlines those factors that must be considered when selecting a solar pumping system, and describes the reasoning that led to the selection of the reference solar system. To provide a basis for comparison, a typical conventional water pumping system is also selected and described.

5.1 FACTORS AFFECTING SOLAR POWERED PUMPING SYSTEM SELECTION

5.1.1 Stand-Alone vs. Hybrid Operations

One of the goals of using solar energy is the displacement of depletable energy resources such as fossil or fissionable fuels. Since solar energy can only be collected during daylight hours, a stand-alone solar powered pumping system in many applications must have some form of water or energy storage to provide water throughout the night and through daytime periods when solar radiation may not be available to drive the system. Such storage provisions, and the associated additional solar collectors, represent significant incremental cost. Unavoidable losses in the storage subsystem result in lower system efficiencies. Careful economic analyses should be conducted to evaluate energy storage against a solar hybrid approach that uses alternate energy sources for overnight operation. Such an evaluation would be particularly appropriate for retrofit installations where the solar system could operate in parallel with existing electrical or mechanical drives, augmenting the conventional system with solar energy during sunny periods.

5.1.2 System Reliability

Pumping systems installed in remote areas must operate with minimal operator attendance. Rugged construction and simple design with less chance for fault cascading are important considerations in selecting the type of solar energy system and the associated prime mover. Frequent breakdowns and requirements for extensive maintenance work are unacceptable because of the economic losses that may result. For example, a season's crop yield may be lost if the water supply is disrupted during a critical irrigation period. Demonstration of high reliability and on-line availability will be a major factor in creating a favorable climate for wide introduction of solar powered pumping systems.

5.1.3 System Efficiency

The overall efficiency of energy conversion is an important consideration. Good efficiency results in lower expenditure for the solar collectors, a major cost item in these systems.

5.1.4 System Operation and Maintenance

The solar powered pumping system should be capable of operating with minimal operator action or monitoring. System startup and shutdown sequences should be automated. Major repairs and corrective maintenance at remote sites are difficult, thus the capability for packaged "plug in" replacement of short-lived components is highly desirable.

System complexity, measured in terms of the type and number of subsystems and components, and by the number of operating steps, should be minimized. A simple system is desirable, particularly in light of its intended remote application. Saleability of such systems declines rapidly as system complexity increases.

It must be assumed that skilled labor is scarce and expensive in remote areas. Consequently, system selection must favor those alternatives that can be operated and maintained with minimal skills. The most frequent maintenance operations should be within the capabilities of farm machinery service personnel, and equipment manufacturer personnel should be available for trouble shooting and for expeditious major repairs.

5.1.5 System Safety and Environmental Impact

Systems that represent fewer and less serious safety hazards, and have low environmental impact, are preferred. Major safety consideration includes personnel safety, fire and explosion hazards and aerial safety. The owner must consider the safety of his employees under OSHA requirements. In addition, he must consider liability for injuries suffered by passersby. The installation is likely to be in locations surrounded by dry natural growth or stands of ripening grain fields that could be ignited from misdirected collectors or from accidental spillage of flammable operating fluids, causing damage to the station as well as potential loss of marketable products. Particular hazards of concern in irrigated areas are the potentially blinding reflector surfaces and tall structures in fields where low flying crop duster planes are used for broadcasting fertilizers and pesticides.

Significant environmental benefits of solar pumping are the conservation of depletable energy sources and reduction of atmospheric pollution. The costs include the loss of arable land where the collectors and energy conversion plant are located. There may be some danger to wildlife, particularly birds and flying insects, from reflected and concentrated light or heat. There is a potential danger of contaminating the ground water with accidental discharges of hazardous working fluids.

5.1.6 Economics

Solar powered pumping systems will be installed in large quantities when the cost of water supplied by stand-alone or hybrid solar systems becomes lower than that obtainable with other energy sources. Aside from conservation, the major incentive for considering solar power is the rising cost of other energy forms. To properly evaluate the economics of solar vs. conventional water pumping, all cost components need to be quantified and related to a common base, such as present worth. Solar systems are characterized by high initial investment and relatively low operating costs. Initial costs of conventional systems are moderate, but high fuel costs cause higher operating costs.

Projections have been made for the times when solar energy will be less expensive than electricity and fossil energy sources. Most of these assume continuing escalation of conventional fuel prices and declining solar equipment costs due to competitive mass production techniques. However, in order to realize a significant reduction in equipment costs, early economic incentives are needed to start the market penetration so that volume demand will create the favorable conditions for cost reductions. A combination of subsidies and tax incentives for the users, as well as for the manufacturers, may be necessary.

5.2 REFERENCE SOLAR POWERED WATER PUMPING SYSTEM SELECTION

The varying technological maturities of the system concepts identified in Table 4-3 do not allow a rigorous comparative evaluation at this time. Economic comparison is especially difficult due to a lack of data developed on a common ground of designs and assumptions. Economic analyses are generally based on projections of probable large volume manufacturing costs rather than actual experience. Within the limited scope of this study, qualitative judgements were made in regard to the key characteristics of these concepts to tentatively select a reference system for cost comparison with conventional water pumping in remote area applications.

Ongoing and planned solar water pumping projects in the U.S., using thermodynamic power cycles, operate almost exclusively with single axis tracking parabolic trough collectors and some form of Rankine power cycles. Experience with the design, construction and operation of these installations will accumulate a significant data base for future commercial projects. Commercial scale, albeit limited volume, manufacturing capability of trough collectors has been established. From the technical point of view, this type of solar system appears to be a sound near term candidate for powering water pumps, once economic viability is reached.

Several recent studies (Ref. 5-1, 5-2, 5-3) indicated that parabolic dish collectors with either Brayton or Stirling cycle engine-generators may also have technical and economic potential in the near future.

Such a concept, as introduced in Section 4.4.2, and as described in more detail in Section 5.3.3, was found to be potentially attractive when considering the following:

- The system concept is adaptable to stand-alone and hybrid applications.
- The component technology required is largely based on state-of-the-art, contributing to a high system reliability. The packaged modular design further enhances this reliability and allows design flexibility to provide power to meet site specific needs without sacrificing system efficiency. It must be recognized, however, that the system as a whole is relatively untested and early application will require intensive development and demonstration efforts.
- The inherent high temperature capability of the parabolic dish collector is optimally coupled with Stirling or Brayton cycles, which excel in cycle efficiency at high temperatures.
- The system operation is relatively simple. "Plug-in" type maintenance appears feasible. The modular design allows the plant to continue its operation, at reduced load, if one or more of the modules fail.
- The system does not use hazardous materials, except as may be posed by storage battery acids. Air or inert gases are used as the only working fluid. The system is compact, and the land requirement is relatively low.
- The system costs are potentially attractive. The modular approach lends itself well to economic mass production of system components. The cost of development programs may also be low since only a few modules are required for representative system tests. However, published cost analyses often use data derived from analogous applications, such as RADAR dishes, rather than actual manufacturing experience, thus the range of uncertainty is comparatively high.

The parabolic dish-Brayton cycle system was selected to be the reference solar powered system. Flat plate and parabolic trough collectors with Rankine cycle engines have a number of commercial and demonstration pumping units already operational, indicating an advanced state of technical readiness. A number of U.S. and foreign manufacturers offer solar collectors as catalog items, allowing greater confidence in cost projections. As a whole, these systems could be considered closest to commercial application at this time. However, their efficiencies and economic potential appear to be less attractive than the parabolic dish systems. Small Rankine engines are comparatively inefficient and there is only a limited size selection. These systems are inherently complex since they commonly use at least two separate working fluid loops. The working fluids tend to degrade with time, and leakage losses must be made up. This operation adds to system complexity and increases the maintenance requirements. The single centralized heat engine normally specified for such systems makes availability dependent on the engine reliability. Land areas required for these systems are comparatively large.

In principle, the central receiver-Rankine cycle system can achieve high system efficiency because of its high temperature capability. However, for a small system this efficiency is severely limited by presently available small heat engines. For example, while modern central power plants operate with steam Rankine cycle efficiencies in excess of 40%, small steam turbines operate at much lower cycle efficiencies of under 20%. The land required for the collector field is comparatively large since the heliostats must be spaced to provide unobstructed line of sight to the receiver.

The parabolic dish-Stirling cycle system has the highest efficiency potential of all the candidate systems. The engines are safer because they operate at comparatively low speeds. However, the system operates with helium or hydrogen at high pressures, which places severe demands on seals. This system may be an excellent candidate in the more distant future if the present sealed engine-alternator development effort is successful.

A central receiver-Brayton cycle system shares some of the advantages of the selected parabolic dish-Brayton cycle system because of the commonality in the power cycle. The power cycle equipment is relatively compact and the use of hazardous working fluids is avoided. However, its centralized approach is less desirable than the modular approach of the selected system in terms of system availability and sizing flexibility.

Photovoltaic systems are often less efficient than solar heat engine systems, but are simple to operate and maintain. They can be modularized for improved availability. Their economic feasibility depends upon the success of current development efforts to mass produce low cost arrays. Cost reductions by factor of 10-20 will be required to make this system competitive. Relatively large land area will be required for these systems.

Although wind machines offer the advantages of simplicity and probable low cost, their operation is dependent on adequate wind velocities which are available at only a few locations in the U.S. The predictability of wind is extremely low. Tower and blade design for wind gusts is difficult as evidenced by repeated failures in the past.

5.3 REFERENCE SYSTEM DESIGN

5.3.1 Reference Application

The potential size of pumping installations covers a range of three orders of magnitude. A review of the growth trends indicates that in the past five years, center pivot irrigation systems have been installed at an average rate of 1800 units per year in Nebraska alone (Ref. 5-4). The center pivot industry estimated that 15,000 to 20,000 units were sold in the U.S. during 1975-1976 (Ref. 5-5). Pumping systems, sized to supply water for one of these installations, were therefore selected as the reference application because of its capability to capture a major segment of the potential market. The characteristics of the selected reference application are listed in Table 5-1.

5.3.2 Conventional Water Pumping Reference System

The conventional technology for water pumping is well developed. System components for conventional pump drives such as electric motors, gasoline, natural gas, or diesel fueled internal

TABLE 5-1

CHARACTERISTICS OF THE REFERENCE CENTER PIVOT SYSTEM

Total Power Requirement (kWe)	150
Irrigated area (acres)	133
Unirrigated area (acres)	27
Maximum coverage (in./day equivalent precipitation)	0.5
Average coverage (in./day equivalent precipitation)	0.25
Yearly total coverage (in. equivalent precipitation)	24
Time for one revolution (hrs)	24
Water pressure of center pivot inlet (psig)	75
Line losses from wells (psig)	10
Number of wells (pumps)	3
Flow capacity (gpm)	500
Effective well lift height (ft)	100
Auxiliary power to drive the center pivot (kWe)	10
Pump type	deep well, turbine
Efficiency of pumps (%)	50

combustion engines are available, off-the-shelf, in a wide range of power ratings. Through prolonged operating experience, a number of reliable, simple, economical and satisfactory systems have emerged.

Selection of the conventional pump drive system for use as a reference for economic comparison with the solar powered alternative was based more on the desire to select the most representative method considering the percentage share of the installed systems, and the likelihood of early replacement by solar power because of economic and institutional reasons. Nearly 43% of the irrigation water pumping power in the U.S. is provided by electricity. Although electricity is the most convenient power source, it is also the most expensive. In addition, power for irrigation is a major contributor to utility system summer peak demands during the daylight hours. Conversion to solar pumping power could materially reduce this problem and conserve scarce fuels. Such incentives favor the early conversion from utility electric to solar stand-alone or augmented systems. Consequently, an electric motor driven pumping system has been selected as the reference conventional water pumping system.

5.3.3 Solar Powered Water Pumping Reference System

The parabolic dish-Brayton cycle was selected as the reference solar system concept, as discussed in Section 5.2. A schematic of this system concept is given in Figure 4-14. The specific design for the reference application has 15 dish collectors. Each dish has a diameter of 30 ft, which is at the middle of the range considered in Reference 5-3. A receiver in the focal point of each collector provides a gas turbine inlet temperature of 1,300 F, which is more conservative than the 1,500 F shown in Figure 4-14. A lower turbine inlet temperature was assumed because achievement of higher temperatures would require the use of very high concentration ratios (1500 or higher) and commensurately high levels of precision in reflector contours and tracking accuracy, which may not be consistent with rugged construction and easy maintenance at this time. The efficiency potential of the Brayton cycle may be exploited more fully in the future, when the solar collector technology reaches maturity.

A Brayton cycle turbine generator, similar in design to that developed by the Solar Division of International Harvester for the U.S. Army, is mounted behind each collector. At 1,300 F, and a pressure ratio of 3.4, the output to the pumps is 10 kWe per engine, for a total of 150 kWe rated power. Ac current is collected from the 15 generators through cables to a central power conditioning station. During daily peak insolation each engine is capable of generating more than 10 kWe. It is assumed that the excess power is fed to the utility distribution system. Local transformer and switchgear substations at the ac motor driven pumps are designed to accept the output of the solar thermal power system for use at the pumps, to draw current from a utility grid when solar generated power is not available or to feed any excess generated power into the grid. Appropriate sensors and an automatic control system are provided to monitor the plant status and to operate the solar thermal power plant on command from the utility. Because of the interface with the utility distribution system, no energy storage is considered.

Section 6

ECONOMIC COMPARISONS

This section discusses the criteria and assumptions used as bases to determine the costs of pumping power, in mills/kWh, for the reference conventional and the solar powered pumping systems. As indicated in Section 5.3, both the conventional and solar power systems are assumed to provide energy to operate identical, electric motor driven water pumps and center pivot irrigators. The cost of these parts of the systems, assumed to be identical, was not considered in the economic comparisons. The cost of energy at the motor terminals appears to be a meaningful figure of merit for economic comparisons between the solar powered system, which is capital intensive, and the conventional system, which is energy cost intensive.

6.1 COST ESTIMATING BASIS

For purposes of establishing a comparable cost baseline, it was assumed that the conventional system receives all of its pumping energy from a local utility. It is further assumed that the solar power pumping system normally provides its own 150 kWe during daytime operation, and during nighttime hours, the pumps are driven by utility power. Therefore the cost of power in the solar system will have a conventional and a solar component. It was also assumed that the cost of electricity from the utility includes the utility operating costs and capital recovery on the power generation and distribution system, which is common to each system.

The cost of the solar generated electricity at the pump motors includes the costs of capital recovery, operation and maintenance. Capital recovery includes depreciation on the installed equipment, interest, return on investment, and taxes (including the effect of an investment tax credit). Operation and maintenance includes the annual costs for repairs, replacements, and labor.

The investment in the solar system is capitalized over the 30 year life by applying a level annual fixed charge rate of 12.8% to the total capital cost. This fixed charge rate is based on 50% debt financing at an annual cost of 8%, and 50% equity financing at an annual cost of 12%. A federal tax rate of 48%, state tax rate of 7%, and an investment tax credit of 10% were assumed. Tax depreciation is based on a double declining balance switching over to straight line. Annual expenses for operation and maintenance are assumed to be 2% of the total capital cost. The utility electrical energy cost is taken to be equal to the prevailing rate, in mills/kWh. The present electrical energy price is assumed to be 40 mills/kWh, and it is assumed to escalate up to 10% faster than the general inflation rate.

It was assumed that the irrigation system operates for 9 months annually. When irrigation is not required, the solar generated power is fed to the utility grid.

The solar powered water pumping system costs are based on the design concept described in Section 5.3.3

The capital cost of the solar pumping system includes the costs of the solar collectors, receivers, open cycle Brayton engines, controls, operation and maintenance, and purchased electric energy from the local utility.

The costs for the solar collectors, receivers, and Brayton engines are based on a nominal annual production quantity of 10,000. This quantity should adequately absorb the required collector and engine development costs, but does not assume a mass production cost basis which could not be realized for the near future.

The miscellaneous costs generally associated with a small construction project are assumed to be negligible. The required land is assumed to be owned by the farmer and is located in an area not covered by the center pivot irrigator. Construction permits are inexpensive, and an environmental impact report is assumed to be not required. Total installation time for the solar system is assumed to be three months, with the majority of the time for the collector foundations. The solar collectors will be shop fabricated and require a minimum of field construction labor. With a construction schedule of three months, interest during construction will be negligible. All lenders fees are assumed to be included in the annual capital charge rate of 12.8%.

6.2 CONVENTIONAL PUMPING SYSTEM ENERGY COST

As outlined above, the energy cost of the conventional pumping system is the cost of electrical energy at the pump motors. Based on a present energy cost of 40 mills/kWh and an escalation rate of 2, 5 and 10% above the general inflation rate of 7%, the cost of electrical energy in future years is shown in Figure 6-1.

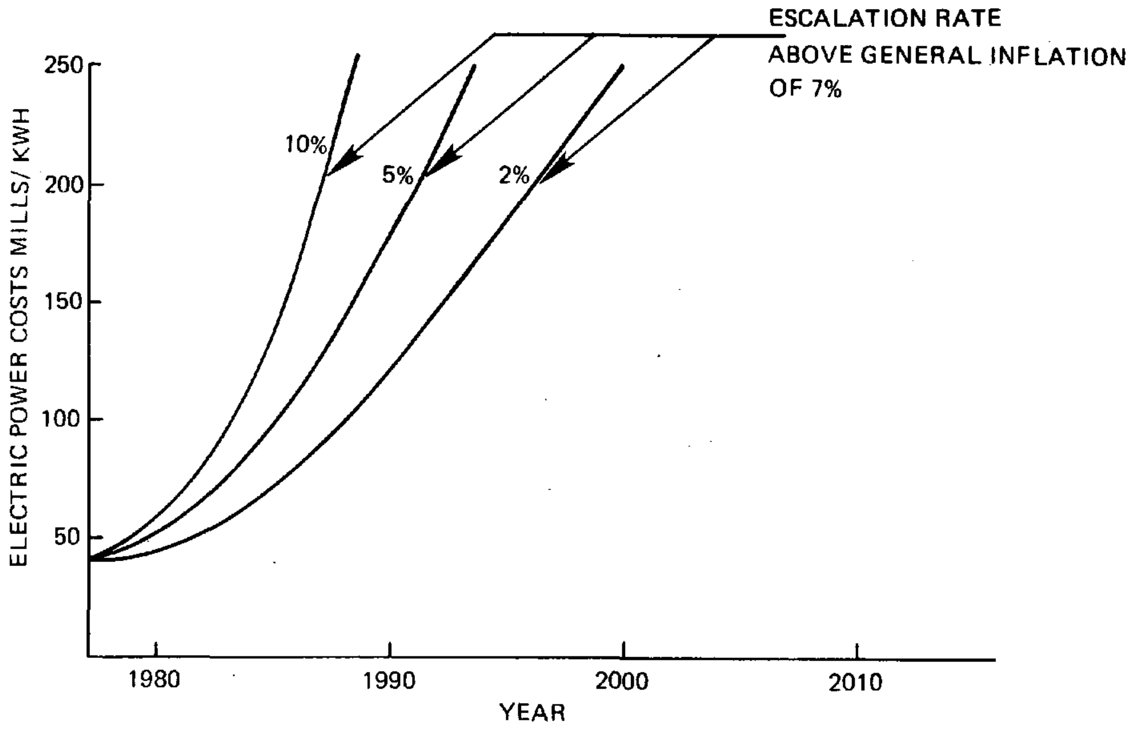


Figure 6-1 ELECTRIC POWER COST ESCALATION

6.3 SOLAR POWERED PUMPING SYSTEM COSTS

The largest single capital cost item in most solar water pumping systems is the collector, which represents typically 50% of the total cost. Early collector cost estimates of one of the first solar parabolic dish test installations, reported in Ref. 6-1, range from $54 to $65 per sq. ft. The same reference also places the cost of mass produced parabolic dish collectors at $18 per sq. ft. (without receiver). Reference 6-2 gives an estimated parabolic collector cost of about $54 per sq. ft. for the deep well irrigation project at Coolidge, Arizona, and projects $16.50 per sq. ft. for larger scale (1000 units) production. Considering that the collector weight is in the order of 23 lb. per sq. ft. of reflector area (Ref. 6-2), the mass production cost projections appear to be optimistic. Assuming that cost effective designs will evolve as a result of quantity production at 20 lb per sq. ft., and a representative mass produced cost of $2.00 per lb. (comparable to automobiles and electric motors), a concentrator cost of $40 per sq. ft. appears to be reasonable and is used in this analysis.

Receiver cost projections range from $400 per kWe (Ref. 6-3), to about $1300 per kWe (Ref. 6-2). Material selection and design configurations have significant effects on the cost. In the absence of a specified design, an average value of $840 per kWe for the receiver was selected for use in the analysis.

The cost of Brayton cycle turbine generators was based on modified flame fired engine generators sold to the U.S. Army by the Solar Division of International Harvester in quantities of 1000 units per year (Ref. 6-3). Unit cost of these engines was to be $1200 per kWe. However, for large production orders, References 6-1 and 6-2 estimate that costs in the order or $120 to $500 per kWe are achievable. $500 per kWe was assumed for this study. An allowance at $300 per kWe was made for miscellaneous controls and electrical switchgear.

It is to be noted that an inevitable uncertainty exists in these assumed costs due to a wide range of cost data extracted from the literature.

The total estimated capital investment for the solar pumping system is summarized below:

ITEM	CAPITAL COST, $	
Collector and Heat Engine	$671,000	
15 - 30 ft Diameter Parabolic Dish Collectors		$424,000
15 - 10 kWe Brayton Cycle Engines		75,000
15 - Receivers & Controls		172,000
Total Equipment Cost	$671,000	
Installation Labor and Bulk Materials (35%)	235,000	
Total Installed Cost	$906,000	
Engineering (8%)	72,000	
Contingency (20%)	196,000	
Total Capital Cost	$1,174,000	

6.4 SOLAR PUMPING SYSTEM ENERGY COSTS

The total annual kWh produced by the system will depend on the available annual insolation. For the purposes of this study, insolation data for Albuquerque, New Mexico were used. From these data, total annual electric energy production from the 150 kWe solar system would average 602,000 kWh, assuming that the system operates 12 months per year. Based on irrigation pump operation at full load during 75% of the year, 500,000 kWh of electric energy must be purchased from the local utility to meet the annual demand of 985,000 kWh to permit 24-hour/day operation during the irrigation season. Solar generated electric energy is 485,000 kWh during the irrigation season.

The annual capital, operation and maintenance, for the solar system for the first year are summarized below:

ITEM	ANNUAL COST
Capital: (0.128)($1,174,000)	$150,000
Operation and Maintenance: (0.02)($1,174,000)	23,000
Total Annual Cost	$173,000

Based on an annual solar electric energy generation of 602,000 kWh, the unit cost of the solar-generated electric energy used by the pumping system is 267 mills/kWh. The cost of utility furnished energy during the irrigation season is $20,000. Assuming that the utility buys back the solar generated power during off-season months at 36 mills per kWh, the owner will be credited with $6000 and will have a net annual utility bill of $14,000. The annual combined cost of energy, both solar and utility furnished, will be $187,000, averaging 190 mills per kWh for irrigation. By comparison, the annual energy cost of the conventional powered irrigation system at 40 mills per kWh would be $39,000.

6.5 COST COMPARISONS

The reference solar system cannot, at present, economically compete with the reference conventional pumping system. As electric energy prices rise, however, the solar energy system may become more attractive.

The timing of achieving economically competitive status depends strongly on:

- the rate of conventional energy cost escalation,
- the pace of improving the technology and cost effectiveness, and
- marketing incentives.

Economic comparisons were made between a conventional, electric driven, pumping system and a solar powered system as described in Section 5.3.3. For purposes of this comparison, it was assumed that the solar powered reference system was installed and operated at the time when techological and economic conditions prevailed, as stipulated in Section 6.1. The annual cost of energy to provide irrigation water was determined for this solar system and for the conventional reference system as a function of the rate of energy cost escalation. As shown in Figure 6-2, the annual irrigation pumping energy costs would not become equal for

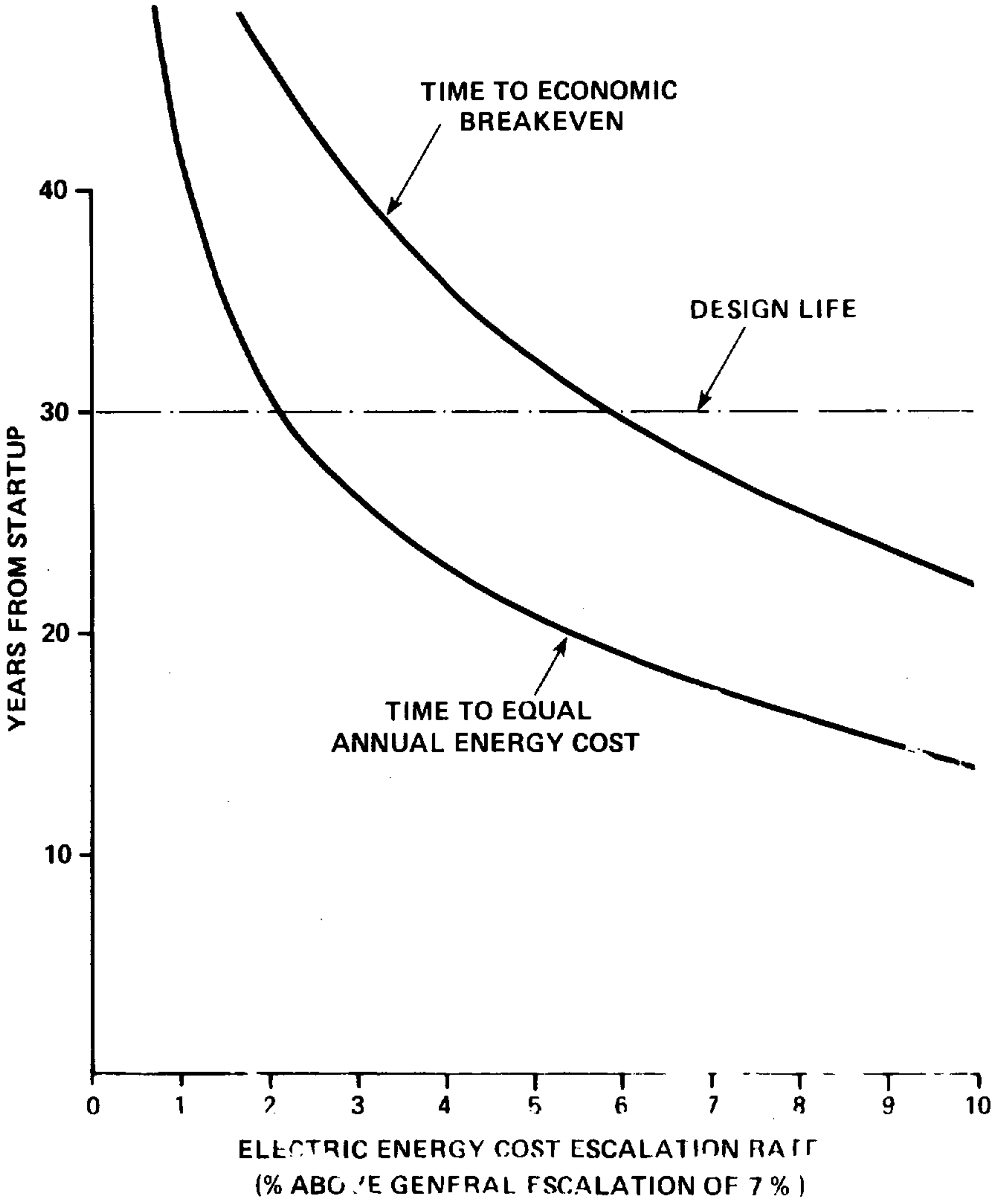


Figure 6–2 SOLAR VS CONVENTIONAL WATER PUMPING COSTS

the two systems within the 30-year design life of the solar system unless the annual energy cost escalation rate (above and beyond the general inflation) exceeds 2%. Another valid index of economic viability is the break-even point between the life-time costs of energy. The second curve on Figure 6-2 shows that the cost of electricity would have to escalate nearly 6% annually for break-even within the design life of the solar plant.

It may be concluded that if the parabolic dish-Brayton cycle concept is to establish early competitive status, strong efforts toward major cost reduction are required. Several areas of study and development, which may improve the performance or cost effectiveness, are identified in Section 7.

6.6 ENERGY DISPLACEMENT POTENTIALS

Although the reference solar powered water pumping system may not be economically competitive with the reference conventional system before year 2000, there may be an incentive in some locations to install a solar system somewhat earlier than expected. Power plants in the Southwest and Midwest are primarily oil- and gas-fired. With fossil fuel prices rising, supplies declining, and availability becoming increasingly subject to government regulation, farmers may elect to install a solar powered system to guarantee at least a portion of their irrigation supply. Solar powered systems will reduce the utility daytime peaking capacity demand, which in many instances is provided by oil-fired gas turbines. Based on a solar irrigation industry which installs 1,000 solar powered systems, each with 150 kWe capacity, in a given year, the annual electrical energy savings would be 602,000 MWh. At an oil-to-electric energy conversion efficiency of 35%, this would reduce oil consumption in the U. S. by approximately 850,000 bbl per year. To maximize the potential for displacing fossil fuels, solar powered water pumping will come under more serious considerations in future years for new installations as well as for retrofit applications.

Section 7

TECHNICAL UNCERTAINTIES AND RECOMMENDED FURTHER STUDIES

A prerequisite for successful marketing of solar powered water pumping systems is the demonstration of the reliability of such systems and a more rigorous definition of costs derived for systems optimized for the specifics of each site and its service conditions. This section discusses the technical issues of the selected parabolic-dish-Brayton, air cycle pumping system which must be resolved by development and demonstration programs. In addition, studies which will help to further the development of this technology are outlined. These studies constitute a logical next step to developing the full potential of solar powered water pumping in remote areas.

7.1 TECHNICAL UNCERTAINTIES

7.1.1 Solar Collectors and Receivers

The parabolic dish collectors build on the technology developed for large radar and microwave transmitter antennas. Design simplifications for improved cost-effectiveness of the dish and its support structure are needed. The less demanding tracking requirements of the solar collectors, in comparison with the radar installations, may permit a less costly support structure design. However, an integrated reflective surface and dish structure design needs to be developed to assure the good contour accuracy needed to project the sunlight to a comparatively small receiver. Production capability for a significant annual volume of solar systems must be developed. An efficient air cooled receiver must be developed for the modules, potentially using heat pipes to transfer the heat energy to the air stream. Consideration should be given to practical methods for periodic cleaning of the reflective surfaces. The large surfaces lend themselves better to automatic vacuum cleaning and washing operations than to manual cleaning. A cleaning system integrated into the collector deserves consideration. Even in the stowed position, the reflective surfaces are still exposed to hail and sleet. Protective measures for such events must be established.

7.1.2 Prime Movers

Small capacity 10-50 kWe Brayton cycle gas turbines are marketed by several manufacturers. These engines must be qualified for solar operations. The high temperature materials technology needs to be pursued to develop corrosion resistant, low cost materials with good strength characteristics for the temperature range of 1,500 to 2,000 F. If development is successful, the operating temperature of the gas turbine can be raised from the 1,300 F assumed for the reference system, and the cycle efficiency can be improved. The modularized assembly, consisting of the collector, receiver, and the Brayton cycle turbine-generator, must be subjected to prototype and demonstration tests to verify its satisfactory performance. A representative cluster of modules should then be tested to ascertain the satisfactory operation of a multi-modular system. Voltage and frequency regulation characteristics of the multiple generating system feeding one or two relatively large inductive loads (the pump drives) must be verified.

7.2 RECOMMENDED FURTHER STUDIES

7.2.1 System Study

The objective of this recommended study is to define suitable solar power systems for low, intermediate and high capacity water pumping application in remote areas.

A review of market potential has indicated that the water pumping power requirements vary from 1 kWe to several megawatts. Site specific conditions and regional water demand contribute to the wide variations. It is clear that no single solar collector and energy conversion approach will serve such a wide range of demand equally well. To assure the best opportunity for wide application of solar energy in water pumping service, it is necessary to identify a range of suitable systems and to evaluate their economic potential in selected rural areas of interest.

7.2.2 Utility Interface Study

The objective of this recommended study is to identify and evaluate the issues related to solar powered water pumping in parallel with energy provided by utilities in order to achieve optimal use of solar energy for water pumping applications.

A potentially large market exists for the use of solar powered water pumping in remote areas where electric power is also available, but where the pumping requirements create undesirable seasonal peak load conditions for the local utility. It appears that the economics of solar installations could be significantly improved and the national energy availability could be assisted by maximum use of the solar energy, whenever available, to reduce peak load demands and perhaps to supply energy to the utility system. System design considerations such as the need and benefits of energy storage, selection, and sizing appropriate storage provisions must be examined adequately in light of interface requirements with the utility system.

7.2.3 Stand-Alone Solar Pumping Power Plant Design Study

The objective of this recommended study is to define a technically feasible and economically attractive solar powered water pumping system which is capable of supplying water requirements in areas where other energy sources are not readily available.

The growing demand for water supplies, the desire to bring more marginal land under intensive farming, and discoveries of mineral wealth in remote areas jointly increase the demand for use of water derived from isolated wells or bodies of water at great distances from power grids. Frequently, these requirements occur in terrain not suitable for overland transportation of fossil fuels. The sparsely populated areas of the North Central States are typical for such a situation in the U.S. Large irrigation projects and municipal water supplies in North Africa, in India and in the Arab countries of Asia as well as the mining communities of Indonesia are representative of potential applications in foreign countries. The cost of conventional power delivered to the pump shaft in these locations, or the technical barriers to providing it, tend to make solar energy a more economically and technically viable alternative. The solar powered system would, of course, have to be able to function without assistance from other power sources and in many cases would have to operate reliably without need for operator action. This recommended study is intended to select and define a solar water pumping system capable of operation in such environments.

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