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SOLAR-POWERED IRRIGATION SYSTEMS

Technical Progress Report, July 1977—January 1978

February 28, 1978

Work Performed Under Contract No. EY-76-C-03-1101-002

Energy and Transportation Division
The Aerospace Corporation
El Segundo, California

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SOLAR-POWERED IRRIGATION SYSTEMS
TECHNICAL PROGRESS REPORT

28 February 1978

Prepared for
DIVISION OF SOLAR TECHNOLOGY
U.S. DEPARTMENT OF ENERGY
Washington, D.C. 20545

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Typing and preparation of much of the art work in this report was accomplished by Chriss Gamez and Micki Lewis.

Organization and editing of the report was accomplished by the study manager, D. E. Lapedes.

FOREWORD

This is the second Technical Progress Report* in the Solar-Powered Irrigation Systems Project, one of several major tasks assigned to The Aerospace Corporation by the U.S. Department of Energy, Division of Solar Technology (DOE/DST), under DOE Contract EY-76-C-03-1101. This Project, which is under the direction of Mr. J. Weisiger, DOE/DST Project Manager, began 1 March 1977 and is currently scheduled to be completed 31 May 1978.

This Progress Report documents accomplishments during the period July 1977 to January 1978. It is organized in a format proposed for the Summary Report which is to be issued at the completion of this Project. Certain Sections of this Progress Report relating to undocumented prior work or to work still in progress and planned to be documented in the Summary Report, carry only the Section title and the words "This Section in Preparation."

The study objective is to determine the technical and economic feasibility and the potential market within the agricultural community for solar power systems designed for pumping water with a possibility of meeting other farm power needs. This report discusses the methodology developed to analyze comparative lifetime costs and the results of applying this methodology to solar-powered irrigation systems serving different size farms. Other topics addressed in the report are the importance of irrigated agriculture to national and regional economies, price projections for fossil fuel and electric power in agricultural applications, irrigation energy market demand, irrigated farm budget analysis, and solar-powered irrigation system market potential.

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* The first Technical Progress Report was issued 15 July 1977 as Aerospace Report No. ATR-77 (7523-24)-1.

CONTENTS

CONTENTS (Cont'd)

CONTENTS (Cont'd)

TABLES

TABLES (Cont'd)

FIGURES

FIGURES (Cont'd)

FIGURES (Cont'd)

1. INTRODUCTION

The concern of the agricultural community with recent increases in costs of electric power and petroleum-based fuels has been noted by local, state, and federal agencies. The result of these escalated costs is seen directly each year in the farmer's balance sheet and indirectly in his requests for increases in federal support prices for farm commodities.

Continued increases in these costs and the threat of power and fuel shortages in the future can only exacerbate the present situation, possibly forcing many farmers out of business. The potential impact of such a reduction in farming on local economies and on the national balance of trade is serious enough to justify an immediate search for means of averting this situation.

Nowhere is this concern for the future of farming underscored more than in those farming communities which are largely dependent on deep-well pumped water for irrigation of crops. Electric power and fuel costs to operate well pumps are increasingly becoming a major factor in the farmer's variable costs, particularly in the southwestern United States.

The importance of irrigation to local and national economies deserves serious consideration. In Arizona, for example, 99 percent of all croplands are irrigated and agriculture is the state's second largest industry. In other states with variable natural rainfall, such as Kansas and Nebraska, irrigation of crops has increased significantly since irrigation can markedly stabilize crop yields. As a factor in the nation's balance of trade, it is estimated that irrigated croplands contribute 13 percent of all agricultural export values.

Alternative power sources, such as solar thermal power, represent a potential solution to rising power costs and potential power shortages. Furthermore, dispersed solar-powered irrigation systems, sited on each farm or installed at a dedicated site serving several farms, can be conceived as a means of power generation in place of, or in addition to, solar power generation by central utilities.

This report analyzes dispersed solar thermal power systems applied to farm irrigation energy needs. The 17 western states, containing 84 percent of nationwide irrigated croplands and consuming 93 percent of nationwide irrigation energy, have been selected to determine where solar irrigation systems can compete most favorably with conventional energy sources. Financial analysis of farms, according to size and ownership, was accomplished to permit realistic comparative analyses of system lifetime costs. Market potential of optimized systems has been estimated for the 17-state region for near-term (1985) and intermediate-term (2000) applications. Technical, economic, and institutional factors bearing on penetration and capture of this market are being identified.

2. IRRIGATION PROJECT OVERVIEW

2.1 STUDY OBJECTIVES AND SCOPE

(This Section in Preparation)

2.2 METHODOLOGY OF STUDY IMPLEMENTATION

(This Section in Preparation)

2.3 SYNOPSIS OF FINDINGS

A major portion of the study has been completed, but only preliminary assessments are available at this time. Synopses of the assessments derived from analyses documented in this report are as follows:

1. Based on results of the lifetime comparative cost analysis, a small segment of the irrigation market becomes available for penetration in 1985 by solar power systems sited on large farms in southeastern Arizona. A substantial portion of the market in the 17 western states would be available for penetration if collector costs could be halved from present estimates of $14 per square foot in 1985 (1977$).

2. Farmer-owned power-distributing cooperatives have comparative lifetime costs considerably lower than the smaller on-farm solar irrigation system applications. Hence, co-ops servicing a large irrigated farm community might well be the first market penetrated.

3. Because of differences in taxation and the cost of borrowed money, the type of ownership of solar irrigation systems (SIS) is a strong factor in establishing SIS's competitive postion with conventional irrigation systems,

i.e., the owner of a large farm, with high earnings and access to favorable loan rates, would be more inclined to consider a SIS than the owner of a small farm.

4. Initial penetration of the irrigation market by small on-farm solar energy systems is encouraged if a nearly uniform energy demand exists throughout the year. If solar-powered systems service only seasonal irrigation needs of the farmer, their cost competitiveness with regard to conventional energy sources is largely diminished. The simplest means to negate this prospect is to use or sell out-of-season solar-generated energy for non-irrigation purposes. The technical and economic viability of this alternative remains to be investigated.

5. Examination of farm crop budgets for three representative states shows that Arizona presently requires the greatest allocation of funds to irrigation fuel costs, particularly for high water demand crops such as alfalfa. Between 1975 and 1985, small increases in irrigation fuel budget allocations are predicted for Arizona, but in Texas and Kansas these percentage costs could increase by a factor of 2 to 3. By 2000, combined fixed and variable irrigation costs are expected to exceed 50 percent of crop budgets in some cases.

6. Irrigated crops are estimated to form a 14 percent share of all export crop values. Loss of the irrigated crop production sector, due to rising prices and possible shortages of conventional energy sources, could have a significant impact on the nation's balance of trade and on local economies.

3. NATIONAL AND REGIONAL SIGNIFICANCE OF AGRICULTURE

3.1 IMPORTANCE OF IRRIGATED AGRICULTURE TO U.S. TRADE BALANCE

This section addresses the importance of irrigated farmland contributions to the nation's export market and balance of trade. In recent years, the U.S. trade deficits have grown to significant proportions despite the positive trade balance found in the agricultural sector. The potential decrease in irrigated farmland which could be brought about by excessive irrigation fuel costs or fuel curtailment is, therefore, considered to be unacceptable.

Growth in agricultural export values is shown dramatically in Figure 3-1. It is of interest to examine the various contributions to these exports. For example, of the $21.89 billion in 1975 export values for all farm commodities, $20.20 billion was contributed by farm crops. Of this total, $15.6 billion was due to five major crops: corn, cotton, wheat, sorghum, and soybeans.

A detailed examination of national crop growing practices showed that, in some cases, irrigated farmlands were major sources of these crops. A summary of these findings is presented in Table 3-1. Almost half of the value of exported cotton comes from irrigated land but, because of the extensive acreage in corn, irrigation exports are the largest for this commodity. Because agricultural yields from irrigated land are significantly greater than from dry land, the percentage contribution shown for irrigated crops is greater than if the accounting was accomplished solely on the basis of the percentage of the irrigated acreage. The aggregated total shows that irrigation contributes $2.14 billion to export values or 13.7 percent of the $15.6 billion 5-crop total export value.

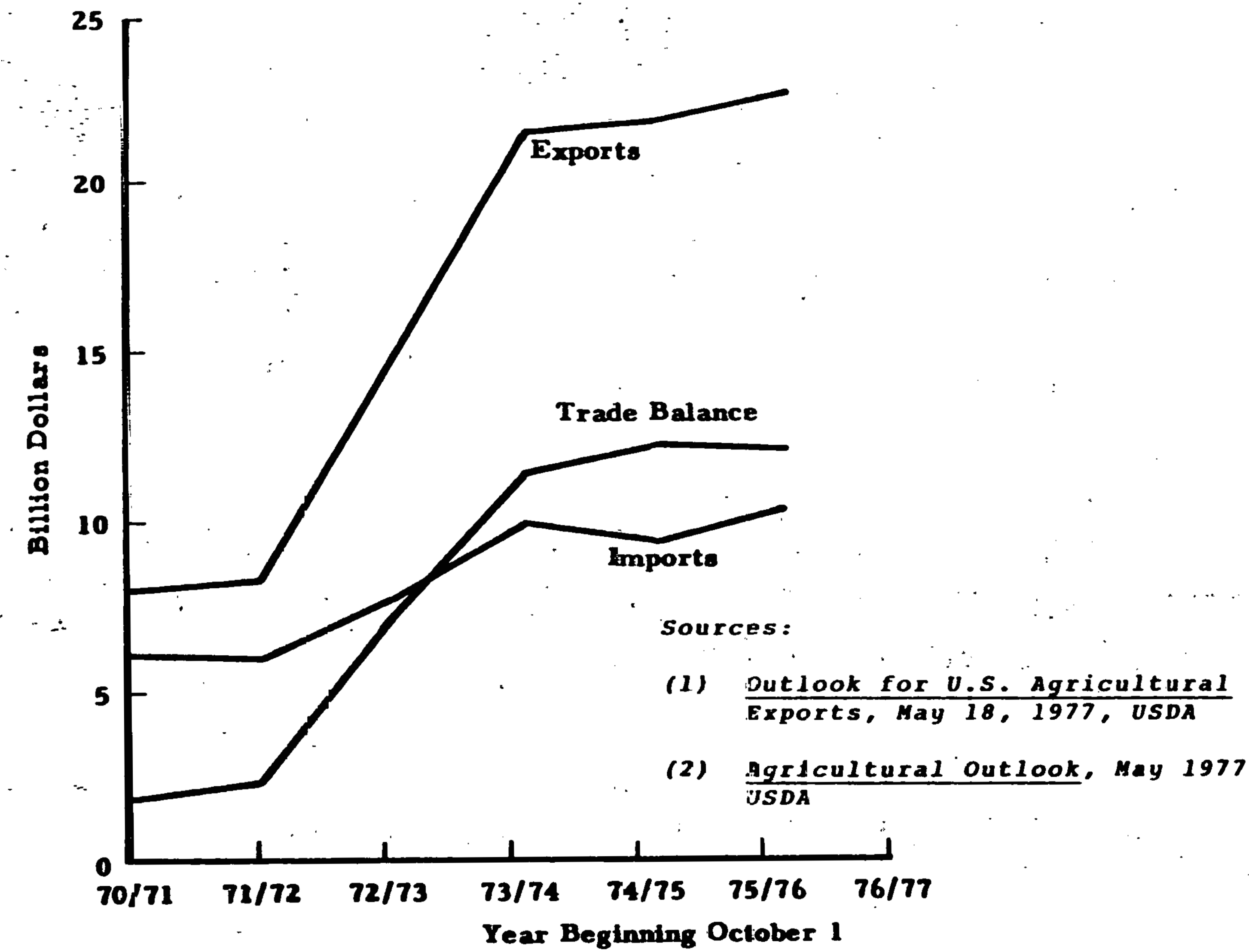

Figure 3-1. U.S. Agricultural Trade Balance

Table 3-1

EXPORT VALUE OF SELECT FARM COMMODITIES (1975)

COMMODITY	VALUE OF EXPORT ($ BILLION)	ESTIMATED VALUE OF EXPORT FROM IRRIGATED LAND ($ BILLION)	ESTIMATED CONTRIBUTION OF IRRIGATION (%)
COTTON	1.199	0.591	49.3
SORGHUM	0.691	0.267	38.7
CORN	4.563	0.789	17.3
WHEAT	5.353	0.455	8.5
SOYBEANS	3.773	0.038	1.0
5 CROPS	15.579	2.140	13.7

Those states that are the leading suppliers of the five irrigated crops are given in Table 3-2. Texas is clearly the leader in production of irrigated cotton, sorghum, and wheat, while Nebraska leads in production of corn and soybeans. Introduction of solar irrigation systems in the states shown could be expected to aid in sustaining an important source of export values if fuel costs become prohibitively high or fuel supplies are subject to disruption.

To illustrate the potential export trade value of commodities, Table 3-3 gives the 1974 trade value of corn and wheat expressed in economically equivalent imported barrels of oil.

3.2 NATIONAL ENERGY CONSUMPTION FOR IRRIGATION

(This Section in Preparation)

3.3 REGIONAL IMPACT OF IRRIGATED CROP VALUES

The sustained development of local economics is extremely important to national economic well being. For those states where agriculture is a major economic sector, reductions in income could come about through loss of irrigated farm lands, resulting from unprofitable operations due to increasing cash outlays for irrigation energy in the future. Such decreases in farm income from reduced sales of agricultural products could produce substantial economic and social dislocations.

Growth in irrigated croplands can be traced directly to improved production yields resulting from irrigation. This effect is well illustrated for the 17 western states which comprise almost half the harvested cropland and crop values of the 48 contiguous states. The value of irrigated land is highlighted in Table 3-4 by comparison of columns 4 and 5 which shows the increased value of irrigated crops due to improved production yields compared to dryland farming. For the 17 western states, 50 percent of all crop values is obtained from the 23 percent of harvested cropland which is irrigated. The last two columns give a direct comparison of irrigated and non-irrigated croplands by expressing their production values on the basis of dollars per acre. Improved yield factors of two or three in

Table 3-2

LEADING GEOGRAPHIC ORIGINS OF SELECT IRRIGATED CROPS CONTRIBUTING TO AGRICULTURAL EXPORT VALUES (1975)

PERCENT ACREAGE*

	COTTON	SORGHUM	CORN	WHEAT	SOYBEANS
	TEX. 50.0%	TEX. 64.0%	NEB. 51.8%	TEX. 37.1%	NEB. 39.5%
	CAL. 31.5%	IOWA 14.3%	KAN. 16.5%	KAN. 12.4%	TEX. 23.7%
	ARI. 11.6%	N.M. 9.2%	TEX. 11.8%	ARI. 11.8%	MIS. 17.5%
	N.M. 3.2%	OKLA 5.0%	COLO 6.0%	N.M. 10.4%	KAN. 6.9%
4 STATE SUBTOTAL	96.3%	92.5%	86.1%	71.7%	87.6%

*Percent of total irrigated land devoted to the given crop; e.g., Texas has 50% of the acreage of all irrigated cotton in the U.S.

Table 3-3

POTENTIAL OF FARM COMMODITIES TO PURCHASE FOREIGN PETROLEUM [1]

(1974)

	OIL VOLUME RELATED TO $1 BILLION SALES OF EACH COMMODITY (MILLION BBL)	
	CORN	WHEAT
OIL IMPORTS EQUIVALENT TO COMMODITY VALUE[2]	71.43	71.43
OIL EQUIVALENT CONSUMED TO PROVIDE COMMODITY VALUE[3]	-5.67	-4.57
NET OIL IMPORTS EQUIVALENT TO COMMODITY VALUE	65.76	66.86

SOURCE: "A National Program of Agricultural Energy Research and Development", Joint Study of NASULGC and USDA

Notes: (1) Net energy concept; total cost of producing exports not included

(2) Based on $14/bbl oil

(3) Includes energy for irrigation, field operations, drying, handling manufacture of pesticides and fertilizers, and shipping. Based on $3/bu corn, $4/bu wheat, 71 bu corn/acre, 29 bu wheat/acre.

Table 3-4

HARVESTED CROPLAND FOR SELECTED STATES
1971-73 AVERAGES

STATE	TOTAL ACREAGE (1000 ACRES)	TOTAL VALUE OF CROPS ($ MILLION)	ACREAGE IRRIGATED (%)	IRRIGATED CROP VALUE (%)	CROP VALUE PER ACRE ($/ACRE)	
					IRRIGATED	NONIRRIGATED
ARIZONA	1,225	377	100.0	100.0	307.8	---
CALIFORNIA	8,614	3,648	76.1	89.3	496.9	189.6
KANSAS	19,893	1,675	7.74	14.1	153.3	78.4
NEBRASKA	16,488	4,647	19.8	44.4	630.2	195.5
NEW MEXICO	1,169	172	68.8	86.0	184.1	65.8
TEXAS	20,017	2,412	34.5	51.8	181.0	88.6
17 WESTERN STATES	139,555	19,217	23.1	50.2	299.1	89.1
48 STATES	308,377	43,676	11.8	26.9	324.3	117.3

irrigated farming over dryland farming can be seen. In some western Nebraska locales characterized by sparse natural rainfall, yield improvements greater than five are commonly found.

The relative importance of irrigated crop production to the economies of six selected states is illustrated in Table 3-5. Irrigated crop sales are shown as a percent of total crop sales in column 1, as reported by the USDA Statistical Reporting Service for the period 1971 through 1973. Irrigated crop share varies from a low of 14 percent in Kansas to 100 percent in Arizona. The second column presents crop sales as percent of agricultural sales in 1975 as reported by the USDA Economic Research Service. Numbers here indicate that crop sales vary from a low of 25 percent to a high of 67 percent of total agriculture sales. In the third column, agriculture sales are shown as a percent of 1975 personal income for each of the six selected states as reported by the Department of Commerce. (State gross product data were not available, and personal income is considered to be an alternative variable that should offer consistent values.) The product of multiplying the three data columns together is the irrigated crop sales as a percent of state personal income. While the resulting irrigation crop sale percentages do not appear to be dominant fractions of state personal income, such as 3.6 percent in the case of California, agriculture is the number one industry in California. It is not difficult to imagine the compounding economic effects in terms of commodity price changes or employment levels that would likely accompany any reductions in irrigated crop sales.

3.4 REGIONAL ENERGY CONSUMPTION FOR IRRIGATION

(This Section in Preparation)

Table 3-5

RELATIVE IMPORTANCE OF IRRIGATED CROP PRODUCTION TO STATE ECONOMIES, SIX SELECTED STATES

State	Irrigated Crop Sales as % of Crop Sales, 1971-73	Crop Sales as % of Agriculture Sales, 1973	Agriculture Sales as % of Personal Income, 1975	Irrigated Crop Sales as % of Personal Income
Arizone	100	53	9	4.8
California	89	67	6	3.6
Kansas	14	54	25	1.9
Nebraska	44	43	42	7.9
New Mexico	86	25	14	3.0
Texas	52	46	9	2.2

4. AGRICULTURAL DATA BASE DESCRIPTION

4.1 DATA SOURCES

(This Section in Preparation)

4.2 CROP MIX

(This Section in Preparation)

4.3 IRRIGATION PRACTICES

(This Section in Preparation)

4.4 PUMP AND POWER DRIVE CHARACTERISTICS

(This Section in Preparation)

4.5 WELL CHARACTERISTICS AND WATER RESOURCES

(This Section in Preparation)

4.6 FARM OPERATING COSTS

(This Section in Preparation)

5. FOSSIL FUEL AND ELECTRIC POWER DATA BASE DESCRIPTION

Under a sub-contract to The Aerospace Corporation, data were provided by Sherman H. Clark Associates on agricultural price projections for six western states for diesel fuel, natural gas, LPG, and electricity in five-year increments to the year 2015 (Reference 5-1). Examples of the data base are presented in this section along with the methodology used to extend the data to the entire 17 western state region and out to the year 2030.

5.1 SURVEY AREAS

In Section 6, Selection of Geographic Regions for Study, states were ranked according to potential for solar irrigation system applications. Arizona, California, Kansas, Nebraska, New Mexico, and Texas were the top six states in this ranking, and they were selected for agricultural price projections formulated by S. H. Clark Associates. Based on the determination of irrigation energy consumption described in Section 7, county clusters having the greatest energy use were identified for each of the six states. These geo-political regions are indicated by dark outline in Figures 5-1 through 5-6. It is these sub-regions that were used by S. H. Clark Associates to define price variations throughout each state. The criterion for establishing regional grouping is that prices for a specific energy source within a state must deviate by 10 percent from one region to another (i.e., each identifiable price region covers variations of ± 5 percent from the mean value for that region).

5.2 BASIC PRICE PROJECTIONS

To determine present prices of agricultural fuels, S. H. Clark conducted a telephone survey of electric and gas utilities, as well as oil and LPG distributors and wholesalers in the six-state area. Prices for electricity and gas represent averages based on total revenue and total energy for the rate schedule selected. When averages were not available

ARIZONA
Counties, County Seats, Mountains, and Rivers

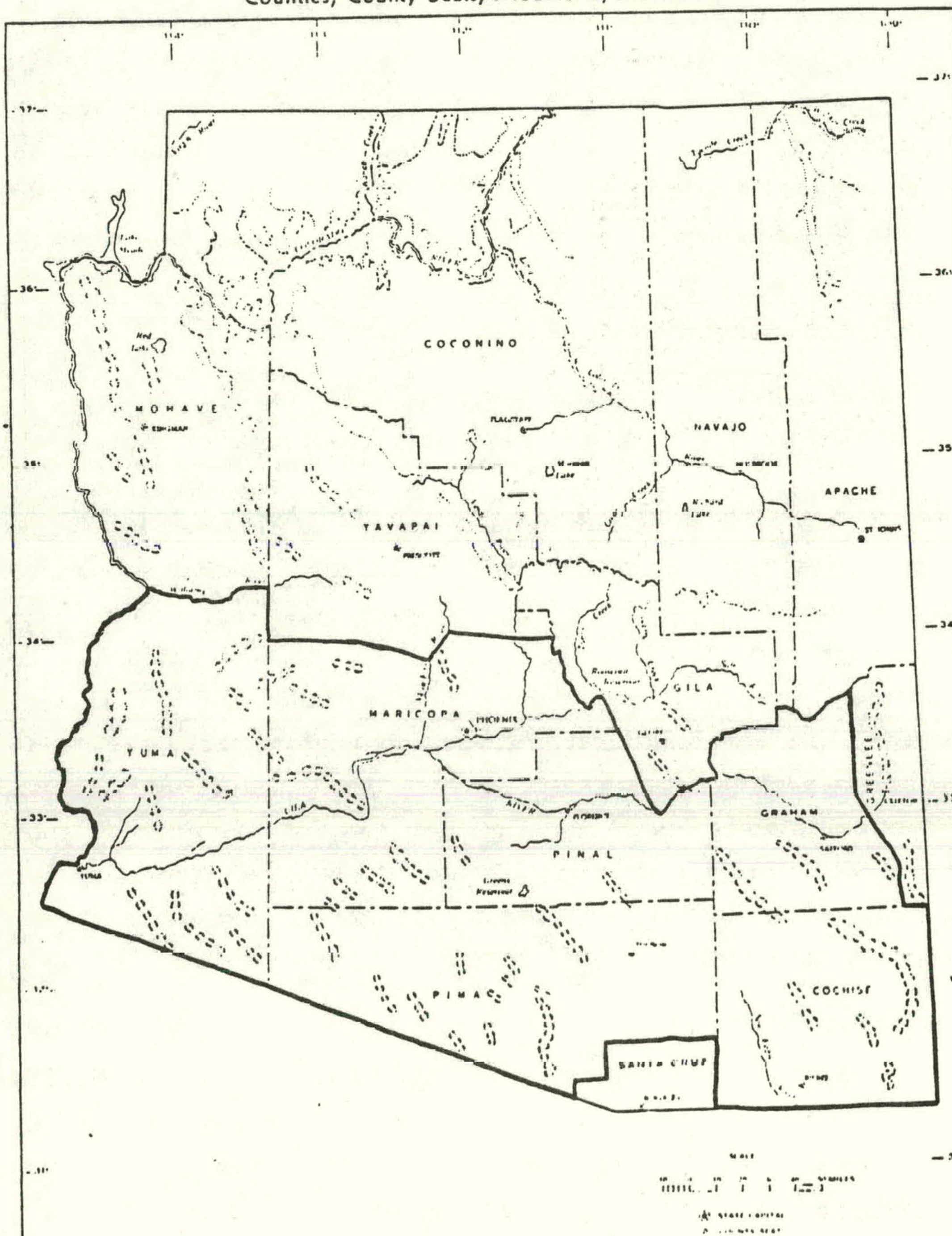

Figure 5-1. Geo-Political Regions of Primary Interest for Solar Powered Irrigation Systems Study -- Arizona

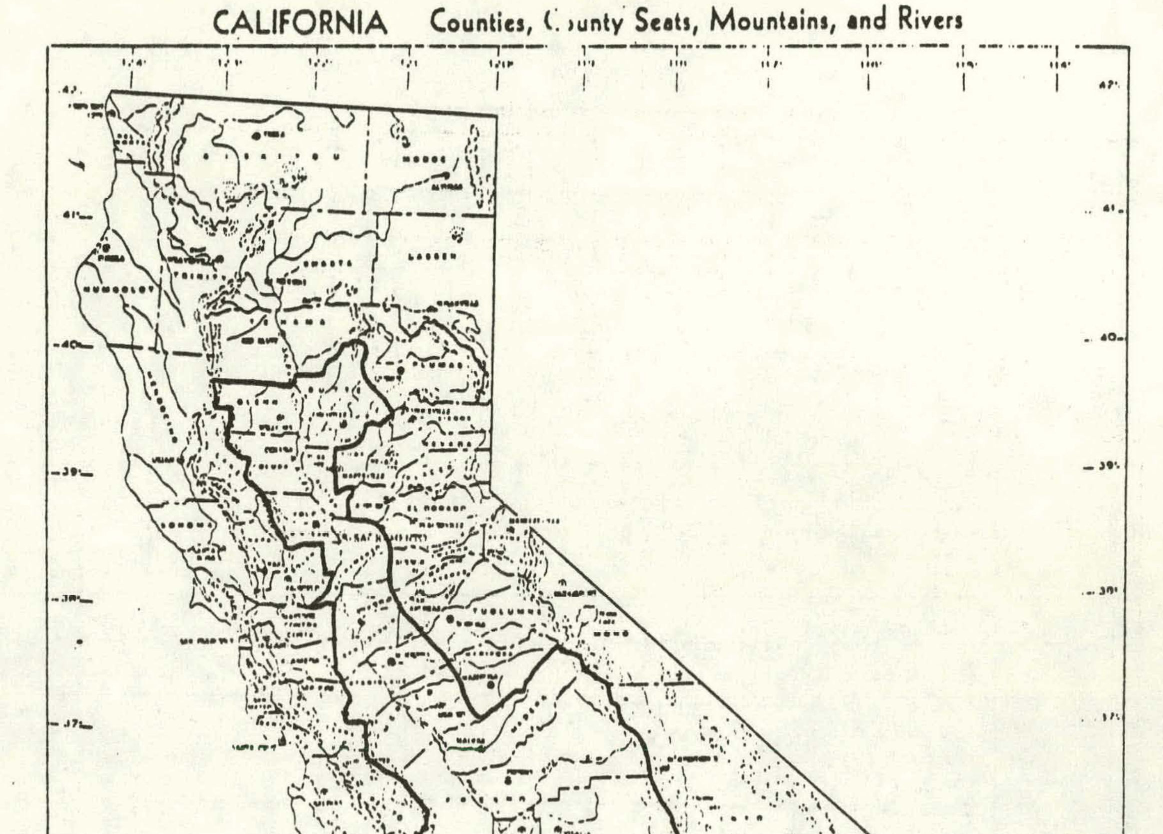

Figure 5-2. Geo-Political Regions of Primary Interest for Solar Powered Irrigation Systems Study -- California

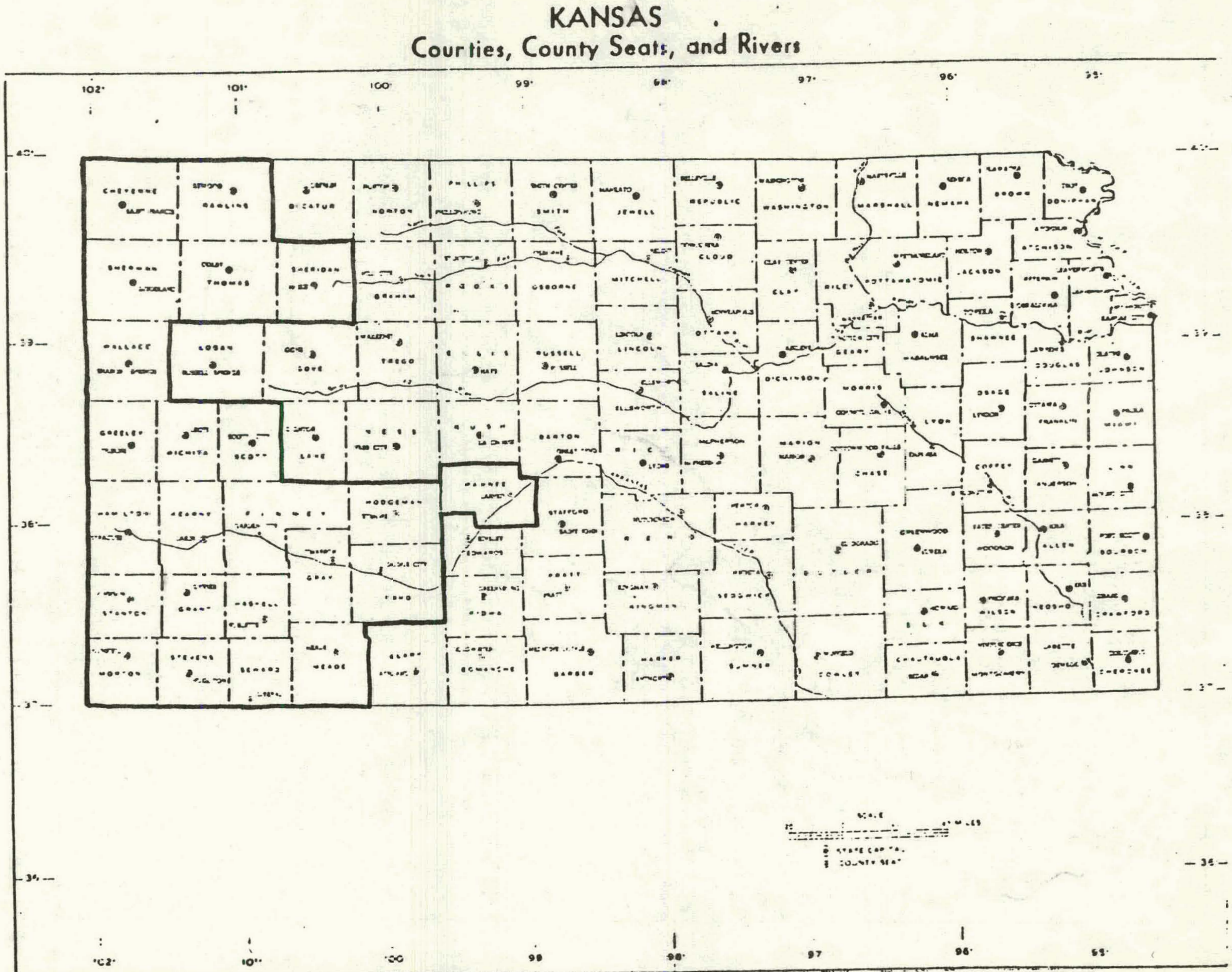

Figure 5-3. Geo-Political Regions of Primary Interest for Solar Powered Irrigation Systems Study -- Kansas

NEBRASKA

Counties, County Seats, and Rivers

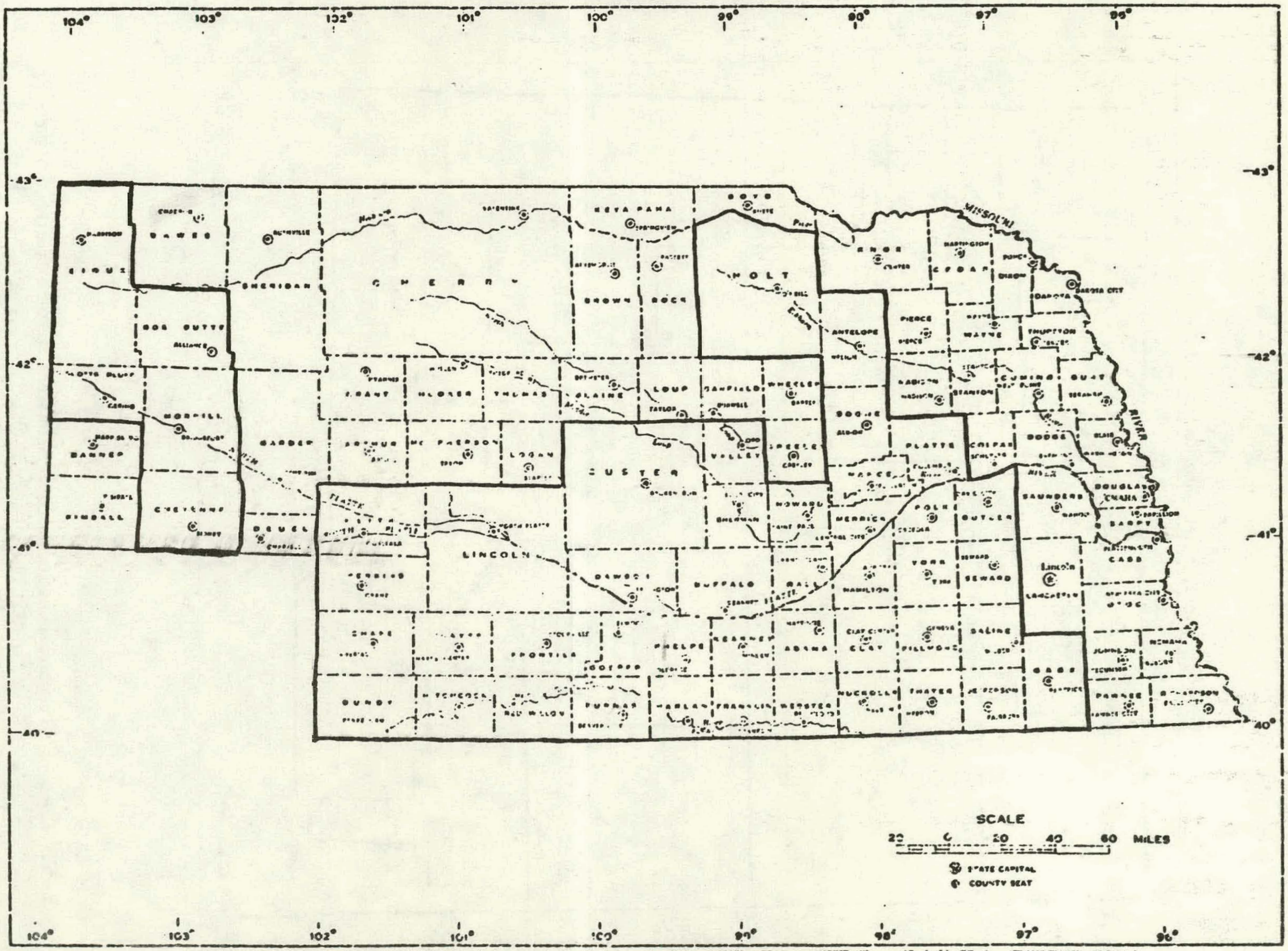

Figure 5-4. Geo-Political Regions of Primary Interest for Solar Powered Irrigation Systems Study -- Nebraska

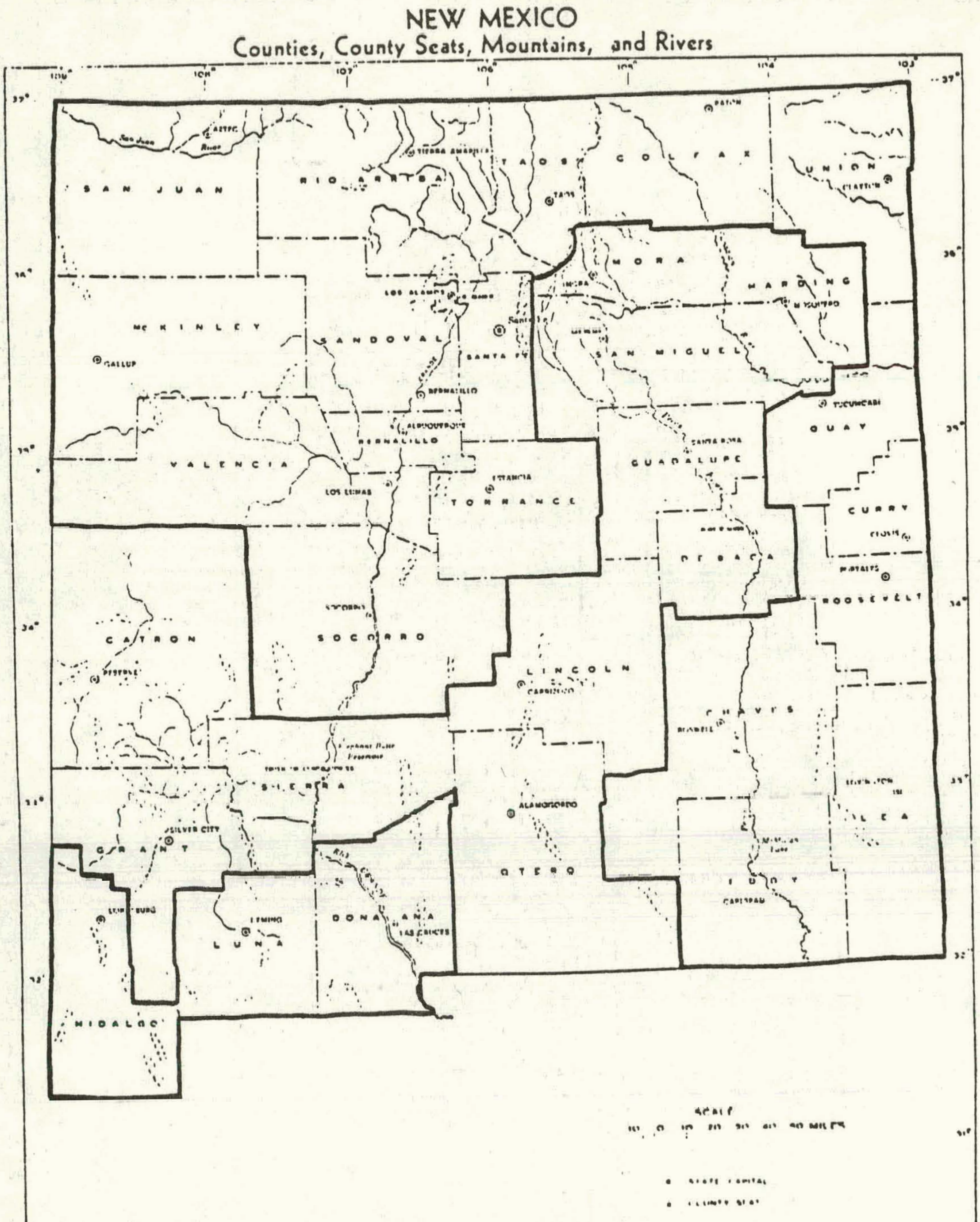

Figure 5-5. Geo-Political Regions of Primary Interest for Solar Powered Irrigation Systems Study -- New Mexico

TEXAS
Counties, County Seats, Mountains, and Rivers

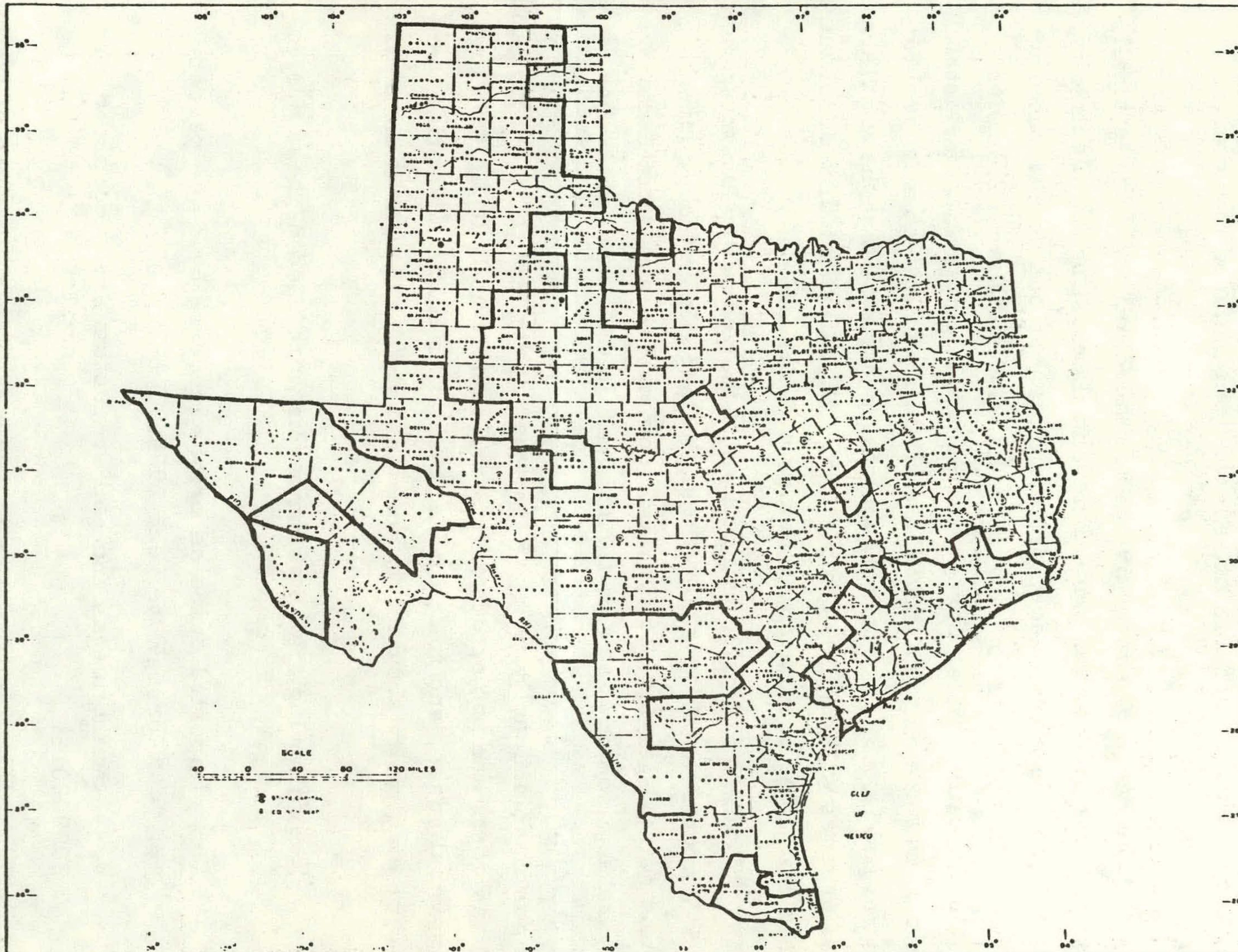

Figure 5-6. Geo-Political Regions of Primary Interest for Solar Powered Irrigation Systems Study -- Texas

from a utility, price data are for the rate applicable to a typical agricultural user. Non-refundable taxes have been included in the price averages.

The range of survey prices for diesel oil and LPG is small in contrast to the substantial price differentials existing for electricity and natural gas. In many cases, price differences can be attributed to (1) access by gas utilities to "new" versus "old" supplies, (2) utility policies in allocating costs between residential, commercial, industrial, and agricultural use sectors, and (3) availability of low-cost federal hydroelectric power. S. H. Clark Associates postulates that these relative price differences will diminish in the future if, as expected, federal intervention in state rate regulations becomes widespread.

Examples of price projections to the year 2015 are given in Figure 5-7 in constant 1977 mills per equivalent kilowatt-hour for electricity and natural gas for residential, commercial, industrial, and agricultural use sectors in central Arizona. In terms of energy input to a pump prime mover (heat engine or electric motor), it appears that natural gas is significantly cheaper than electricity. Both diesel fuel and natural gas costs are projected to increase rapidly until 2000, then level off for several years, and to again increase after 2015. The price projections for electricity show fairly constant growth throughout the entire period.

The following major assumptions were used in these projections:

1. Imported crude oil prices increase by 2 to 4 percent per year through the year 2000.

2. Synthetic-gas and -oil production are widespread from 2000-2015.

3. Electricity prices increase with a lag because of rising fuel and generation costs and continuing contract renewals

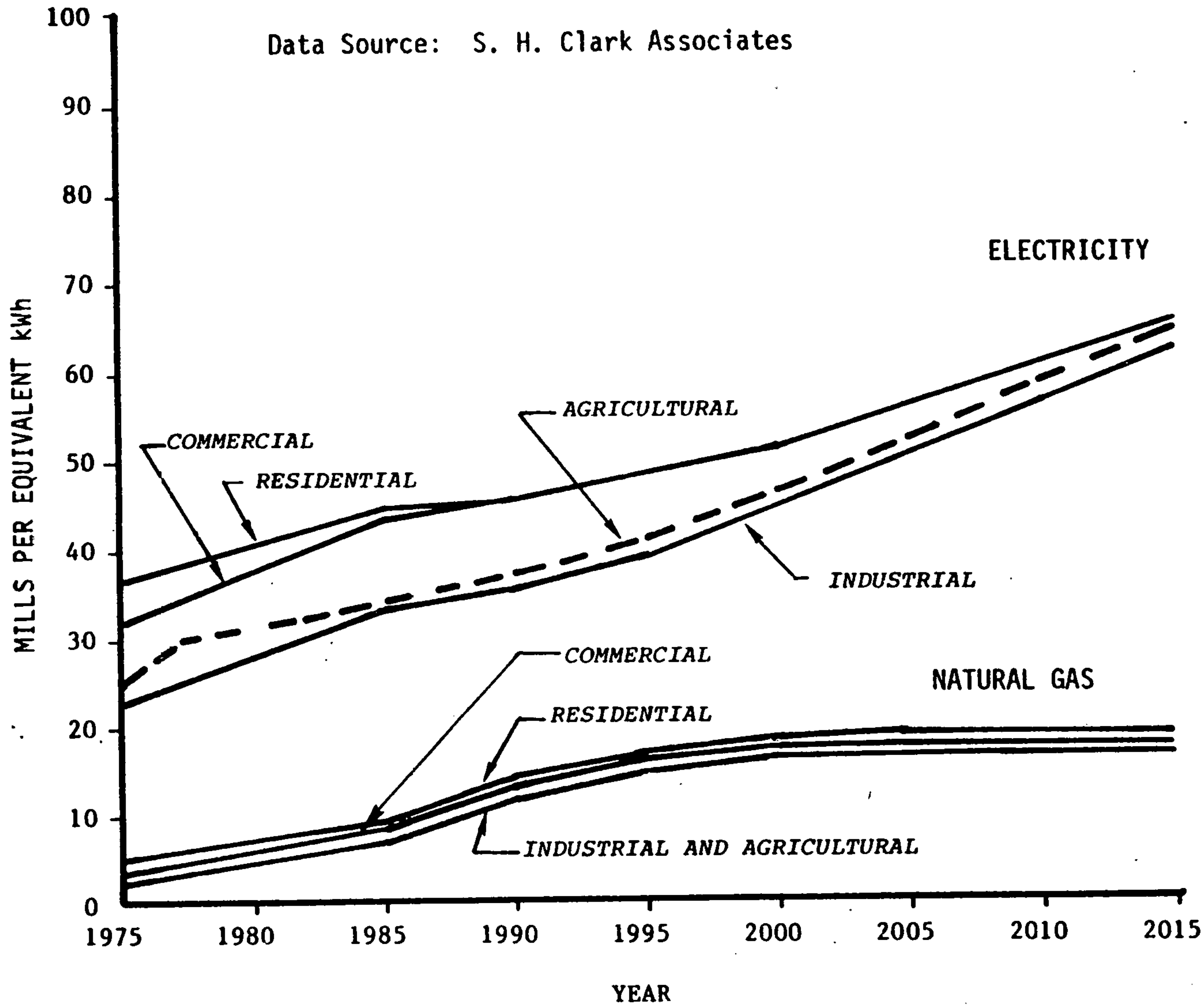

Figure 5-7. Projected Energy Prices for Arizona

through the year 2015.

4. Petroleum fuel prices escalate 2 percent per year after 2015.

5. Large current price variations, both those based on location and on rates of consumption, decrease over time.

The results are quite different, however, when costs are expressed in the form of work done. By accounting for the energy conversion efficiencies of the prime mover and pump combination, irrigation pumping costs expressed in 1977 dollars per acre foot per foot of lift show electricity to be the cheapest energy source in central Arizona after 1987. The following conversion factors were used:

Energy Source	Units to Pump 1 Acre-Ft/Ft of Lift
Natural Gas (0.0105 therm/ft^3)	29.0573 ft^3
LPG	0.2953 gal
Diesel Fuel	0.1778 gal
Electricity	1.8952 kWh

These factors are based on previously developed estimates of the efficiencies of typical prime movers and pump units (Section 4). Price comparisons illustrating this point are graphically displayed for four energy sources in Figure 5-8 along with relative costs for diesel fuel and LPG.

Price projections after 2015 were accomplished by Aerospace after consultation with S. H. Clark Associates. (It was assumed, for example, that electricity prices will increase at decreasing exponential rates as advanced generation technologies are adapted.) This extended projection was needed for comparing conventional energy costs to solar energy costs for 30-year lifetime irrigation systems purchased in 2000.

5.3 PRICE COST PROJECTIONS FOR EXTENDED GEOGRAPHIC REGION

For states other than the six primary study states, it was necessary to choose proxy energy prices for irrigation pumping, since price

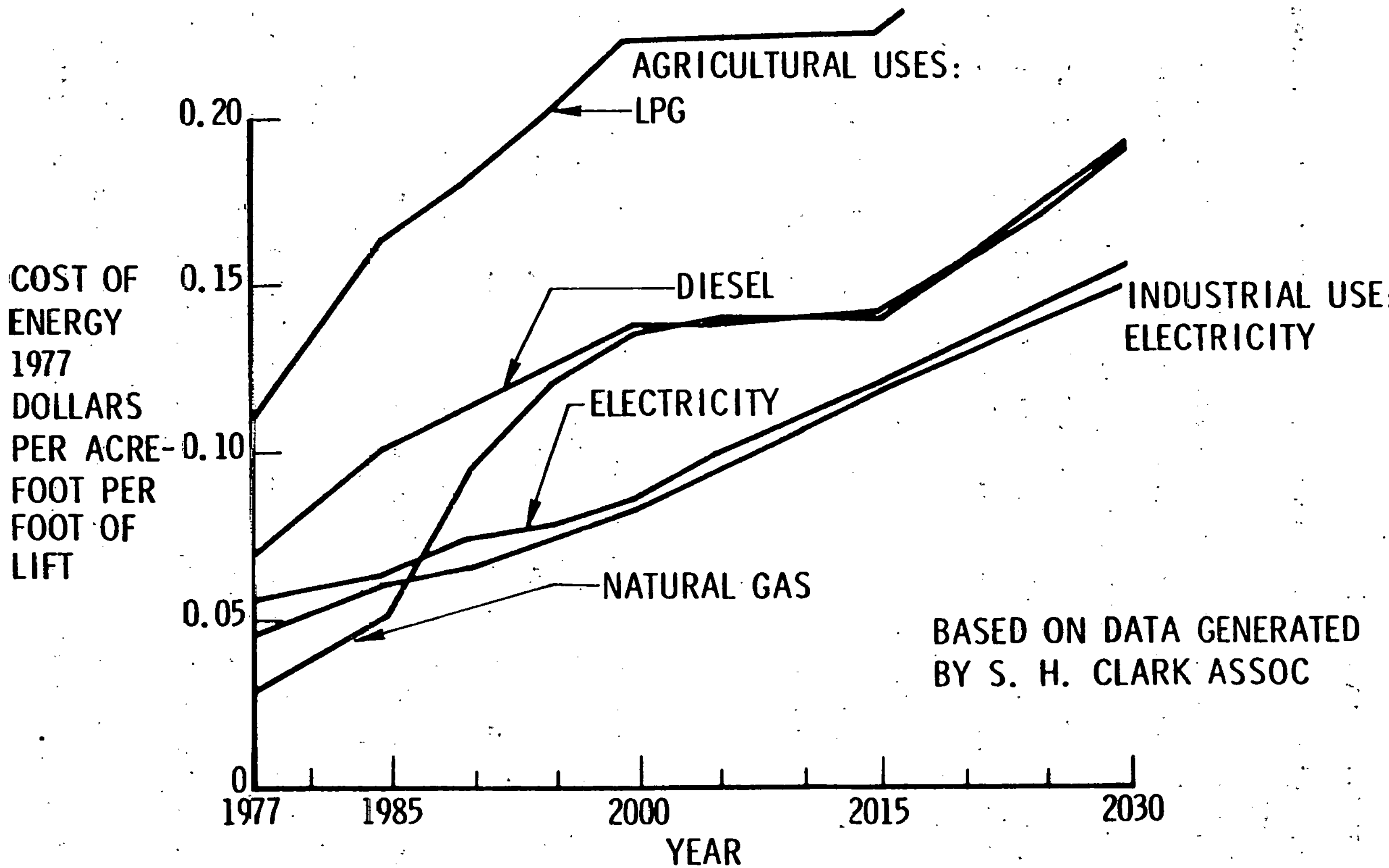

Figure 5-8. Price Projections for Conventional Energy Sources in Arizona on the Basis of Work Done to Pump Water

projections specific to agriculture were not available. By comparing irrigation energy prices to those of other sectors within the six study states, it was found that electricity costs for irrigation were most often comparable to electricity prices for the commercial sector, irrigation natural gas costs were comparable to natural gas prices for the industrial sector, and diesel fuel costs for irrigation were comparable to light fuel oil prices for the residential sector. Price projections for similar energy sources supplied to the residential, commercial, and industrial sectors were also provided by S. H. Clark Associates for all 48 contiguous states (Reference 5-2). These energy costs along with the aforementioned correlations, were used to determine irrigation energy costs in the other 11 western states.

6. SELECTION OF GEOGRAPHIC REGIONS FOR STUDY

6.1 SELECTION CRITERIA

For a new product, such as a solar-powered irrigation system, estimates of potential market areas must be based on judgemental criteria in lieu of more definitive facts normally available for traditional or evolving product lines. Within present study guidelines, the following five regional selection criteria are considered to be most applicable:

(1) large irrigation acreage
(2) potential growth in irrigation acreage
(3) high energy use per acre
(4) high levels of insolation
(5) poor prospects for continued low cost fossil energy supplies.

The subsequent discussion offers illustrations of geo-political regions satisfying one or more of the above criteria.

6.2 RANKING OF STATES

The map shown in Figure 6-1 gives the distribution of irrigation in the nation. Approximately 83 percent of all irrigated cropland is found in the 17 western states but, because of the extensive use of deep well groundwater supplies, this region constitutes 93 percent of nationwide irrigation energy consumption.

Irrigated land area, energy use per acre, insolation levels, and type of irrigation energy supplies are summarized in Table 6-1 for the 17 western states. In descending order, Texas, California, Nebraska and Kansas clearly lead in irrigated land area. Energy intensity is greatest in Arizona, New Mexico, and Nebraska where crop irrigation requirements are high and where deep wells and/or high-pressure irrigation systems are prevalent (Table 6-2). The southwestern states of

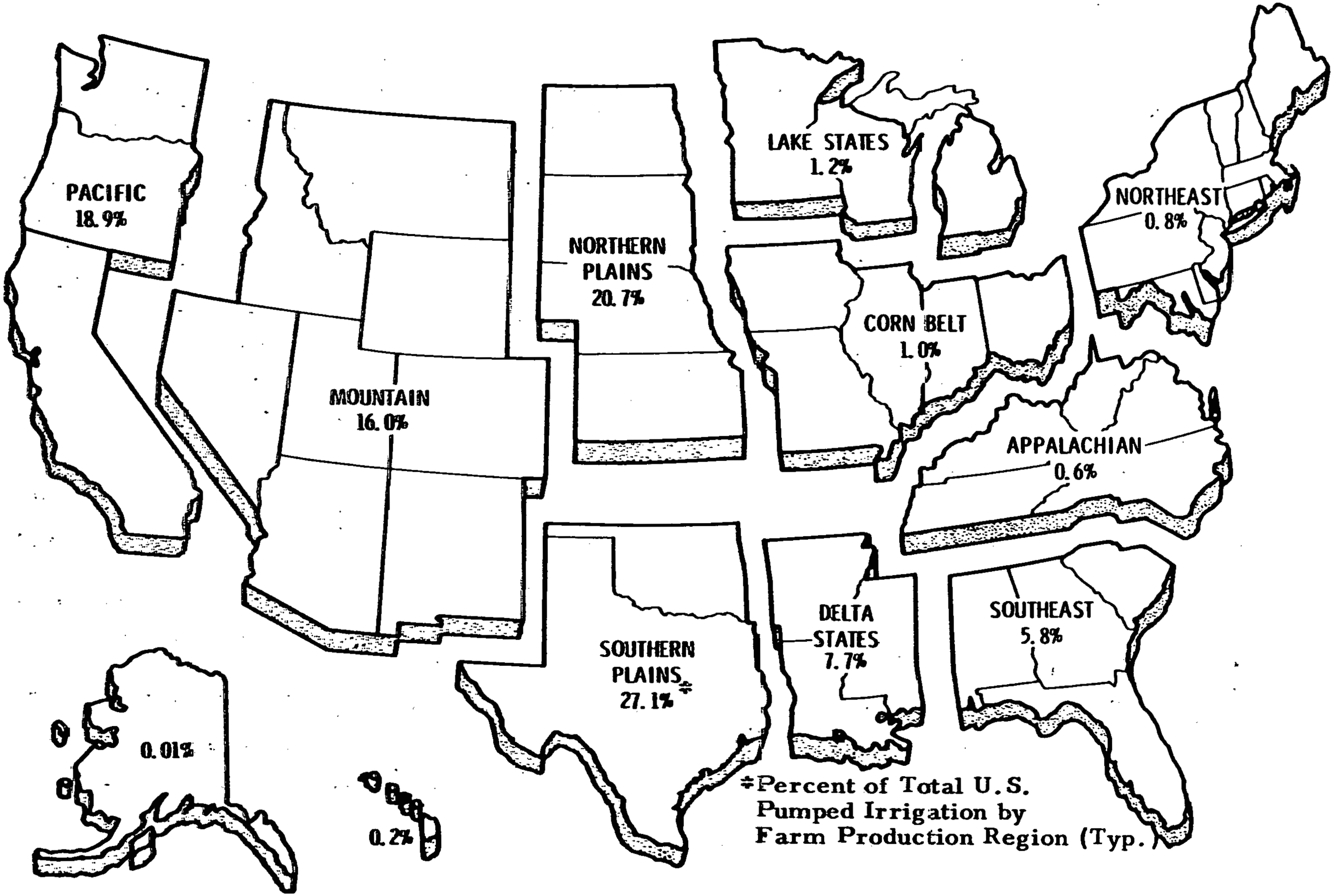

Figure 6-1. National Distribution of Irrigated Acreage

Table 6-1

STATE CHARACTERISTICS FOR REGIONAL SELECTION CRITERIA

State	Irrigated Land (1000 Acres)	Irrigation Energy Intensity (10^6 Btu/Acre)	Mean Daily Solar Insolation (kW-Hr/M^2)	Division of Energy Sources %				
				Electric	LPG	Diesel	Nat. Gas	Gasoline
Arizona	552	40.8	5.81	70	0	0	30	0
California	4250	3.8	5.23	98	0	0	2	0
Colorado	900	7.5	4.65	70	12	5	10	3
Idaho	850	7.4	4.36	96	1	1	1	1
Kansas	2230	10.8	4.65	17	10	12	60	1
Montana	40	7.8	4.19	96	1	1	1	1
Nebraska	4070	30.9	4.36	27	14	35	23	1
Nevada	170	14.6	5.52	78	1	20	0	1
New Mexico	634	33.8	5.81	30	15	10	40	5
North Dakota	33	3.9	4.13	76	2	16	0	6
Oklahoma	680	12.5	4.94	25	20	10	40	5
Oregon	188	7.9	4.30	100	0	0	0	0
South Dakota	43	6.5	4.30	40	25	25	5	5
Texas	7090	10.4	5.23	30	5	5	60	0
Utah	160	12.3	5.23	88	3	6	0	3
Washington	200	10.1	3.90	99	0	1	0	0
Wyoming	125	9.0	4.88	85	2	8	4	1

Sources: (1) "Energy Use for Pumping Irrigation Water in the United States, 1974", G. Sloggett, 1976
(2) "Determination of the Feasibility of Using Solar Energy for Irrigation Pumping", D. L. Larsen, 1976
(3) 1976 Irrigation Survey, Survey Issue of the Irrigation Journal

Table 6-2

IRRIGATION CHARACTERISTICS FOR SELECTED STATES

State	Percent of U.S. Sprinkler-Irrigated Land	Average Feet of Lift		Feet of Water Applied Per Season
		Ground Water	Surface Water	
Arizona	0.39	350	0	5.50
California	11.76	110	10	3.17
Kansas	4.84	180	15	1.50
Nebraska	12.39	100	20	1.83
New Mexico	1.21	350	5	2.50
Texas	14.47	200	40	1.50

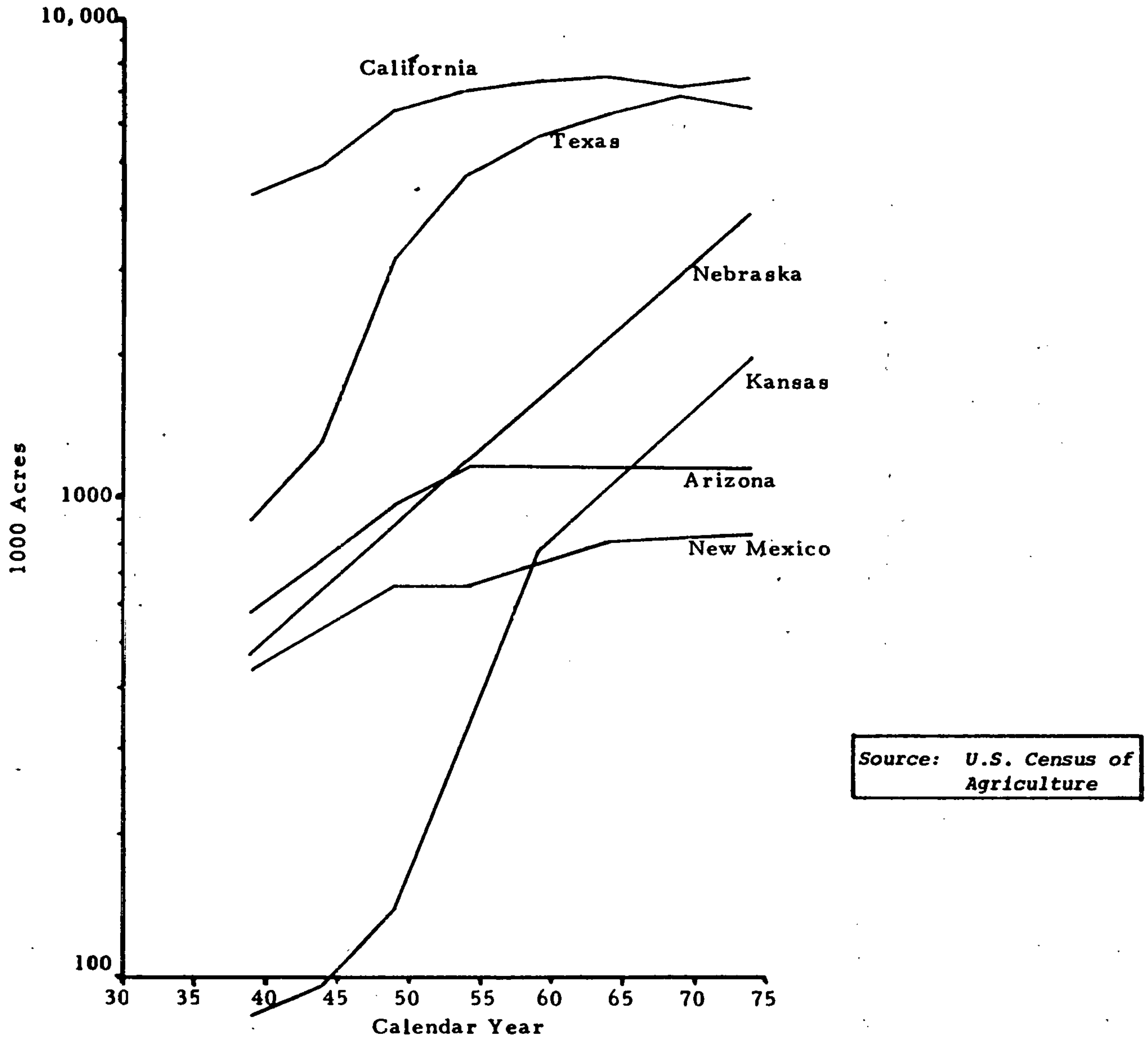

Figure 6-2. Irrigated Land in Farms

Arizona and New Mexico excel in experiencing high insolation levels. Increasingly scarce natural gas is the major irrigation energy source in Kansas and Texas.

Arizona, California, Kansas, New Mexico, Nebraska and Texas are states that dominate with respect to one or more of the above four criteria. Their irrigated acreage growth characteristics are also impressive. Historical growth in irrigated farmland for these six states is illustrated in Figure 6-2. A combination of unsuitable soil and terrain, limited water supplies and acreage, and higher fuel and land costs may have slowed the growth of irrigated lands in Arizona, California, New Mexico and Texas. However, growth in irrigated farmland shows no slowing for Kansas and Nebraska where rapid expansion is evident. Much of this recent expansion can be attributed to the introduction of center pivot sprinkler systems, permitting uneven terrain to be converted from cattle grazing land or unproductive land to high yield crop production.

7. IRRIGATION ENERGY MARKET DEMAND

7.1 DESCRIPTION OF IRRIGATION MARKET ENERGY DEMAND COMPUTER PROGRAM

Specification of irrigation system energy demand characteristics is a necessary prerequisite to selection of solar thermal power system designs matched to such characteristics. When considering the complex variation in crop irrigation needs, pumping depths, irrigation systems, and pump power units, it becomes obvious that a computer program is required to permit rapid access to the massive data base needed for selective calculations of energy demand profiles, (and to perform these calculations). These profiles consist of the individual monthly expenditure of energy to irrigate a given crop. Profiles are available for up to 26 different crops for each county in the 17 western states. The data base, program logic, and print format for the computer program are briefly described in this section.

7.1.1 Data Base

7.1.1.1 County Crop Acreages

Except for three crops (rice, sugar beets and oranges), the county irrigated crop acreages were obtained from the 1969 Census of Agriculture. The county irrigated crop acreases for rice, sugar beets and oranges were obtained from various statistical reporting service reports.

7.1.1.2 Crop Water Use Coefficients

The irrigation water requirements for individual crops are available from the Soil Conservation Service, USDA. Only the "normal year" coefficients are considered in the simulator program.

Consumptive irrigation requirements (CIR) can be converted to irrigation water use by dividing the CIR by the on-farm irrigation efficiency. Two levels of on-farm irrigation efficiency are considered, "1975 normal" and "1975 high." The first efficiency reflects current irrigation practices, while the second efficiency reflects improved irrigation practices.

Irrigation water use coefficients are only listed according to the Water Resources Council's Sub-Areas (SA). Therefore, it was assumed that all the counties belonging to one sub-area will have the same irrigation water use coefficients.

7.1.1.3 County Pumping Depth

The County Pumping Depth is defined as the yearly average depth (in feet) relative to the ground surface from which the water is pumped for irrigation. For each county in the 17 western states, the county pumping depth is the sum of the county water level plus the draw down for the appropriate state. County water levels for the 17 western states were obtained from various geological survey agencies.

State draw down figures are derived by subtracting the average state water level from the state pumping depth estimated by irrigation experts. A weighted average procedure is used to derive the state water level from the county water levels.

7.1.1.4 Distribution of Sprinkler Irrigation Method and Determination of Weighted Lift

The fractional division of irrigation sprinkler methods is obtained from the 1975 Irrigation Survey published in the Irrigation Journal. The survey gives the state-wide areas irrigated for each of the following systems: tow line and side roll, center pivot, hand move, solid set, gun and drip. The distribution of sprinkler methods by county is assumed to be the same as for the entire state. The feet of lift for each of the sprinkler methods, combined with the method's percentage, is used to compute a weighted average lift for state-wide sprinkler irrigation.

7.1.1.5 Acres Under Sprinkler Irrigation

The proportion of land irrigated by sprinkler in each state is obtained from the Irrigation Journal. In general, only a small fraction of the irrigated acres is under sprinkler irrigation. All the counties in a state are assumed to have the same sprinkler acreage fraction as the entire state.

7.1.1.6 Distribution of Power Units

Five power units are commonly used in irrigation: gasoline, natural gas, LP gas, diesel, and electric. A great variation exists in the proportions of these units between the states. Farmers in the Pacific states generally use electrical motors. The distribution of power units by state is obtained from the Irrigation Journal. It is assumed that all the counties in the state have the same power unit distribution as the entire state.

7.1.1.7 Distribution of Water Sources

Three sources of water for irrigation are considered: ground water, surface water pumped, and surface water not pumped. Energy is required only for the first two sources.

Data on the average lift of pumped surface water and on the proportion of irrigated cropland receiving water from each of the sources were obtained from Sloggett (Reference 7-1). It is assumed that all the counties in the state receive water from the same source as the entire state, e.g., the fraction of state water supplied by ground water sources is the same fraction used to estimate county ground water supplies.

The distribution of water sources is used to adjust crop acreages, reflecting the fact that not all irrigated land requires energy for ground water pumping or surface water pumping.

7.1.2 Program Logic

The logic flow paths in the computer program are illustrated in Figures 7-1 and 7-2. The first figure shows how the county information file is created; the second figure shows how the energy calculations are performed and how energy is aggregated for each county and for each state. Equations used in the calculations are presented in Table 7-1; a list of definitions for all the variables is given in Table 7-2.

7.1.3 Print Format

Examples of the tabulated results from computer calculations are given in Tables 7-3 and 7-4. The former table shows crop-by-crop monthly energy demand for a given county whereas the latter table gives the same data for an entire state. The first part of each table (designated "Table 1") gives monthly and yearly aggregated energy consumption at the input to electric pump drive systems if they were eventually to serve the entire geographic area. The second part of the table (designated "Table 2") gives the yearly aggregated energy input to all types of pump drive units as they are presently distributed throughout a geographic area. The last column, "Energy in Fossil Fuels", accounts for energy losses in electric generating utility systems and in transmission to the user's site. Therefore, it shows energy consumed by fossil fuels delivered on-site to mechanical pump drives (e.g. diesel engine) as well as that delivered to boilers at central electric generating stations.

7.2 ENERGY DEMAND PROFILES AND AGGREGATE DEMAND

Typical results from the computer program are illustrated in Figure 7-3 where semi-monthly irrigation energy demand in megawatt-hours (MWh) is shown as a function of month during the year for an 80-acre Arizona alfalfa farm. Two discrete values were plotted for each month and connected by a straight line to improve visibility. The 550 MWh for the season is obtained by summing the semi-monthly demand figures, not by integrating under the apparent curve.

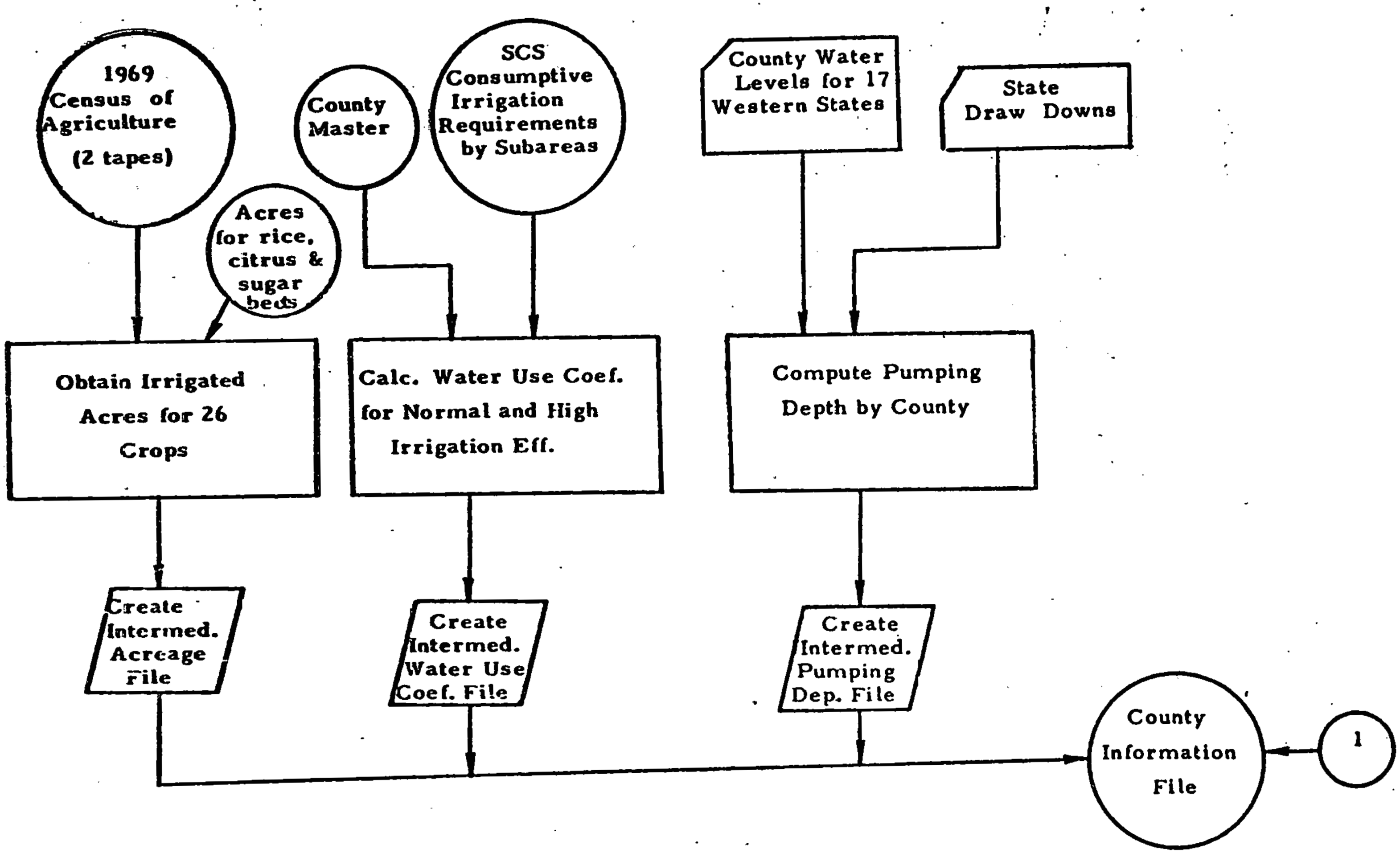

Figure 7-1. Flow Chart Creating County Information File

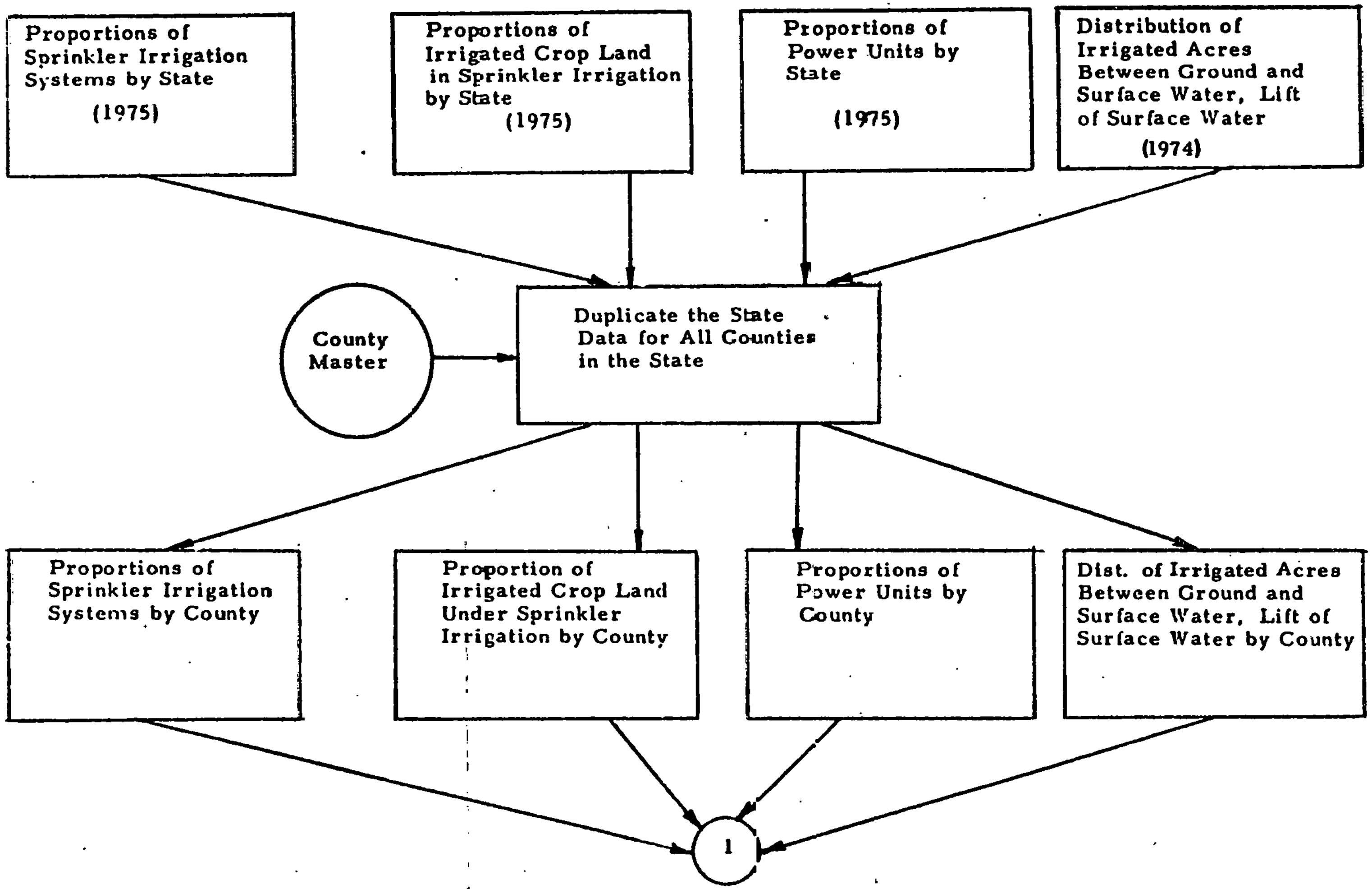

Figure 7-1. Flow Chart Creating County Information File (Cont'd)

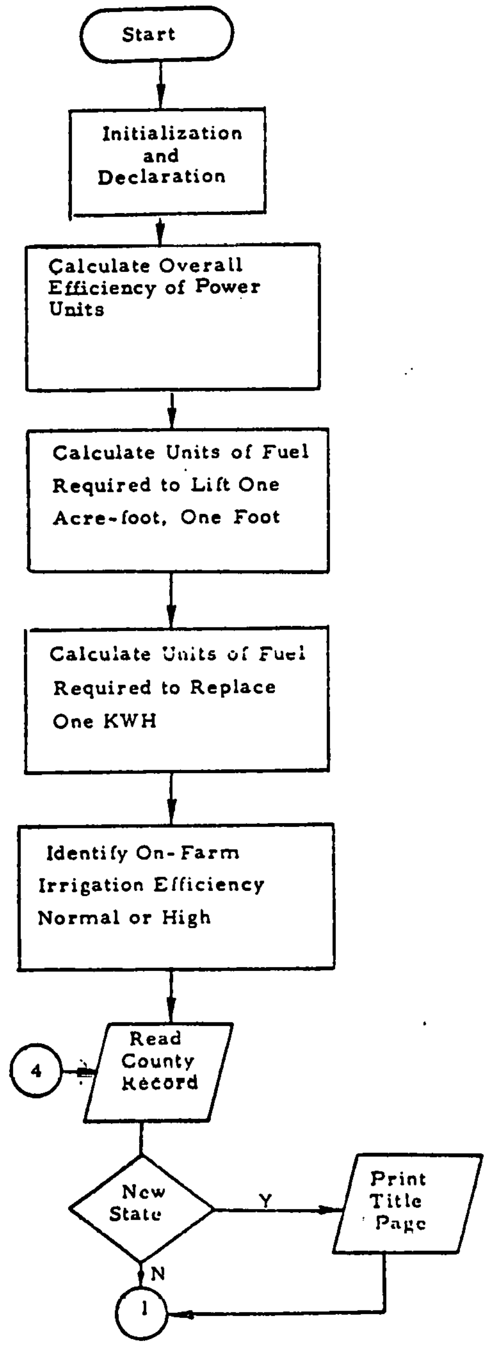

Figure 7-2. Flow Chart for Energy in Irrigation Simulator Program

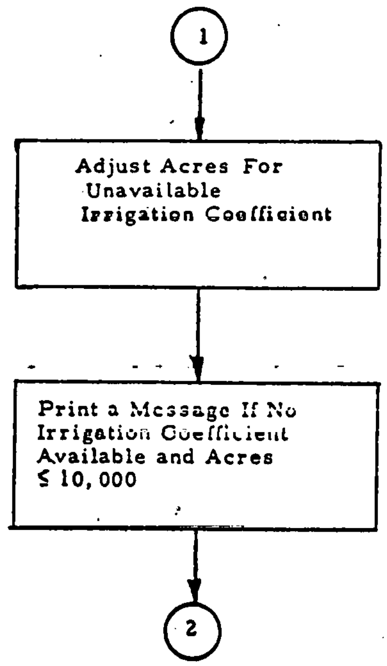

Figure 7-2. Flow Chart for Energy in Irrigation Simulator Program (Cont'd)

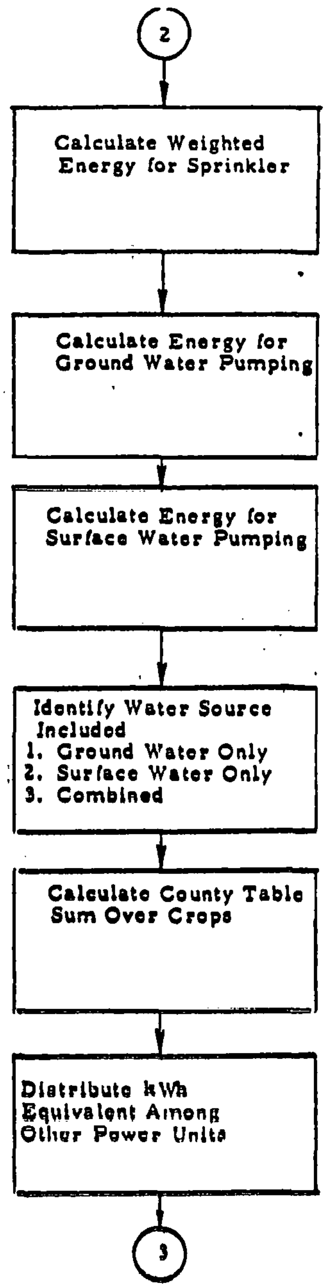

Figure 7-2. Flow Chart for Energy in Irrigation Simulator Program (Cont'd)

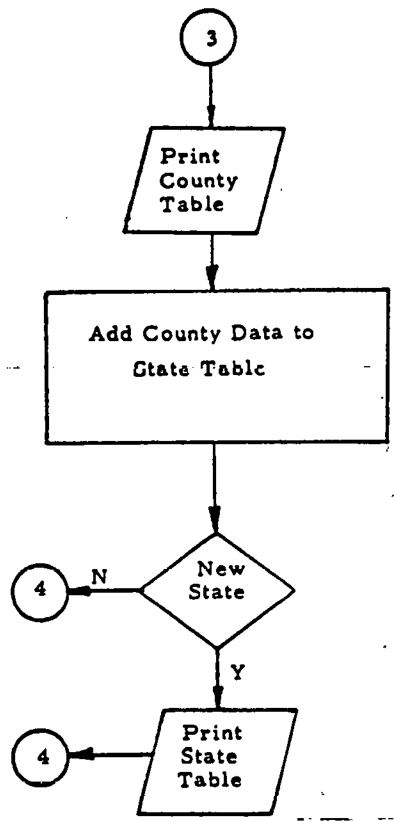

Figure 7-2. Flow Chart for Energy in Irrigation Simulator Program (Cont'd)

Table 7-1

List of Equations

Weighted lift for sprinkler methods:

$$\text{LIFTSP} = \sum_{k=1}^{6} (\text{PROPSP}_k)(\text{SPHEAD}_k) \quad (1)$$

Energy for applying one-acre foot by sprinkler:

$$\text{KWHSP} = [(\text{LIFTSP})(2.0489)](\text{PROPSP}) \quad (2)$$

Energy for pumping one-acre foot from ground water:

$$\text{KWHGR} = (\text{LIFTG})(2.0489) \quad (3)$$

Energy for pumping one-acre foot from surface water:

$$\text{KWHSR} = (\text{LIFTS})(2.0489) \quad (4)$$

Energy required by crops on ground water only:

$$\text{KWHG}_{ij} = (\text{ACRE}_i)(\text{PROPG})(\text{WTR}_{ij})(\text{KWHGR}+\text{KWHSP}) \quad (5)$$

Energy required by crops on surface water pump only:

$$\text{KWHS}_{ij} = (\text{ACRE}_i)(\text{PROPS})(\text{WTR}_{ij})(\text{KWHSR}+\text{KWHSP}) \quad (6)$$

Energy required by crops on combined ground water and pumped surface water:

$$\begin{aligned}\text{KWHCO}_{ij} = {} & (\text{ACRE}_i)(\text{PROPS})(\text{WTR}_{ij})(\text{KWHSR}) \\ & + (\text{ACRE}_i)(\text{PROPG})(\text{WTR}_{ij})(\text{KWHGR}) \\ & + (\text{ACRE}_i)(\text{WTR}_{ij})(\text{KWHSP}) \quad (7)\end{aligned}$$

Table 7-2

List of Variables

$ACRE_i$	is the irrigated crop acreage of the ith crop;
PROPG	is the proportion of the county irrigated crop land receiving ground water;
PROPS	is the proportion of the county irrigated crop land receiving pumped surface water;
WTR_{ij}	is the water use coefficients of the ith crop in the jth month (acre-feet/acre);
LIFTG	is the county required lift for ground water (feet);
LIFTS	is the county required lift for surface water (feet);
LIFTSP	is the county weighted lift required for sprinkler application (feet);
PROPSP	is the proportion of the county irrigated crop land under sprinkler;
KWHSP	is the amount of electricity required for sprinkler application in the county;
$KWHG_{ij}$	is the amount of electricity required by the ith crop application in the county in the jth month for ground water;
$KWHS_{ij}$	is the amount of electricity required by the ith crop in the jth month for surface water;
$KWHCO_{ij}$	is the amount of electricity required by the ith crop in the jth month for combined ground and surface water
$PROPSP_k$	is the proportion of the kth sprinkler method;
$SPHEAD_k$	is the head (feet) required by the kth sprinkler method;
KWHGR	is the amount of electricity required for pumping of ground water;
KWHSR	is the amount of electricity required for pumping of surface water;

i=1, 2....26 for the 26 possible irrigated crops;
j=1, 2....13 for the 12 months and the yearly coefficient;
k=1, 2.... 6 for the 6 sprinkler methods;

Table 7-3

ENERGY REQUIREMENTS OF IRRIGATION - COCHISE, ARIZONA

** GROUND WATER **

COUNTY GROUND WATER LIFT (FEET) =	264.94
PER CENT OF ACRES IRRIGATED BY GROUND WATER =	82.00
WEIGHTED SPRINKLER HEAD (FEET) =	174.55
PER CENT OF ACRES IN SPRINKLER IRRIGATION =	4.43

TABLE 1. CROP MONTHLY ELECTRIC REQUIREMENTS (KWH) - ALL NUMBERS IN THOUSANDS

CROP	ACREAGE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEARLY
WHEAT	5.040	307	769	2229	2767	845	0	0	0	0	0	0	0	6917
CORN GRAIN	1.642	0	0	0	0	0	0	336	1139	739	165	0	0	2379
CORN SILAGE	0.262	0	0	0	0	0	0	56	180	118	6	0	0	360
SORGHUM GRAIN	46.119	0	0	0	0	0	0	10272	33019	21646	4769	0	0	69706
SORGHUM SILAGE	0.245	0	0	0	0	0	0	52	166	112	4	0	0	336
BARLEY	1.552	47	213	544	1029	296	0	0	0	0	0	0	0	2130
DECIDUOUS ORCHARDS	1.668	0	0	0	0	163	407	407	244	81	0	0	0	1303
VEGETABLES	2.859	0	0	0	0	0	0	0	0	65	283	589	589	1526
LEGUME HAY	4.168	0	0	1303	1811	2510	2669	2479	1938	2097	1335	499	0	16642
OTHER HAY	0.109	0	0	0	13	37	55	66	56	39	13	0	0	283
COTTON	9.503	0	0	0	72	1159	3188	5796	6014	4202	1684	145	0	22461
SUGAR BEETS	4.330	561	462	990	1616	2377	2276	1166	0	0	165	495	561	10669
IRISH POTATOES	0.170	0	0	9	84	121	32	0	0	0	0	0	0	246
CROPLAND PASTURE	4.458	0	0	0	567	1625	2361	2722	2381	1550	491	0	0	11716
OTHER PASTURE	0.591	0	0	0	68	194	284	324	284	185	59	0	0	1397
OTHER CROPS	6.301	432	721	2066	3699	2930	2498	1105	0	0	48	192	240	13932
TOTAL	90.917	1346	2164	7141	11927	12256	13793	24807	45426	30834	9220	2120	1390	162429

TABLE 2. IRRIGATION ENERGY CONSUMPTION

GASOLINE (GALLON)	0.000
NATURAL GAS (CUBIC-FEET)	747127.750
LP GAS (GALLON)	0.000
DIESEL (GALLON)	0.000
ELECTRICITY (KWH)	113700.063

Table 7-4

ENERGY REQUIREMENTS OF IRRIGATION - ARIZONA

** GROUND WATER **

PER CENT OF ACRES IRRIGATED BY GROUND WATER = 82.00
WEIGHTED SPRINKLER HEAD (FEET) = 174.55
PER CENT OF ACRES IN SPRINKLER IRRIGATION = 4.43

TABLE 1. CROP MONTHLY ELECTRIC REQUIREMENTS (KWH) - ALL NUMBERS IN THOUSANDS

CROP	ACREAGE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEARLY
WHEAT	57.963	5728	12171	13729	41099	12541	307	0	0	0	0	217	2966	108768
CORN GRAIN	5.665	0	0	10	143	336	626	1599	3403	2018	477	0	0	8613
CORN SILAGE	4.662	0	0	1	18	143	306	2559	7472	4857	306	0	0	15661
SORGHUM GRAIN	157.757	0	0	199	2783	6601	12404	48644	120767	75405	17228	0	0	284030
SORGHUM SILAGE	9.241	0	0	4	61	173	359	2526	7372	4723	224	0	0	15412
OATS	0.614	41	33	328	508	169	5	0	0	0	0	1	2	1186
BARLEY	132.903	7311	29166	65348	110877	39050	0	0	0	0	0	0	247	259939
DECIDUOUS ORCHARDS	7.277	0	0	0	0	1466	3665	3665	2204	733	0	0	0	11734
CITRUS ORCHARDS	58.510	7299	7299	11337	14012	20479	25858	29934	28856	24806	19678	12134	8639	210337
VEGETABLES	85.873	0	0	0	6	17	55	93	54	3061	12418	23736	23736	63176
LEGUME HAY	157.909	0	14433	67249	91718	123570	135056	129349	104752	109488	66870	38416	0	879400
NON-LEGUME HAY	1.838	0	1	2	275	705	1028	1161	1029	690	247	2	0	5138
HAYSEED	4.963	0	94	778	1464	2529	3150	3466	3017	2479	1182	319	0	18477
OTHER HAY	2.456	0	4	10	382	997	1457	1649	1478	976	335	8	0	7296
COTTON	292.844	0	0	0	4431	46608	127150	232391	243930	166722	73673	6421	0	901275
SUGAR BEETS	13.590	2275	8690	3944	7153	9288	9949	4714	0	0	642	2111	2322	43289
IRISH POTATOES	11.610	0	0	753	8096	11440	3107	38	0	0	0	0	0	23433
CROPLAND PASTURE	41.950	0	95	246	6807	17823	25795	28849	25585	17006	5913	191	0	128318
OTHER PASTURE	10.969	0	47	122	1651	4090	6039	6618	5861	3914	1434	94	0	29839
OTHER CROPS	117.915	9201	14822	43962	92366	97232	77145	27020	0	0	1450	5978	5860	364235
TOTAL	1177.893	31355	73284	228028	391346	385261	432371	524274	555778	415878	202078	89626	43771	3379550

TABLE 2. IRRIGATION ENERGY CONSUMPTION

	UNITS	ENERGY INPUT TO PUMP DRIVER	ENERGY INPUT TO PUMP DRIVER	ENERGY IN FOSSIL FUELS
GASOLINE	0.000E+00 GAL	0.000E+00 BTU	0.000E+00 KWH	0.000E+00 BTU
NATURAL GAS	1.555E+10 CUFT	1.632E+13 BTU	4.782E+09 KWH	1.632E+13 BTU
LP GAS	0.000E+00 GAL	0.000E+00 BTU	0.000E+00 KWH	0.000E+00 BTU
DIESEL	0.000E+00 GAL	0.000E+00 BTU	0.000E+00 KWH	0.000E+00 BTU
ELECTRICITY	2.366E+09 KWH	6.074E+12 BTU	2.366E+09 KWH	2.605E+13 BTU
TOTALS		2.440E+13 BTU	7.148E+09 KWH	4.237E+13 BTU

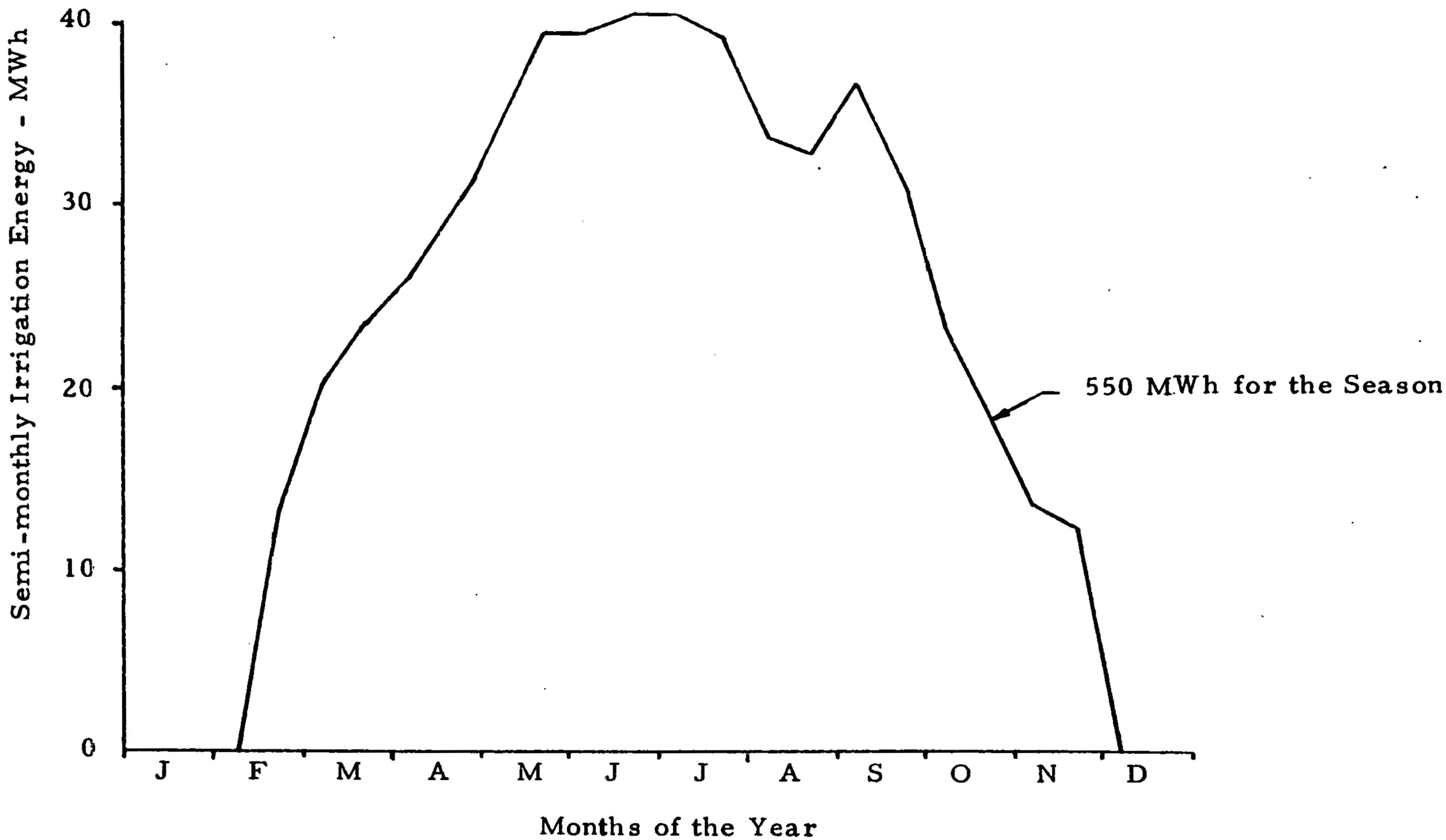

Figure 7-3. 80 Acre Alfalfa Farm in Cochise County, Arizona

Figure 7-4 illustrates the methodology used for aggregating energy demand by crop and by geo-political region. The process is repeated for all 17 western states.

Table 7-5 summarizes the irrigation market energy demand for pumping groundwater by state for three cases: (a) energy delivered to pump drive unit (all pumps driven by electric motors); (b) energy delivered to pump drive unit (drive units conform to the current mix of petroleum- and natural gas-fueled engines and electric motors; (c) energy delivered in the form of fuel to engine-driven pumps and to electric-generating utilities. The lower efficiency of engines compared to electric motors is evident by the decreased use of energy for Case (a) when compared to Case (b). There are no decreases noted, of course, for states such as Oregon and Washington that rely solely on electric power for irrigation pumping. Because of California's high reliance on electric power, there would be little decrease in energy demand if the entire state were to rely on electric power for irrigation.

Overall, 346.3×10^{12} Btu of irrigation energy in fossil fuels is required just for pumping groundwater supplies. An additional 141.6×10^{12} Btu is required for surface water pumping, resulting in a grand total of 487.9×10^{12} Btu, using a 1969 data base for irrigated acreage. Continued growth in this acreage can be expected to result in major increases in irrigation energy expenditures out to 1985. After that time, limitations in land and water availability would be expected to slow this growth, exclusive of any negative impact from increased costs of energy or curtailment of energy supplies.

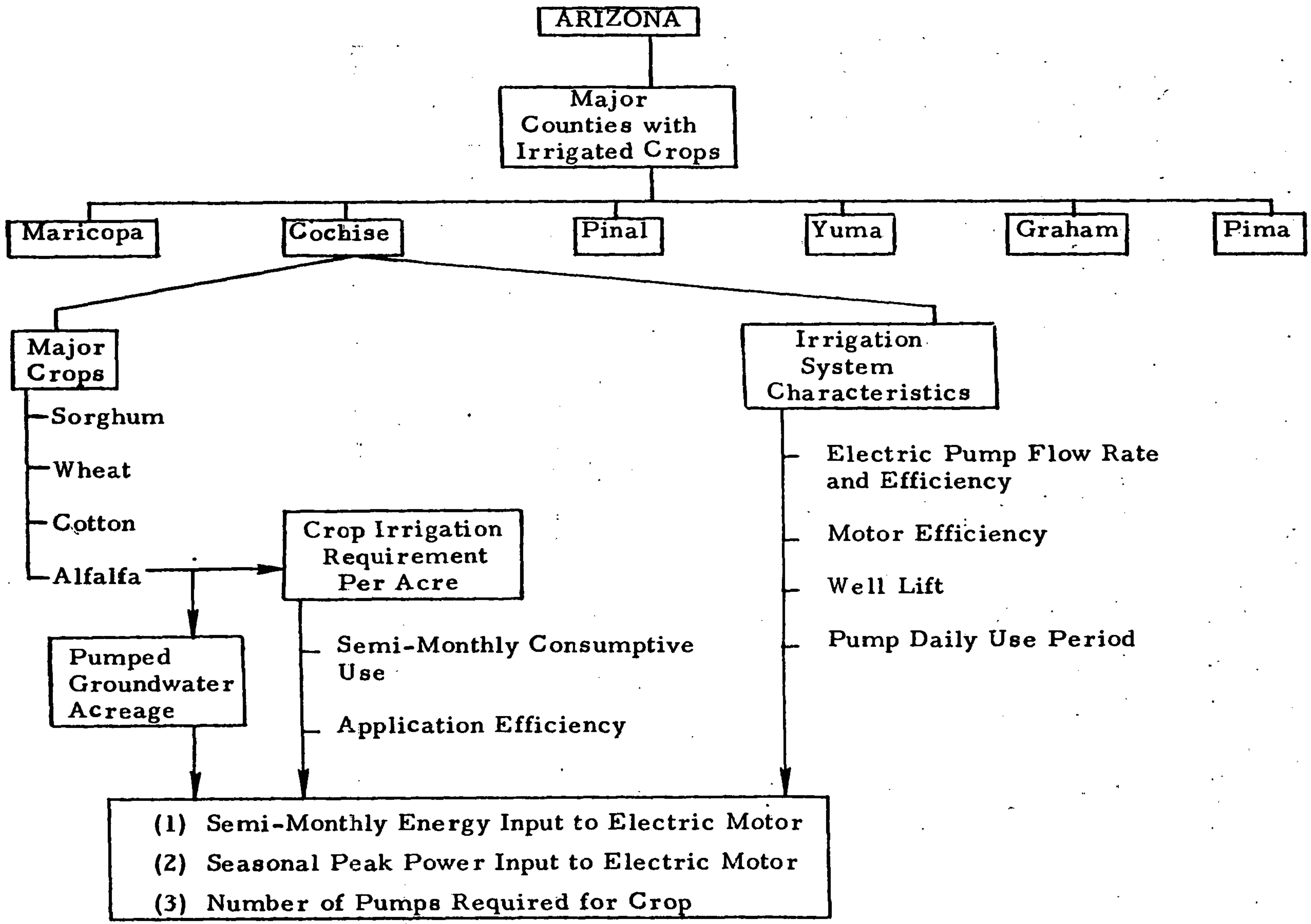

Figure 7-4. Example of Methodology for Establishing Market Energy Demand

Table 7-5
IRRIGATION ENERGY MARKET DEMAND SUMMARY
(GROUNDWATER SOURCES)

State	Energy Demand		
	Motor-Driven Pumps (10^9 kWh)	Engine- and Motor-Driven Pumps (10^9 kWh equiv.)	Fuel Energy (10^{12} Btu)
Arizona	3.38	7.15	42.4
California	4.91	5.27	54.5
Colorado	1.04	2.12	12.8
Idaho	3.58	4.07	40.0
Kansas	1.37	5.40	20.2
Montana	0.32	0.36	3.5
Nebraska	1.64	5.49	22.1
Nevada	0.13	0.21	1.5
New Mexico	1.31	4.54	18.5
North Dakota	0.07	0.12	0.8
Oklahoma	0.71	2.58	10.2
Oregon	0.95	0.95	10.4
South Dakota	0.10	0.30	1.3
Texas	6.25	22.11	89.7
Utah	0.36	0.50	4.1
Washington	1.00	1.00	11.0
Wyoming	0.29	0.42	3.3
TOTAL	27.41	62.59	346.3

8. SOLAR-POWERED IRRIGATION SYSTEM CONCEPTS AND APPLICATIONS

8.1 DESIGN CONCEPTS

The various design concepts that have been proposed for dispersed solar irrigation systems (SIS) can be organized into four insolation collector/receiver categories: (1) parabolic trough, concentrating collector with linear focus receiver; (2) paraboloidal dish, concentrating collector with point focus receiver; (3) heliostat reflector field focussing on a central receiver; (4) photovoltaic panels (concentrating or non-concentrating). The heated fluid from the first three collector/receiver subsystems can be directed to a heat exchanger for transfer of energy to a working fluid or be distributed directly as a working fluid to a heat engine.

Thermal storage is considered for many applications because it enables the system to use more of the captured insolation for power generation. This is due to the fact that these systems generally must operate at a single design point to retain high efficiency and, therefore, insolation variations due to cloud passage or sun-collector view angles are unacceptable. Water storage has also been considered in a similar context as a means of using more of the generated energy throughout the year. Peak summer irrigation energy needs can be met with a smaller SIS if water stored out-of-season is used to supplement the water pumped by SIS in season.

Different forms of heat transfer and working fluids are available for selection by system designers. Organic fluids have proved to be suitable for the lower range of operating temperatures and are favored for low pressure system designs. At the higher temperatures, water and air are favored as selections for the working medium.

Engine design concepts are presently concentrated in versions of the Rankine cycle, with turbine expanders receiving more attention than piston expanders. The Brayton cycle has been examined for high temperature air applications. Rather than having a mechanical output drive system, many designs include an electric generator geared to the turbine output shaft so that electric power can be produced for use with motor-driven irrigation pumps.

In parallel with analytical programs for dispersed solar thermal power systems, experimental programs have been designed to gain experience, under operational conditions, with actual hardware and to derive from this experience data needed to validate system analyses and to support design improvements. A summary of characteristics of four solar-powered irrigation systems that are presently being tested or near to installation is given in Table 8-1. Three of the four systems rely on a field of distributed linear focus parabolic trough concentrating collector/receivers for using energy in direct normal insolation to raise the temperature of a heat transfer fluid. Energy in the heat transfer fluid is then transferred in a heat exchanger to the working fluid for a Rankine cycle turbine which, in turn, delivers shaft mechanical power directly to an irrigation pump or delivers electric power to a motor-driven irrigation pump. The fourth system in the table uses two rows of photovoltaic panels for conversion of insolation to electric power that is delivered to a motor-driven irrigation pump after passing through a battery storage system and subsequently a DC-AC inverter.

All of these designs are based on current technology, and three of the four systems are presently functioning. Operation of the DOE/DST Willard, New Mexico, facility commenced officially on 8 July 1977. The DOE/DST Coolidge, Arizona, facility is presently being designed and is targeted for installation completion by mid-year 1979; full operation is not expected until system tests are completed later that year. The Northwestern Mutual Life Insurance Company, Gila Bend, Arizona, facility has been functioning since May of 1977. DOE/DST's photovoltaic system at Mead, Nebraska, became operational in August of 1977.

Pictorial representations of each system are given in Figures 8-1 through 8-9.

Table 8-1

SUMMARY OF CHARACTERISTICS FOR SOLAR POWERED IRRIGATION SYSTEMS

Project Sponsor	Project Managers	Irrigation System Location	System Functions	Power/Energy Output	Required Land Area
DOE/DST	Sandia Labs, Albuquerque N.M. (New Mexico State Univ. Assist)	Schrimpsher Bros. Farm, Willard, Estancia Valley, New Mexico	Pump water from 110 Foot deep well to 4.5 AF pond; water then pumped to end roll sprinkler by diesel engine	25 shp to 630 gpm pump; 10^7 Btu/Day thermal; 200 kWh/ Day electric; 23 Hr/Day	1 1/4 Acres (EST.)
DOE/DST	Sandia Labs, Albuquerque N.M. (Univ. of Arizona Assist)	Dalton Cole Farm, Coolidge, Arizona	Pump water from 3 deep wells (285-780 gpm, 390 Ft lift, 24 Hr/day) to Furrow irrigation of crops	150 kW Electric to 3 pump motors plus 24 kW auxiliary power	6 Acres; 48,960 Sq. Ft. collector field
Northwestern Mutual Life Insurance Co.	Scientific Advances, Subsidiary of Battelle Memorial Institute, Columbus, Ohio	Gila River Ranch, Gila Bend, Arizona	Delivers 10,000 gpm with 14 ft. lift from one-acre tail-water recovery basin to irrigation canal	50 shp; in 9.5 Hr period Delivers 5.6 x 10^6 gal. on longest days in June	1/4 Acre
DOE/DST	MIT Lincoln Labs & Univ. of Nebraska, Lincoln, Nebraska	Mead Experiment Station, Nebraska	Pump 1000 gpm reservoir water for 80 acres corn/ soybeans; dry crops in off-season, 2 grain bins, 5 hp each; 12 hr/day	23.5 kW * Electric peak, 6.2 A 150 V. panels to 10 hp electric motor	1/3 Acre for Collectors

* 25 kWe eventually

Table 8-1

SUMMARY OF CHARACTERISTICS FOR SOLAR POWERED IRRIGATION SYSTEMS
(Continued)

Collector Array	Energy Storage	System Power Unit	Sun Tracking
Acurex distributed, linear concentrating focus, parabolic trough, covered with Alcoa Alzak 6720 ft^2, 8 modules in 14 rows, 6 ft x 10 ft aperture, 90 degree rim angle; 420°F outlet, 240°F inlet of Caloria HT-43 heat transfer fluid in black chrome-coated steel tube receiver enclosed by ~~pyrex glass tube~~	Above ground 23 hr (summer) 6500 gal tank of Caloria HT-43 connected to 8000 gal expansion tank below ground; 4.5 AF water pond	Barber-Nichols Rankine cycle turbine; Freon-R113 working fluid; turbine inlet of 325°F, 220 psi; pump mechanical drive (measured efficiency of 15%)	East-to-West; N-S axis for collectors (shadow band tracker controlling motor driving an 8-collector array)
Acurex distributed linear concentrating focus, parabolic trough, covered with Alcoa Coilzak, 43,200 ft^2, 6ft x 10ft aperture, 90 degree rim angle; 600°F outlet, 407°F inlet of Caloria HT-43 heat transfer fluid in black chrome coated steel tube receiver enclosed by pyrex glass tube	Above ground, 50 Ft x 11 Ft dia., 30,000 gal active volume; Calcria HT-43 plus rock & sand; 16×10^6 Btu	Sundstrand Rankine cycle derated turbine, Toluene working fluid, power to 3 pumps/motors	East-to-West, N-S axis for collectors (shadow band tracker controlling motor driving an 8-collector array)
Hexcel distributed, linear concentrating focus, parabolic troughs, aluminum honeycomb; 5580 ft^2, 9 rows, 80 ft long; 300°F outlet; water heat transfer fluid in black-coated copper pipe enclosed in insulated aluminum jacket with pyrex glass front window	None	Barber-Nichols Rankine cycle turbine; Freon-R113 working fluid; pump mechanical drive	East-to-West, N-S axis for collectors (photo-transistor sensor system controlling electro-mechanical drive)
28 flat Photovoltaic panels with 656 Solarex & 1248 Sensor Tech Modules, 120,000 circular silicon cells; 6000 Ft^2; 2 rows 325 Ft. long	Lead-acid batteries, 85 kW-HR, converted to 220 V. 3 phase AC (DC power for inverters)	Photovoltaic output to pump AC motor	E-W single axis, tilt to any angle

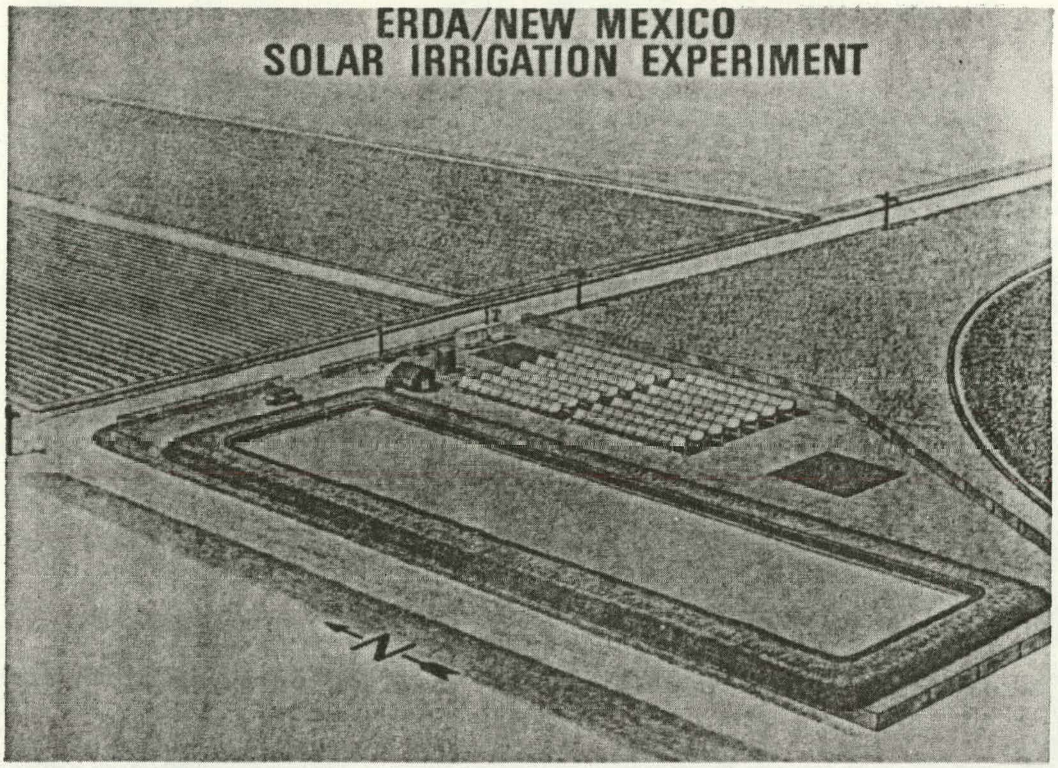

Figure 8-1. DOE/DST - 25 HP Willard, New Mexico Facility

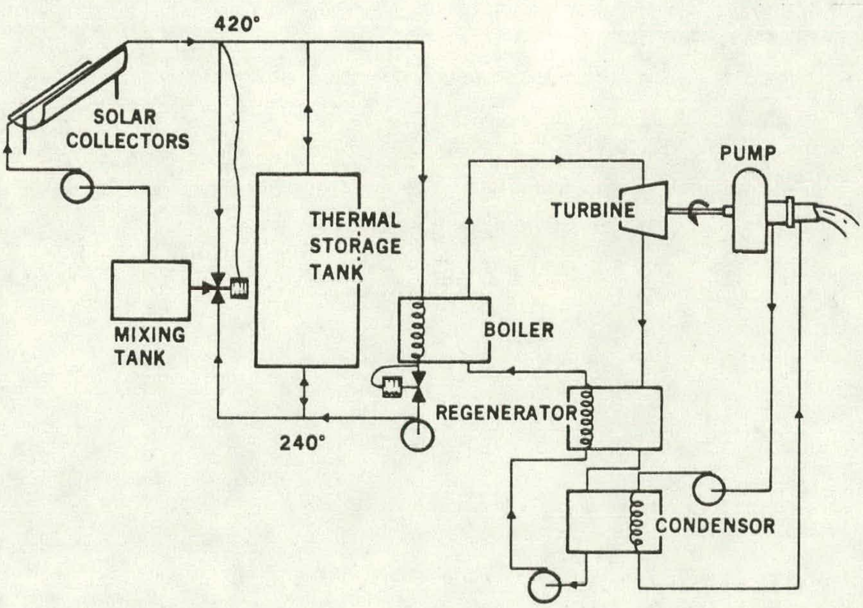

Figure 8-2. Schematic of DOE/DST - 25 HP Willard, New Mexico Facility

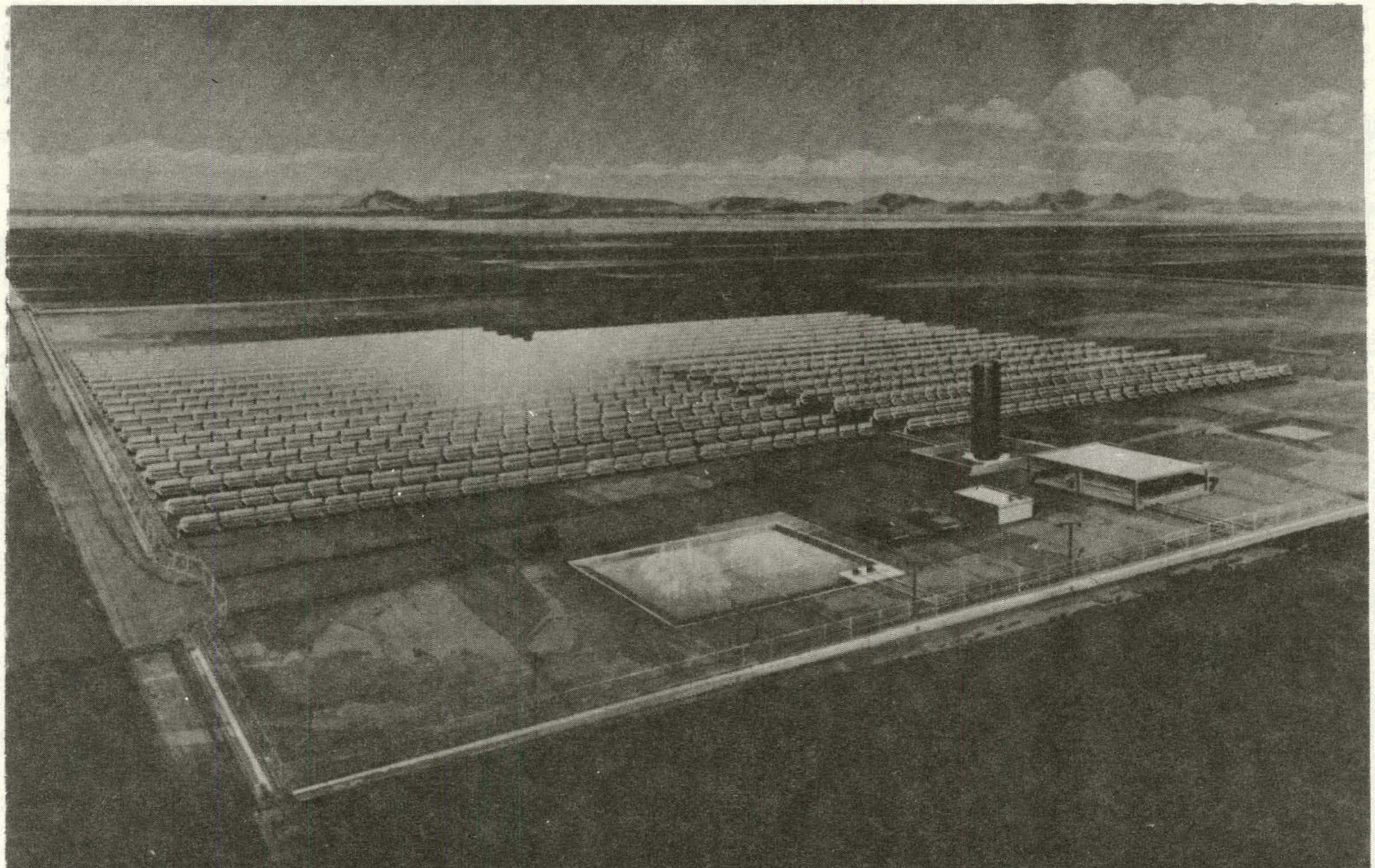

Figure 8-3. DOE/DST - 150 kW_e Deep Well Irrigation Facility Coolidge, New Mexico

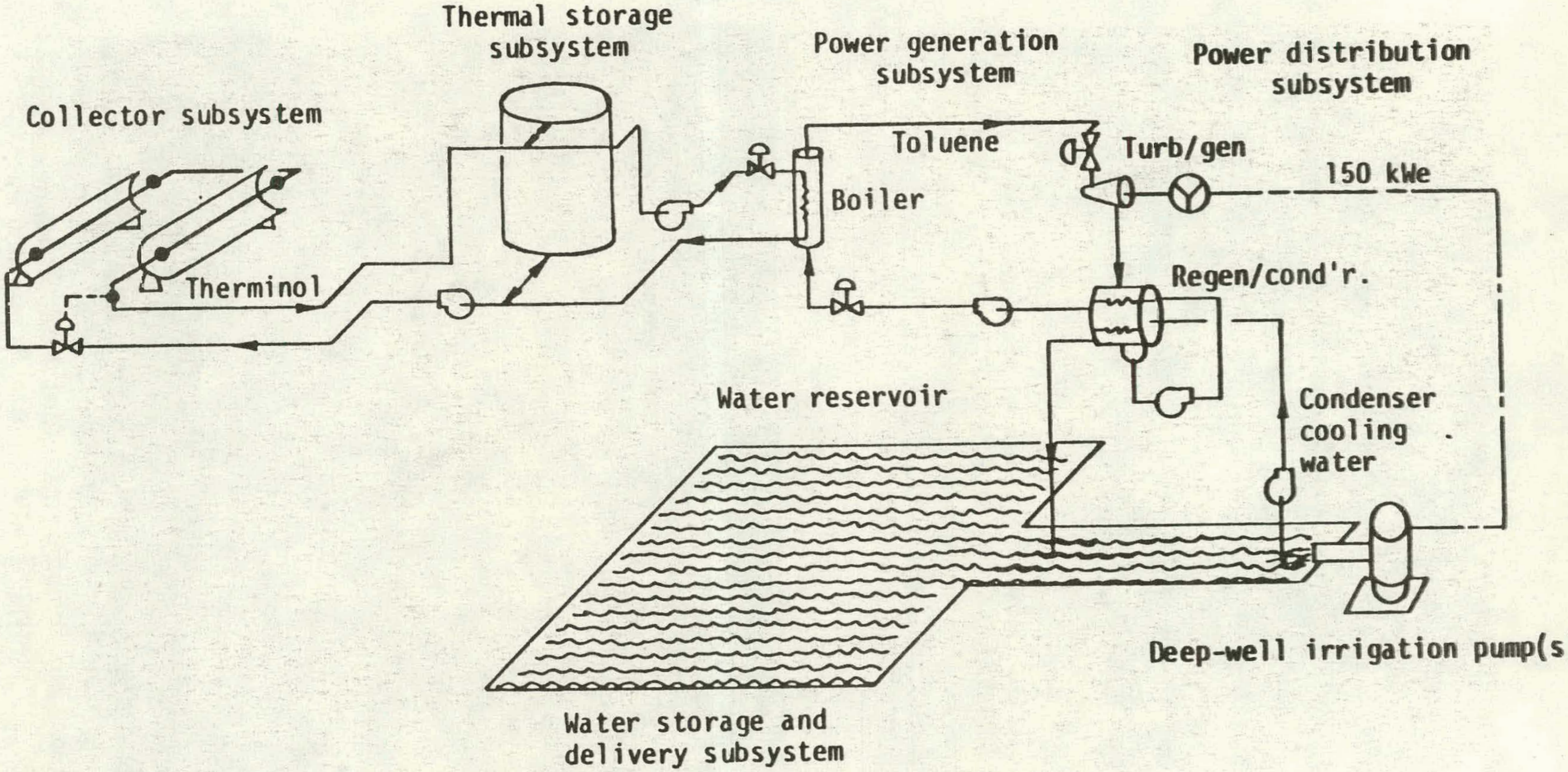

Figure 8-4. Schematic of DOE/DST - 150 kWe Deep Well Irrigation Facility, Coolidge, Arizona

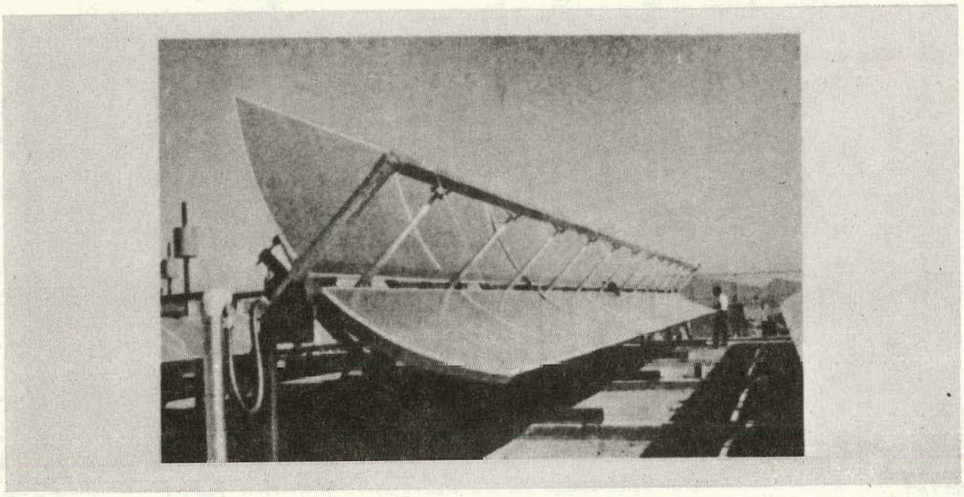

Figure 8-5. One Row of Collector Field for Northwestern Mutual Life Insurance Co., 50 HP Irrigation System, Gila Bend, Arizona

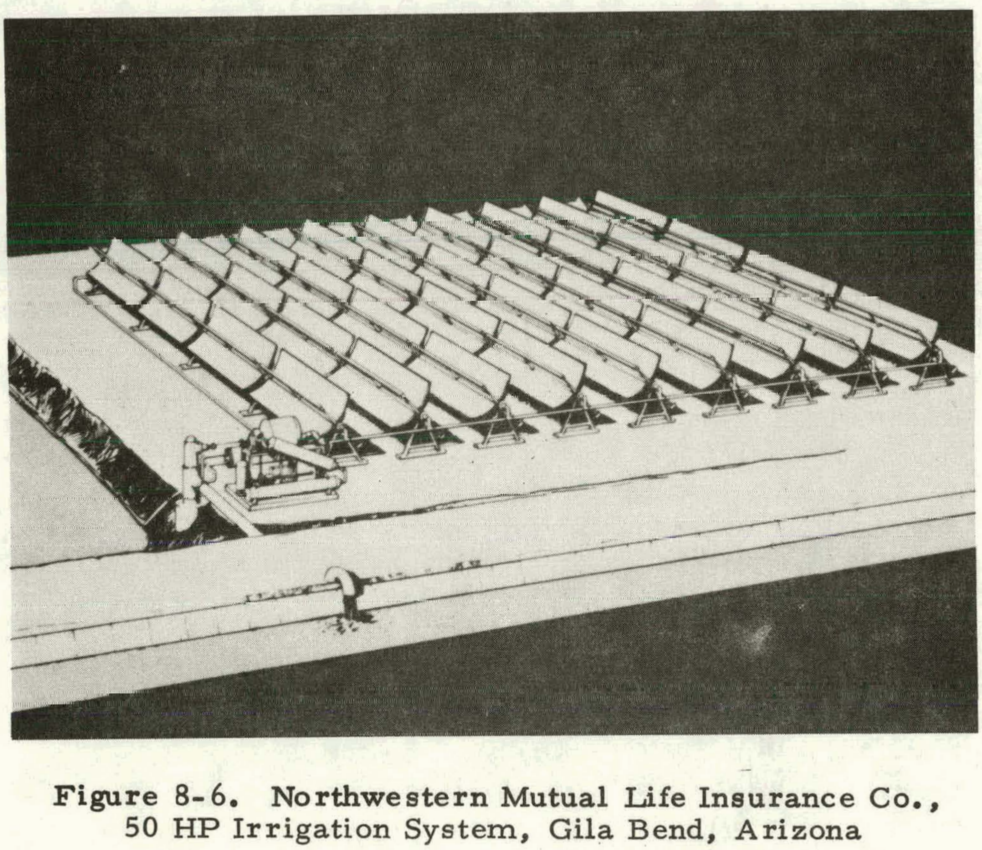

Figure 8-6. Northwestern Mutual Life Insurance Co., 50 HP Irrigation System, Gila Bend, Arizona

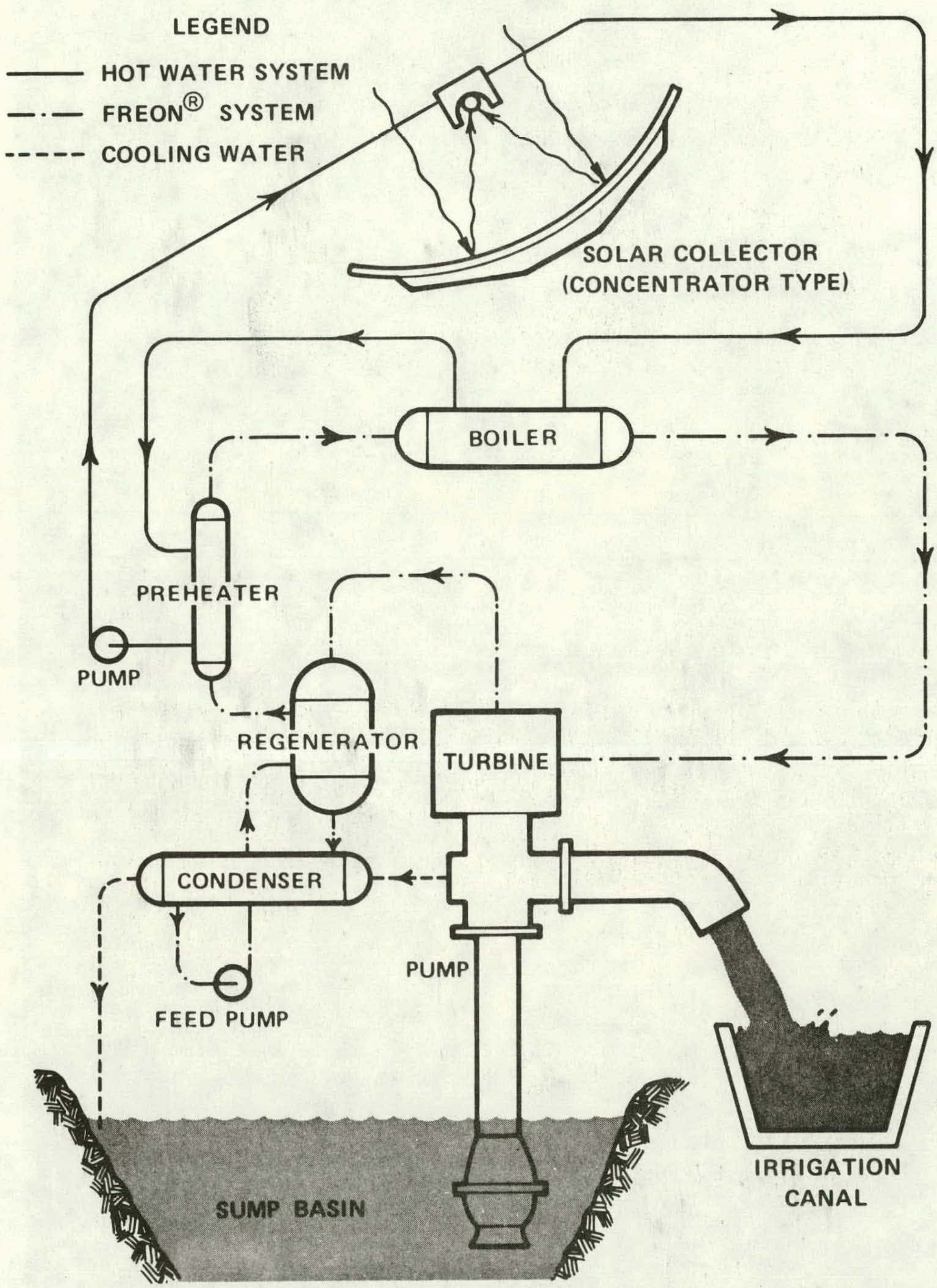

Figure 8-7. Schematic of Northwestern Mutual Life Insurance Co., 50 HP Irrigation System, Gila Bend, Arizona

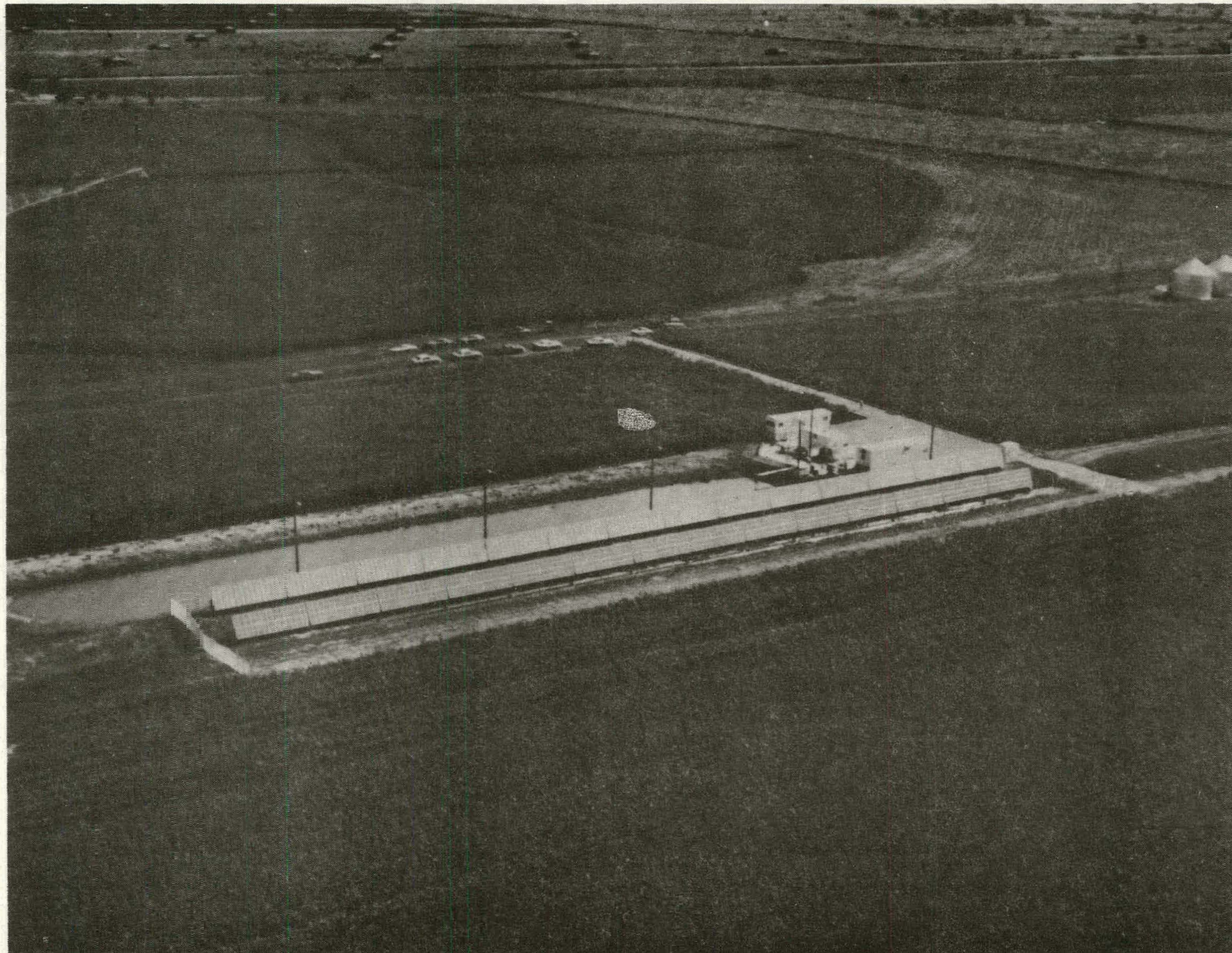

Figure 8-8. DOE/DST - 25 kWe Photovoltaic Irrigation System, Mead, Nebraska

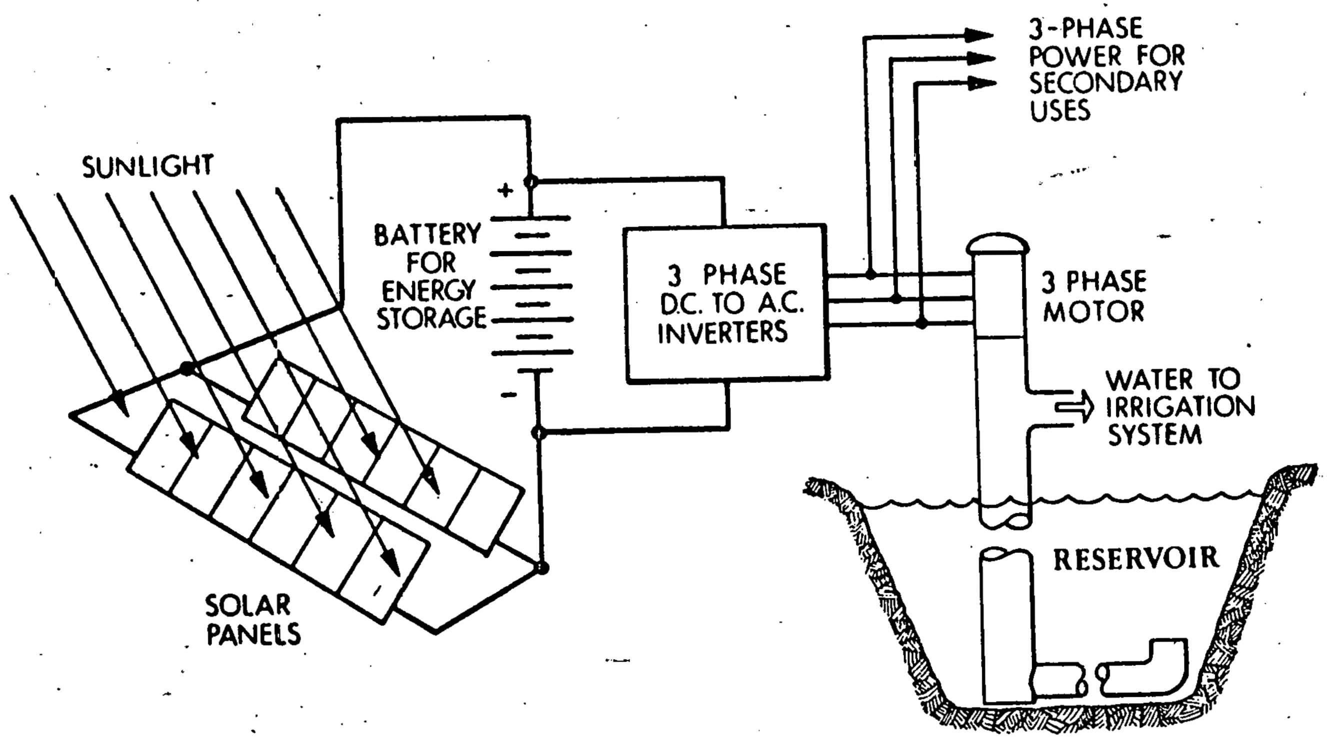

Figure 8-9. Schematic for DOE/DST - 25 kWe Photovoltaic System, Mead, Nebraska

8.2 OPERATING CONCEPTS

(This Section in Preparation)

8.3 APPLICATION CONSIDERATIONS

(This Section in Preparation)

9. SOLAR-POWERED IRRIGATION SYSTEM FINANCIAL ANALYSIS

For the purpose of conducting financial analyses of solar-powered irrigation systems, the decision maker is taken to be an individual farmer (or group of farmers). The decision under consideration is whether to continue purchasing energy for crop irrigation from conventional sources, or to install a solar power system. Essentially, this decision becomes one of making little or no investment in plant and equipment, with the expectation of high annual charges which are likely to increase each year in real terms, versus a relatively high initial investment, accompanied by comparatively low annual costs.

From the general perspective of maximizing net cash flow over some specified period of time, the decision rule is clear: select the energy system which yields the highest after-tax net discounted value. However, while this may be a useful rule to apply to corporate decision making, it may not be totally realistic to apply it to decisions made by farmers without taking into account additional considerations. To begin with, farmers typically have low liability-to-asset ratios. The addition of a solar energy system would undoubtedly have a significant impact on this ratio for most farmers. Second, farmers are currently realizing relatively low returns on the estimated value of their assets. This raises questions about their ability to obtain financing for solar power systems. Third, a solar system would initially require higher cash outlays than would be needed for conventional energy sources, even though a reverse of this situation could be anticipated at some future date. This could place a strain on the farmer's annual operating budget during the first years of employing a solar powered system. Finally, the annual costs for the solar system are fixed (assuming purchase through long term financing) and would be difficult to suspend or reduce in the event of crop failure, while conventional sources of energy possess a much higher level of flexibility in that they are paid for as they are used.

While acknowledging that the above considerations are important, it is nevertheless necessary to first demonstrate that solar systems possess an economic advantage over conventional energy from the farmer's point of view in order to assume that he will have any interest at all in making the substitution. This is the rationale behind the financial analyses conducted in the present study. The introduction of farm risk factors into future analyses would be desirable in order to account for the special considerations just discussed.

9.1 METHODOLOGY FOR ANALYSIS

The financial analysis methodology discussed in this section has been derived specifically for application to the agricultural sector. This multi-variate element of the business community has proven to be extremely difficult to model with one set of characteristics. Hence, for this analysis, three different farm sizes have been examined for the case where one or more small solar-powered irrigation systems are sited on the farm. In addition, financial factors have been derived for a large solar thermal/electric power cooperative situated on a dedicated site and serving the needs of many farms or an entire farm community.

A comparative economic evaluation of solar-powered irrigation systems is complicated by the fact that the majority of the costs of solar energy, i.e. purchase cost, occur in the first year*, whereas the costs of conventional energy sources are incurred year-by-year. Conventional energy costs are relatively low now, but are expected to rise fairly rapidly in future years. Hence, they constitute a non-uniform stream of costs over future years.

Because the value placed on financial resources of any enterprise varies with time, the lifetime costs of competing energy sources must be compared in a manner which takes into account the year in which the various costs occur. This is accomplished by discounting the value of future expenses

*Other costs for maintenance, taxes, etc. are borne by the farmer each year over the system lifetime (assumed to be 30 years for initial analyses) to a present value. The present value can then be expressed alternatively in the form of uniform annual expenditures over a specified period of time.

To compare solar and conventional energy costs in this study, the Equivalent Cost Ratio, or ECR, is used as the figure of merit. It is defined as the annualized lifecycle costs of solar energy divided by the annualized lifecycle costs of conventional energy saved through the use of the solar system. (An annualized amount is that annunity which has the same present discounted value as does a stream of unequal payments when evaluated over the same time period.)

The major components of the ECR are shown in Table 9-1. The annualized lifecycle costs of solar energy are shown as the product of the capital costs of the solar power system (CC) and an annualized cost rate (ACR). The annualized lifecycle costs of conventional energy are the product of the annual amount of fuel which the solar system displaced (FD) and the per unit annualized conventional fuel cost (AFC) factor. Thus, the Equivalent Cost Ratio is defined by the equation:

$$ECR = \frac{ACR \times CC}{FD \times AFC} \qquad (9\text{-}1)$$

This is a very convenient formulation in that it allows the financial factors (ACR), the cost estimates (CC), the performance estimates (FD), and the alternative energy cost estimates (AFC) to be displayed separately. If one changes independently of the others, the ECR changes proportionately. This is important in simplifying the financial analysis of solar thermal system applications in a nonhomogeneous agricultural energy market. The succeeding discussion will cover determination of the ACR and AFC factors. Capital costs and fuel displacement are discussed in Section 10.

The Annualized Cost Rate (ACR) is defined to be the annualized lifecycle costs of solar energy expressed as a fraction of the original capital cost of the system. The components of ACR are shown in Table 9-2. The four components are the capital costs, operation and maintenance costs, insurance costs, and property taxes. On the assumption that the

Table 9-1

ELEMENTS OF EQUIVALENT COST RATIO (ECR)

$$ECR = \frac{\text{ANNUALIZED LIFECYCLE COSTS OF SOLAR ENERGY}}{\text{ANNUALIZED LIFECYCLE COSTS OF DISPLACED CONVENTIONAL ENERGY}}$$

$$= \frac{ACR \cdot CC}{FD \cdot AFC}$$

SYMBOL	DESCRIPTION
ECR	Equivalent Cost Ratio
ACR	Annualized Cost Rate
CC	Original Capital Costs of Solar Plant
FD	Units of Conventional Fuel Displaced Per Year
AFC	Per Unit Annualized Cost of Conventional Fuel

Table 9-2
ELEMENTS OF ANNUALIZED COST RATE (ACR)

ACR = ANNUALIZED LIFECYCLE COSTS OF SOLAR PLANT AS A FRACTION OF ORIGINAL CAPITAL COSTS

= ACCR + AOMR + AIR + APTR

SYMBOL	DESCRIPTION
ACR	Annualized Cost Rate
ACCR	Annualized Capital Cost Rate
AOMR	Annualized Operation and Maintenance Cost Rate
AIR	Annualized Insurance Cost Rate
APTR	Annualized Property Tax Cost Rate

farmer obtains a loan for the capital costs, all costs will then be incurred yearly over the life of the system. The use of ACR to represent these costs is based on the ability to express each of these variable annual costs as a uniform annual fraction of the original capital cost of the system. Thus, the ACR is easily derived as the sum of the four component costs, as shown in the equation:

$$ACR = ACCR + AOMR + AIR + APTR, \qquad (9\text{-}2)$$

where ACCR is the annualized capital cost rate, AOMR is the annualized operation and maintenance cost rate, AIR is the annualized insurance cost rate, and APTR is the annualized property tax cost rate.

The method of calculating each of the components of ACR is summarized in Table 9-3. The capital cost component is calculated as

$$ACCR = \frac{CRF}{1 - \tau} \quad (1 - \alpha - \tau \cdot DPF), \qquad (9\text{-}3)$$

where CRF is the capital recovery factor, τ is the marginal income tax rate, DPF is the depreciation factor, and α is the applicable investment tax credit rate. These factors are those commonly used in lifecycle costing; a more complete discussion of them can be found in most financial analysis and engineering economics textbooks. (See, for example, Reference 9-1 and Reference 9-2.) The quantity $(1 - \tau)$ is included in the denominator of Equation 9-3 in order to convert that term to a pre-tax quantity which is then consistent with the other terms in the ECR formula.

The operation and maintenance cost rate (AOMR) and the insurance cost rate (AIR) require no separate calculations. Both have been estimated directly as a fraction of the original system capital cost, as described later in the next section.

The annualized property tax rate (APTR) differs from the applicable statutory tax rate (τ_P). It is assumed that property taxes are levied as a constant percentage of the equipment's assessed valuation, and that the valuation will decline over time on the basis of a straight-line

Table 9-3

CALCULATION METHODOLOGY FOR ANNUALIZED COST RATE (ACR)

$$ACR = ACCR + AOMR + AIR + APTR$$

$$ACCR = \frac{CRF}{1 - \tau} \left(1 - \alpha - \tau \cdot DPF \right)$$

AOMR = Data input, no calculation necessary

AIR = Data input, no calculation necessary

$$CRF = \frac{k}{1-(1+k)^{-N}}$$

$DPF = (N \cdot CRF)^{-1}$, for straight-line depreciation

$$APTR = \tau_P \left(1 - \frac{1}{Nk} + \frac{1}{(1+k)^N - 1}\right)$$

SYMBOL	DESCRIPTION
CRF	Capital Recovery Factor
τ	Marginal Income Tax Rate
DPF	Depreciation Factor
α	Investment Tax Credit Rate
N	System Operating and Accounting Life Time and Loan Term
k	Discount Rate (after-tax cost of business capital)
τ_P	Local property tax rate on assessed valuation

depreciation method. The formula shown for APTR takes into account this decline in the amount of property tax paid each year when measured in constant dollar terms (without inflation).

Calculation of the unit annualized conventional fuel cost (AFC) factor is accomplished through use of the equations displayed in Table 9-4. In brief, the procedure is to sum a non-uniform stream of conventional energy costs (described in Section 5) and redistribute the costs as a uniform yearly cost over a specified annuity period. The specific method employed discounts the unit fuel (or electric energy) cost accruing in any given year, t, to a present value. A discounted unit conventional energy cost is calculated for each year of competing solar power unit operation. The sum of these costs is then annualized through use of a capital recovery factor.

9.2 SELECTION OF BASELINE VALUES FOR PARAMETERS

The financial inputs necessary for calculation of the ACR are summarized in Table 9-5 for farms of three sizes and for a rural electric power cooperative. The values shown are best estimates based on limited information supplied by agricultural economists and business firms, lending institutions, electric power cooperatives, and various federal agencies. Further research will clarify under what circumstances the given values may change.

The marginal income tax rates for farms vary from zero for the smallest farms to 50 percent for the largest, with an average value of 30 percent. This average value is the one typically used by agricultural specialists in work done for the various state extension services of the U.S. Department of Agriculture. This was confirmed by several telephone conversations with extension economists, including two consultants to Aerospace. This average value is also used in the financial analysis of electric cooperatives. Although almost all cooperatives are operated as non-profit and, therefore, are tax-free corporations, the tax cost is actually assumed by the co-op members who pay increased income taxes

Table 9-4
CALCULATION METHODOLOGY FOR ANNUALIZED CONVENTIONAL FUEL COST (AFC)

AFC = Annualized Fuel Cost = CRF · PVFC

$$CRF = \frac{k}{1 - (1+k)^{-N}}$$

$$PVFC = \sum_{t=1}^{N} FC_t \, (1+k)^{-t}$$

SYMBOL	DESCRIPTION
AFC	Annualized Fuel Cost
CRF	Capital Recovery Factor
PVFC	Present Value of Fuel Costs
k	Discount Rate (after-tax cost of business capital)
N	Last Year of Costs
t	Year in which fuel cost accrues
FC_t	Fuel Costs accruing in year t

Table 9-5

INPUTS FOR CALCULATION OF ACR FINANCIAL COST FACTOR

ITEM	FARMS			ELECTRIC COOPERATIVE
	LARGEST	AVERAGE	SMALLEST	
INCOME TAX RATE (τ)	0.50	0.30	0.00	0.30
REAL COST OF CAPITAL				
Pre-Tax	0.05	0.05	0.05	0.02
After-Tax (k)	0.025	0.035	0.05	0.014
O&M COSTS (AOMR) (Fraction of Plant Cost)	0.01	0.01	0.01	0.02
INSURANCE COSTS (AIR) (Fraction of Plant Cost)	0.005	0.005	0.005	0.0025
PROPERTY TAX RATE (τ_p)	0.02	0.02	0.02	0.02
INVESTMENT TAX CREDIT (α) (Fraction of Plant Cost)	0.10	0.10	0.00	0.00
DEPRECIATION	STRAIGHT LINE, 30 YEARS			

on higher net earnings due to reduced deductions for the cheaper (than non-cooperative) energy costs. Since each customer is also a member, and since the members control the policy of the cooperative, it has been assumed that equipment purchase decisions of the cooperative will reflect the tax liabilities of its customers.

The entire capital cost of the solar power system is assumed to be raised by borrowing funds from financial institutions. While this may not absolutely reflect an eventual scenario (i.e. some cash outlay of the borrower may be required by the lender), the analysis is simplified without affecting the accuracy of the results to any degree. The cost of borrowed capital is estimated to be 5 percent in real terms (not including a premium for expected inflation) for each of the farm groups. This is similar to the farm mortgage rate which prevailed during the early 1950s in the United States, when the inflation rate was close to zero and it was unlikely that people expected high inflation rates in the future (Reference 9-3). Therefore, 5 percent is the pre-tax cost of capital used in analysis of small, average, and large farms.

The real cost of capital to electric cooperatives is estimated to be 2 percent, the rate that was charged on loans made to co-ops by the Rural Electrification Administration until recently. Currently, the rates charged to established co-ops are 5 percent, the increase reflecting the rise in interest rates which has generally followed recent inflationary experiences. In particular cases, a few loans are still being made to newly formed co-ops at 2 percent rates (Reference 9-4). For analysis of co-ops, the pre-tax cost of capital was taken to be 2 percent.

The after-tax cost of capital has been used in this analysis as the discount rate for ECR calculations. The after-tax cost of capital (k) is calculated by multiplying the pre-tax interest rate by the quantity $(1 - \tau)$. This reflects the fact that interest rates are deductible for income tax purposes and leads to real discount rates of 5 percent for small farms, 2.5 percent for large farms, and 1.4 percent for co-ops. While this procedure can only approximate the appropriate discount rate, the results are consistent with the notion that larger borrowers can obtain cheaper funds because of both lower estimated business default risk (in some cases due to diversification) and lower fiscal unit transaction costs in the capital markets.

The annualized operation and maintenance rate (AOMR) is shown also in Table 9-5 for all groups. It is given as a constant 1 percent of the original plant cost for farms* and as 2 percent for co-ops. These rates are derived from documented costs experienced in recent years by conventional electric generating utilities and from conversations with operators of modern, automated irrigation sprinkler equipment (Reference 9-5). The higher costs expected for co-ops reflect the greater reliability which must be maintained by a centralized power generation and/or distribution system. O&M cost data from experimental and demonstration solar thermal systems will be instrumental in finalizing these estimates.

The insurance costs shown are typical of those used in similar analyses (Reference 9-1). They were confirmed by contacts made with an independent insurance rate advisory service (Reference 9-6). Public utilities were found to be in one of the lowest risk groups for fire and property damage insurance. Thus, the rate shown for co-ops is lower than that for farms. Insurance costs are assumed to be constant over time for all user groups.

The baseline statutory property tax rate used is 2 percent of assessed valuation, based on data provided by agricultural economic consultants. Geographic variations in this rate have not been considered in the present analysis.

The Internal Revenue Service currently allows an investment tax credit of 10 percent for irrigation equipment. This rate is used for

*Assumes use of farm labor for operations and a portion of maintenance requirements.

analysis of large and average farm sizes*. While a 10 percent credit on a major capital purchase (such as a solar system) is large relative to the annual tax liabilities of most farms, the credit can be distributed over a ten year period by being applied to both previous and future taxes. Also, certain leasing and other contractual arrangements can be made to "sell" such credits to other parties.

Straight-line depreciation over the entire 30-year expected lifetime of the solar power system is applied to all market groups, for both income tax and property tax valuation purposes.

The resulting components of the ACR and the aggregated ACR for each group are shown in Table 9-6. The ACRs range from 9.3 percent for the smallest farms to 8.0 percent for the largest, and to 7.8 percent for co-ops. The lower rate for co-ops reflects their lower cost of borrowed capital. That advantage is nearly offset, however, by higher operation and maintenance costs and lack of investment tax credits. The narrow range in ACRs suggests that possible future modifications to the input data will have little effect on the present results. However, financial circumstances leading to lower ACRs should be identified for use in refined market penetration analyses.

With regard to determination of the annualized fuel cost (AFC) factor, both the capital recovery factor and the present value calculations are dependent on the value of the discount rate, k. As in the determination of the ACR, a pre-tax value of 5 percent was used for this term.

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*The smallest farms are not expected to generate sufficient income tax liability against which to apply the tax credit, and non-profit co-ops have no taxes against which to claim the credit.

Table 9-6

ACR FINANCIAL COST FACTORS

ITEM	FARMS			ELECTRIC COOPERATIVE
	LARGEST	AVERAGE	SMALLEST	
DISCOUNT RATE (k)	.025	.035	.050	.014
COST COMPONENTS (Annualized Fraction of Plant Cost)				
Capital (ACCR)	.053	.056	.065	.044
O&M (AOMR)	.01	.01	.01	.02
Insurance (AIR)	.005	.005	.005	.0025
Property Tax (APTR)	.012	.012	.013	.011
TOTAL ANNUALIZED COST RATE (ACR)	.080	.083	.093	.078

10. COMPARATIVE COST ANALYSIS FOR SOLAR POWERED IRRIGATION SYSTEMS (SIS)

10.1 DESIGN CONCEPT AND APPLICATION SELECTION

In view of the present system emphasis on parabolic trough collectors and Rankine cycle engines (Section 8), this solar irrigation system concept was adopted for comparing lifetime costs of solar systems with systems that are dependent on conventional energy sources. The engine was conceived as a turbine-generator unit so that electrical power could be transferred by underground cables to a motor-driven pump (or pumps). This approach offers some flexibility in system siting because the SIS would not have to be located at the pump.

Organic fluids were used as both heat transfer and working fluid mediums with a peak system operating temperature of 600°F.

Thermal storage was used to stabilize and extend the SIS daily operational period. Water storage was included in the analysis as an option to determine effects on comparative system performance and lifetime costs. Standby electric power from a local utility was also retained as an option.

Comparative analyses were conducted in detail for two geographic locations - Arizona and Nebraska. These locales were selected because of their potential for SIS applications, which were identified in Section 6, and because of the major differences in crop growing season and insolation levels. These application sites should be considered as bounding cases.

10.2 DESCRIPTION OF SIS SIMULATION COMPUTER PROGRAM

(This Section in Preparation)

10.3 SIS COMPARATIVE PERFORMANCE AND LIFETIME COST

Based on the seasonal energy demand generated by the Irrigation Market Energy Demand Computer Program (Section 7), SIS collector area, engine size, thermal storage and water storage levels were systematically varied so that an optimized system size could be determined for the particular demand schedule. Optimization was based on minimizing the ratio of SIS lifetime costs to the costs of displaced conventional energy over the same period. This figure of merit, the equivalent cost ratio (ECR), has been discussed in detail in Section 9. System lifetime has been selected as 30 years for the base case analysis of a 1985 SIS installation on a small farm.

It should be recognized that system optimization based on a minimum ECR emphasizes cost comparisons rather than performance, which is measured by percent fuel displacement of a given annual energy demand by the SIS. This is because system sizing for a minimum ECR does not always result in maximum fuel displacement.

Earlier analyses had clearly indicated that standby electric power from utilities was essential to achieving a minimum ECR since costs for stand-alone systems proved to be excessive. Therefore, all analyses considered this type of system operation.

10.3.1 Arizona Farm Application Site

Performance and cost evaluations of SIS were conducted for an 80-acre alfalfa farm in Cochise County, Arizona. Cochise County was selected as a potential site because of the recent rapid increases in prices for electricity and natural gas (Section 5), the extensive use of natural gas for fueling engine-driven pumps, the potential curtailment of natural gas in the future, and the high energy intensiveness of the area due to the need to extract groundwater from wells with pumping depths of up to 600 feet, but averaging about 420 feet. Alfalfa was selected because of its long growing season, thereby using as much of the SIS-generated energy as possible for improved cost effectiveness. The 80-acre crop size was established by calculating the average number of acres of alfalfa served by a single deep well pump in Cochise County. (Farms are generally much larger than 80 acres and so the term "80-acre farm" really refers to an 80-acre tract of land devoted to raising alfalfa on a multi-crop farm.)

10.3.1.1 Energy Balance for Three Operational Strategies

Four turbine sizes of 40, 80, 112 and 200 kW_e were evaluated for the following operational strategies:

(a) Basic System

(b) Basic System with Water Storage

(c) Basic System with Option of Surplus Energy Sales to Utilities

Operational strategy (a) is similar to the conventional irrigation mode where electric or natural gas energy is used to run irrigation pumps to meet the required irrigation schedule. In this operational mode, most of the energy is supplied by the SIS, and the remaining undisplaced energy is available from a local utility or from a standby heat engine. Irrigation energy demand for alfalfa begins in February, peaks during the summer months, and then gradually declines to zero by December. Thus, with operational strategy (a), there would be a significant amount of unused energy available during winter months, depending upon the size of SIS. If the SIS is large and meets most of the required energy during peak irrigation months, then the amount of unused energy during off-peak season would also be great, resulting in significantly higher costs for the energy produced.

These drawbacks of operational strategy (a) are partly overcome by strategy (b), where a water reservoir is added to the basic SIS, so that water can be pumped by excess solar energy during the off-peak season, stored in a reservoir and withdrawn during peak irrigation months. However, this strategy has the disadvantages of additional costs of water storage, evaporation losses and potential withdrawal of farmland for the reservoir. (Withdrawn land for the reservoir may be as great as 5 percent of the irrigated acreage. Compared to this, land withdrawn for the basic SIS is only 1.5 percent.)

The disadvantages of strategy (b) can be overcome by strategy (c) where excess solar energy produced during the off-peak season is sold back to utilities at the same cost at which the standby energy is purchased from them.* In this operational mode, the shape of the irrigation energy demand is not critical. However, utility attitudes and pricing structure may deny this form of operation in some locales. Electric power supplied by the SIS during utility peak load hours may be advantageous to utilities since this power may relieve the utilities' need for additional capital expenditures to meet growth in peak loads.

Using the SIS simulation model, the three operational strategies were evaluated to obtain a corresponding near-optimum conceptual configuration by making system tradeoffs of collector size, amount of high-temperature storage and water reservoir size. An example of this type of trade-off is illustrated by the carpet plot in Figure 10-1. Figures 10-2 through 10-13 show the energy balance and system economics for each of the strategies for each of the four turbine sizes. Energy displacement is shown as a percent of the annual irrigation demand (in this case 550 MW_e) contributed by the SIS (directly or from water storage). The percent balance of annual demand is supplied by the utility. Evaporation losses and SIS surplus energy (or sales of SIS surplus energy) are also expressed as percents of the annual demand. For example, an 80 kW_e turbine system displaces 85 percent of annual demand (77 percent supplied directly by the SIS and 8 percent indirectly from water storage). Surplus SIS-generated energy is nineteen percent of annual demand. Thus, with an 80 kW_e turbine, a SIS generates 104 percent of the 80-acre alfalfa energy requirement (85 percent gainfully utilized for irrigation and 19 percent surplus). Reducing the surplus energy by pumping more water into storage in the

* This cost equivalency may not be considered by utilities as adequate compensation. The impact of reductions in utility purchase price on SIS equivalent cost ratio is discussed in Section 10.3.1.3.

SOLAR IRRIGATION SYSTEM FOR COCHISE COUNTY, ARIZONA

ECONOMICS OF WATER AND HIGH-TEMPERATURE STORAGE SYSTEMS

WITH DISTRIBUTED COLLECTOR

(1985 Installation)

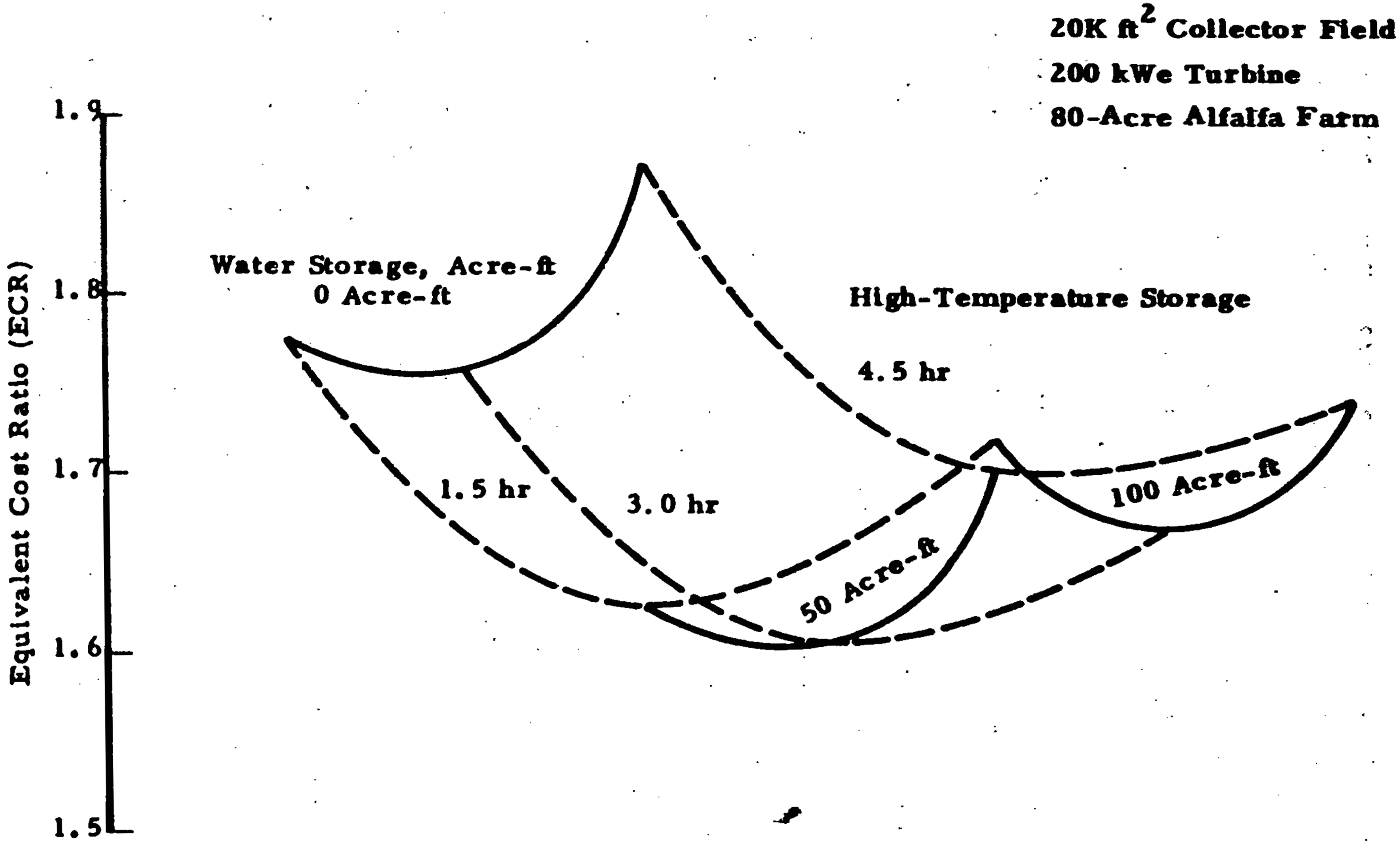


Figure 10-1. Example of ECR Optimization

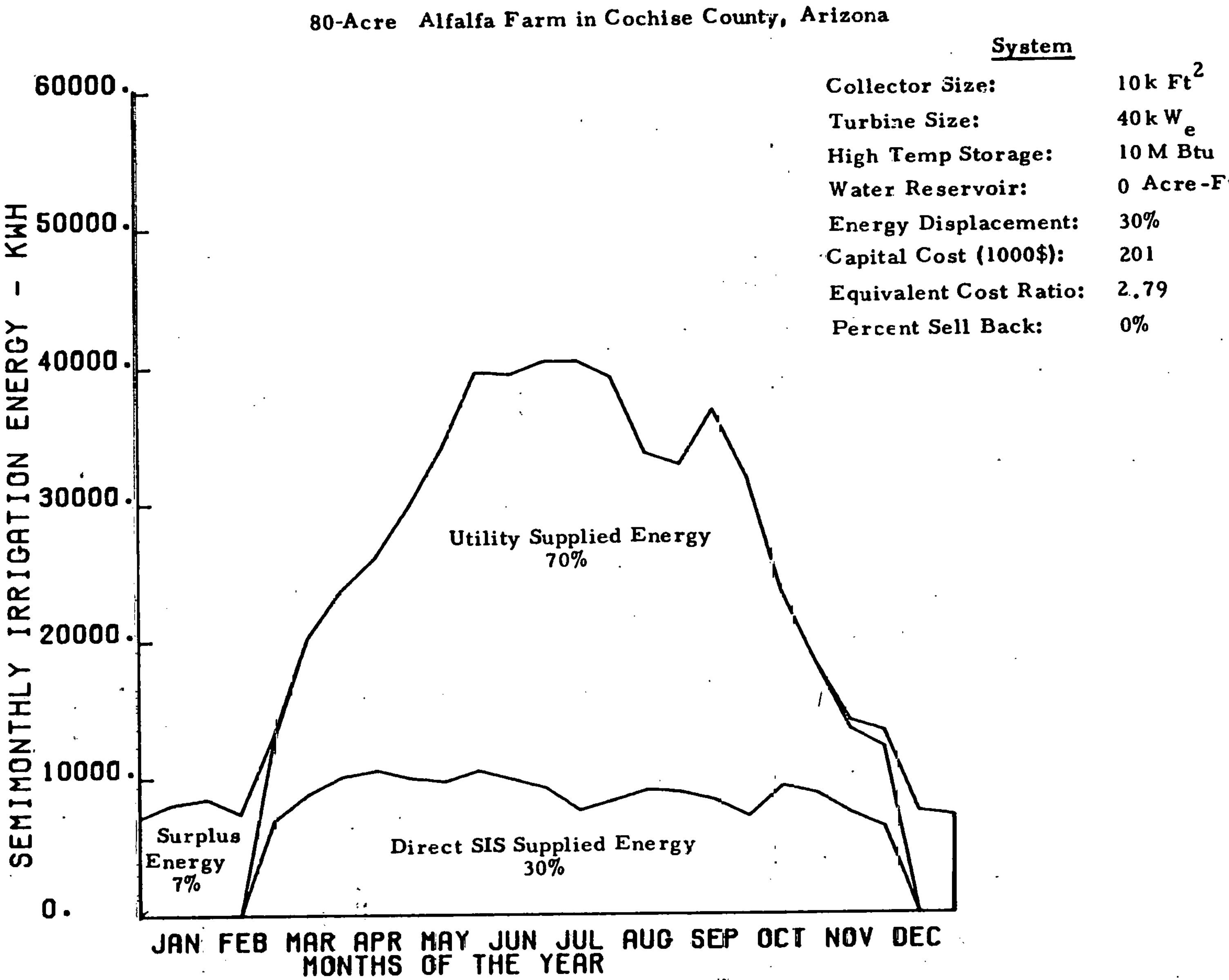


Figure 10-2. SIS Energy Balance and System Economics, 40 kW_e Turbine, Strategy "a"

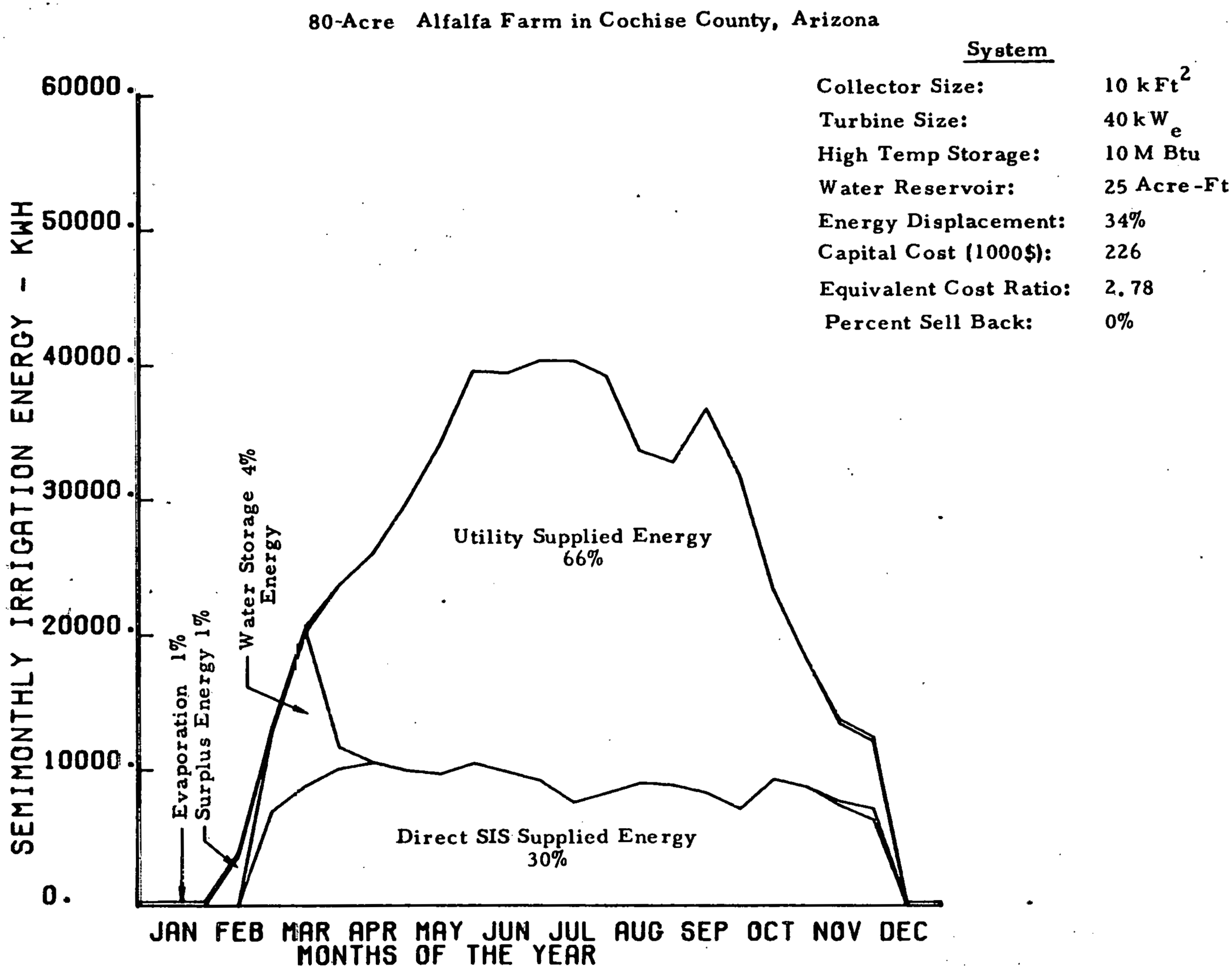


Figure 10-3. SIS Energy Balance and System Economics, 40 kW$_e$ Turbine, Strategy "b"

80-Acre Alfalfa Farm in Cochise County, Arizona

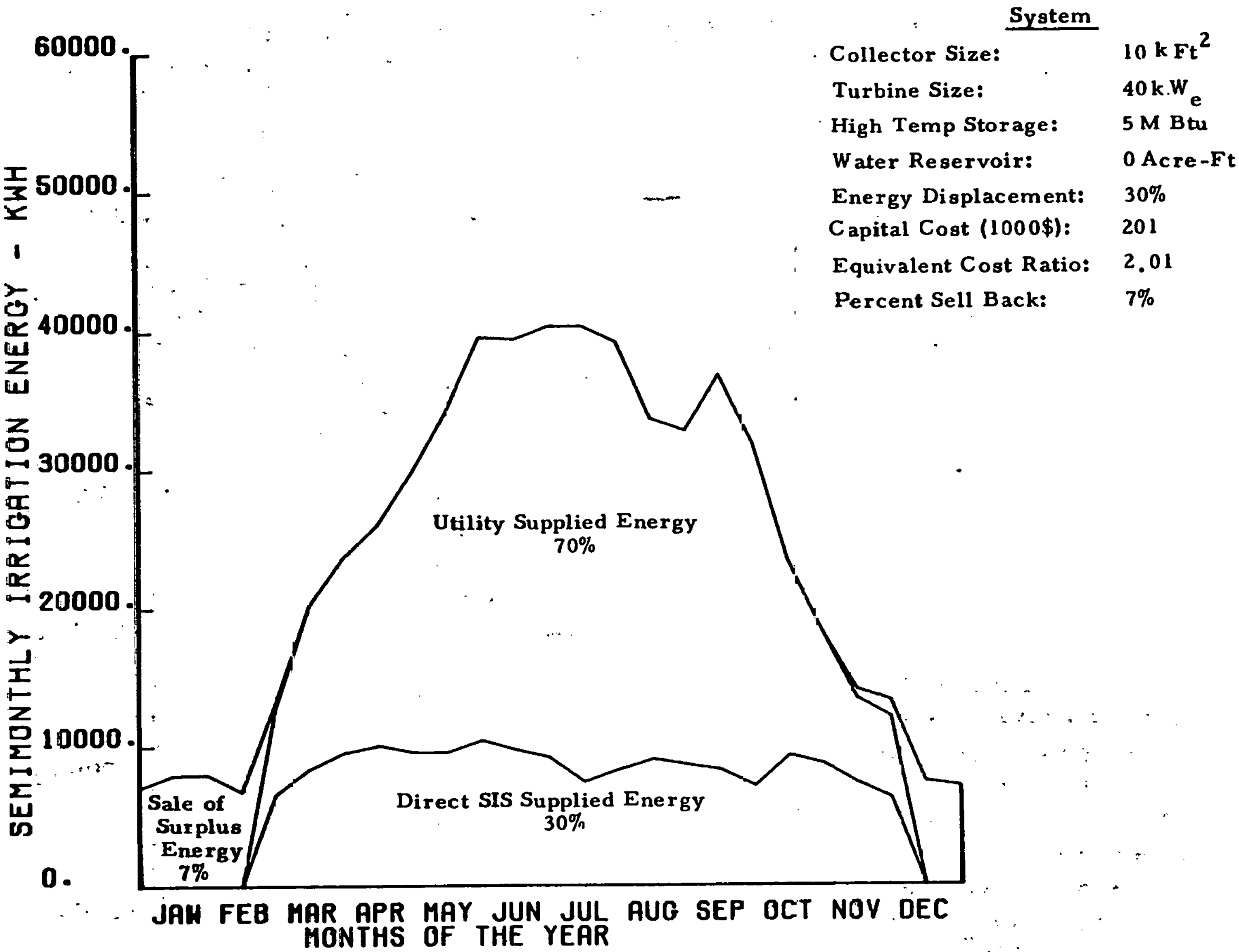


Figure 10-4. SIS Energy Balance and System Economics, 40 kW$_e$ Turbine, Strategy "c"

80-Acre Alfalfa Farm in Cochise County, Arizona

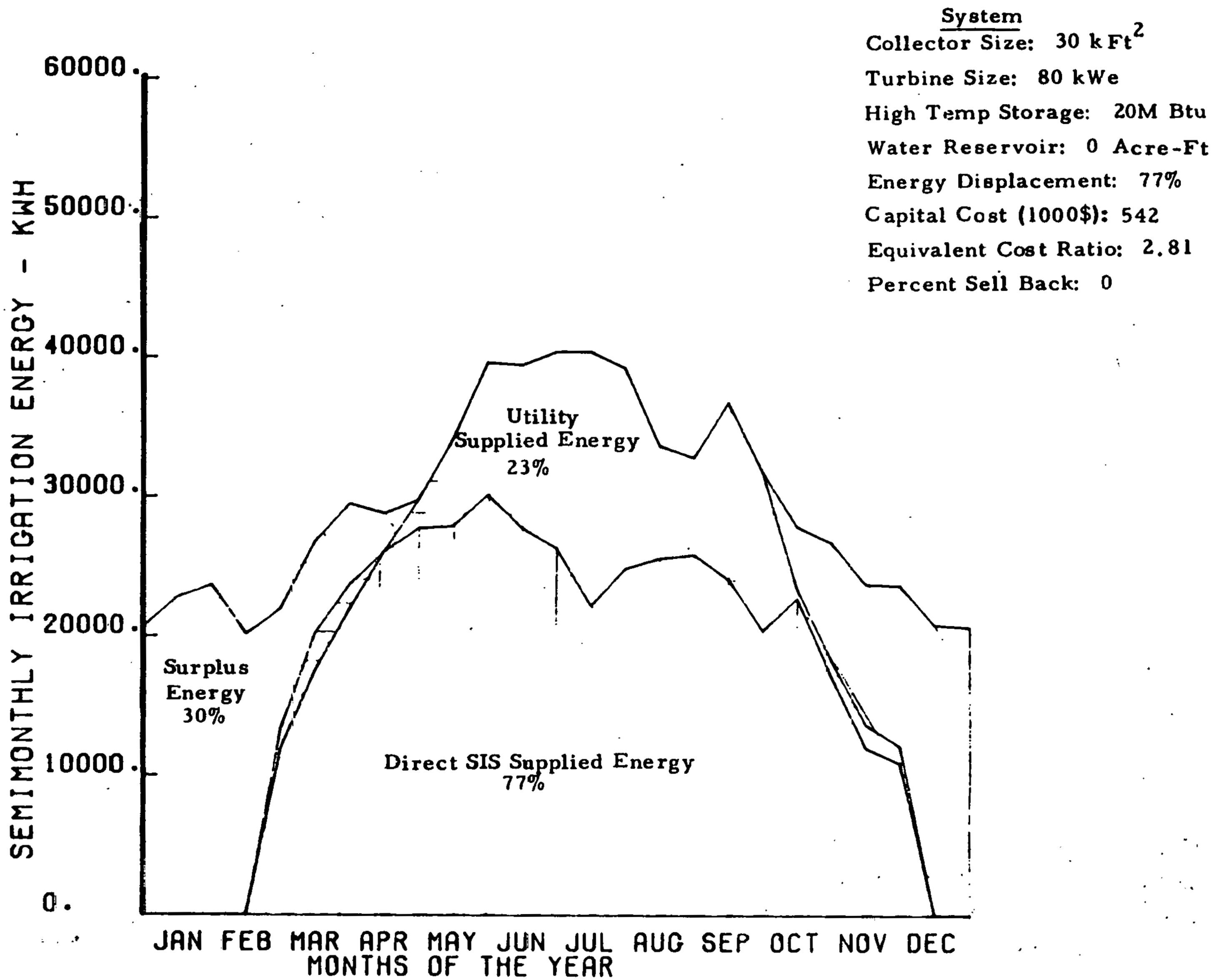


Figure 10-5. SIS Energy Balance and System Economics, 80 kW_e Turbine, Strategy "a"

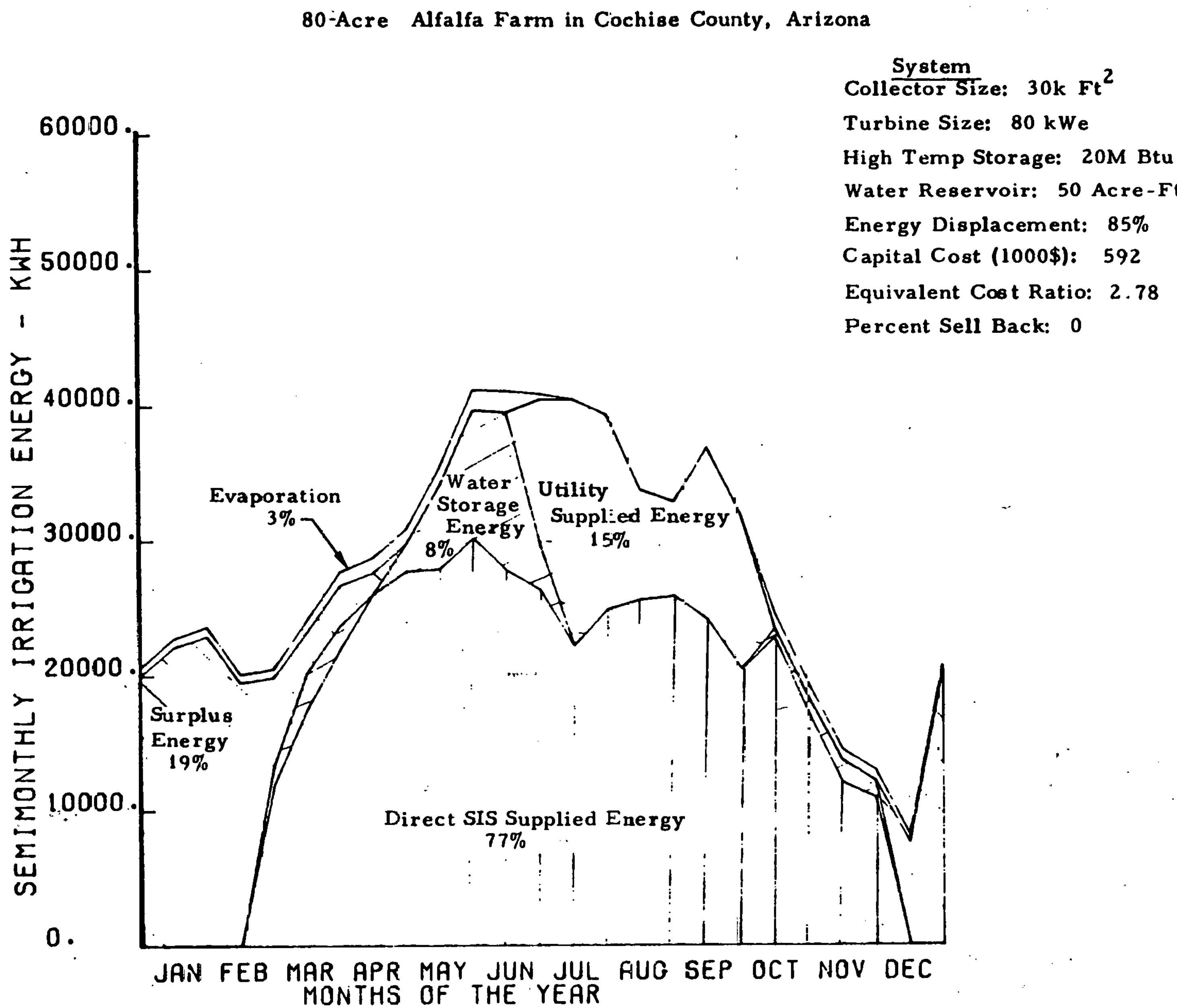


Figure 10-6. SIS Energy Balance and System Economics, 80 kW_e Turbine, Strategy "b"

80-Acre Alfalfa Farm in Cochise County, Arizona

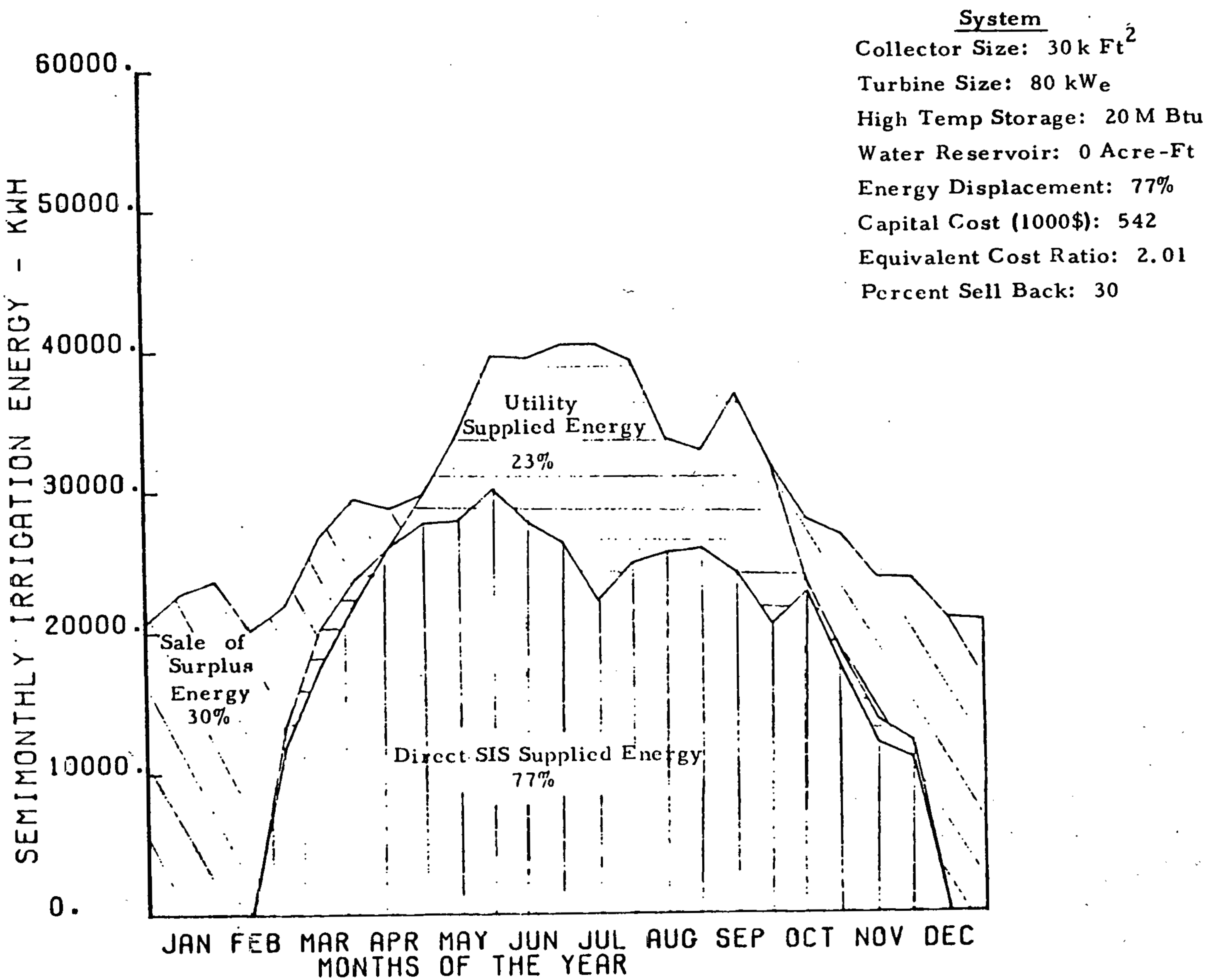


Figure 10-7. SIS Energy Balance and System Economics, 80 kW$_e$ Turbine, Strategy "c"

80-Acre Alfalfa Farm in Cochise County, Arizona

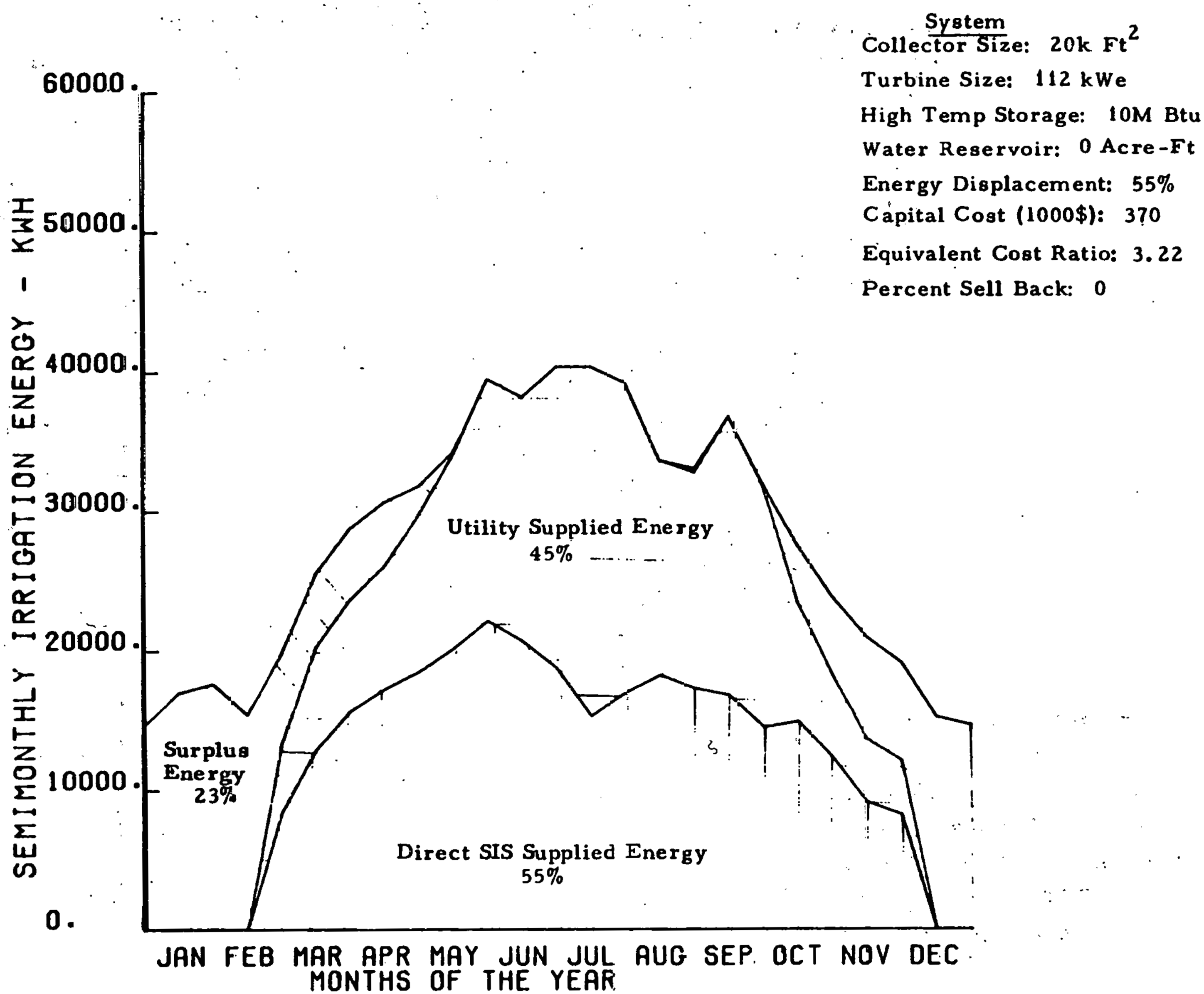


Figure 10-8. SIS Energy Balance and System Economics, 112 kW_e Turbine, Strategy "a"

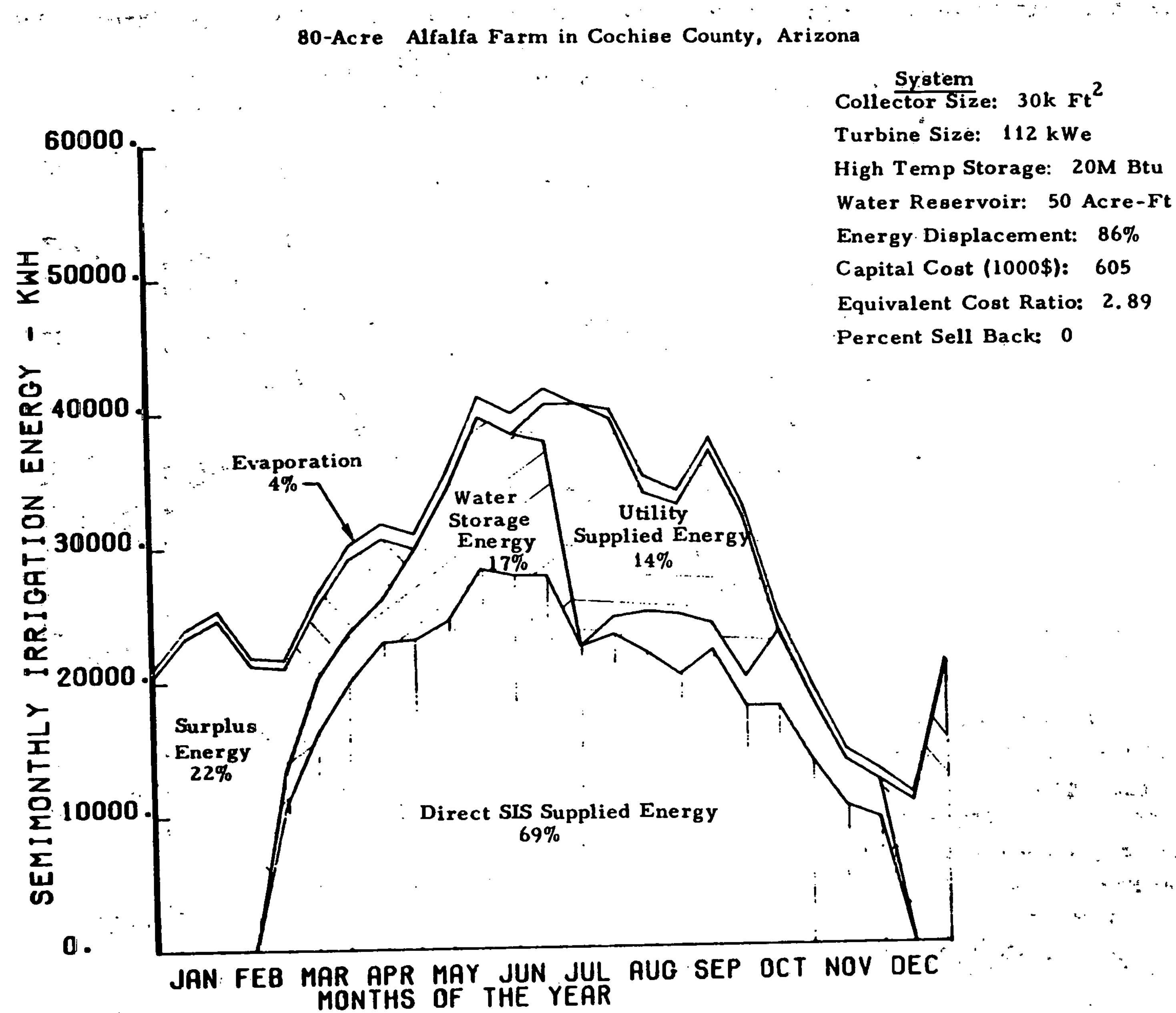


Figure 10-9. SIS Energy Balance and System Economics, 112 kW_e Turbine, Strategy "b"

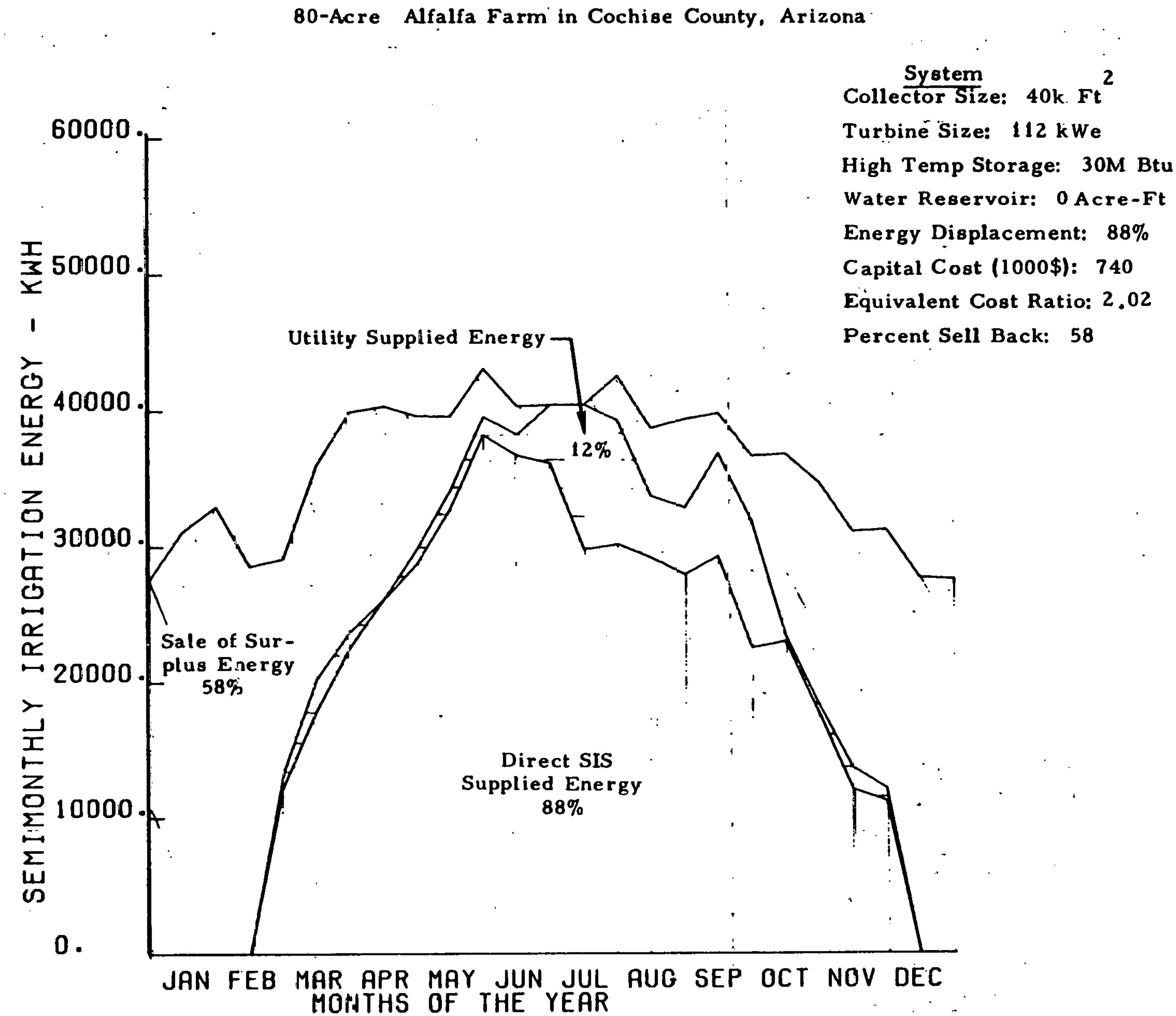


Figure 10-10. SIS Energy Balance and System Economics, 112 kW_e Turbine, Strategy "c"

80-Acre Alfalfa Farm in Cochise County, Arizona

System
Collector Size: 20 Ft^2
Turbine Size: 200 kWe
High Temp Storage: 10M Btu
Water Reservoir: 0 Acre-Ft
Energy Displacement: 56%
Capital Cost (1000$): 405
Equivalent Cost Ratio: 3.27
Percent Sell Back: 0

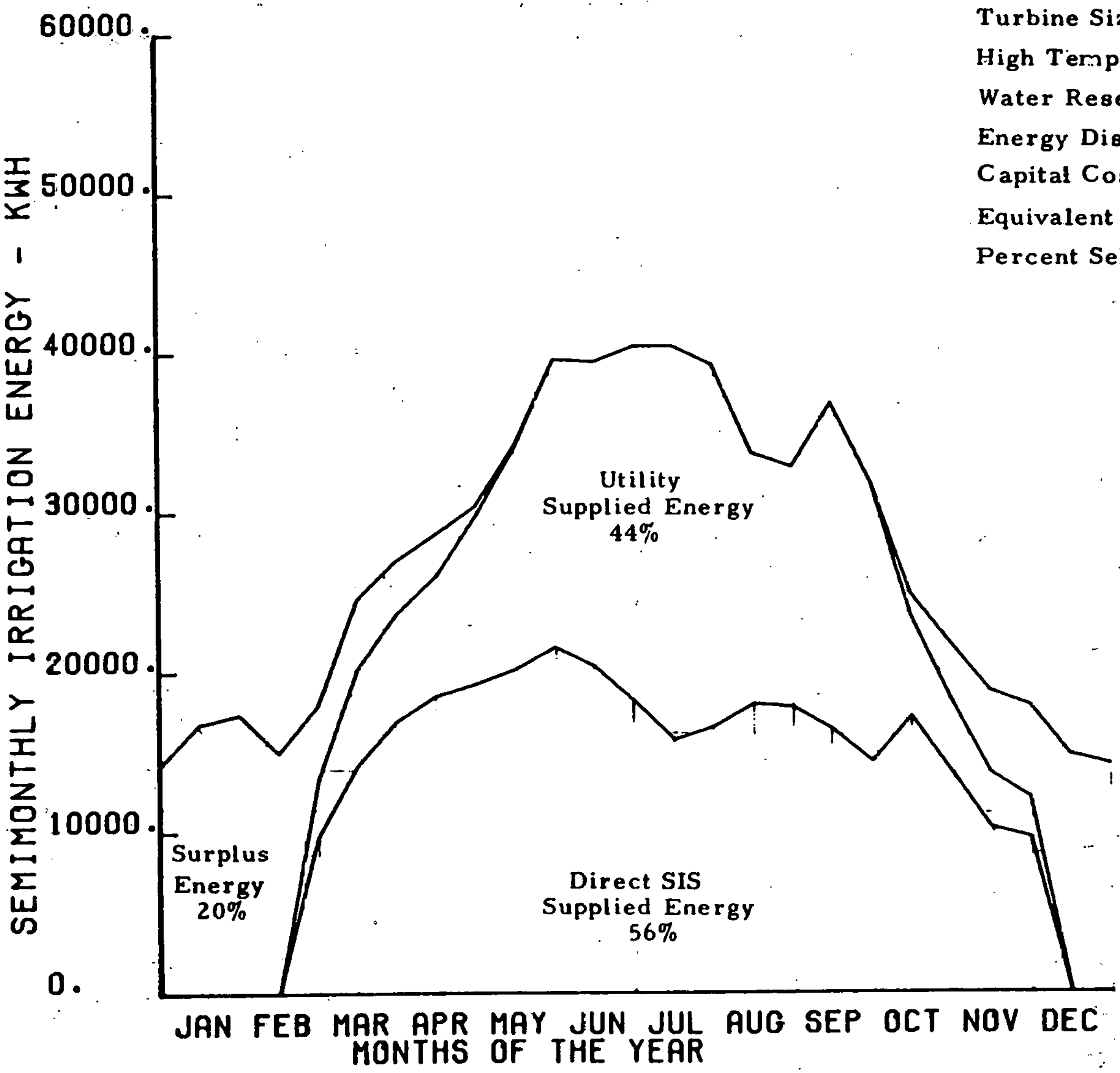


Figure 10-11. SIS Energy Balance and System Economics, 200 kW_e Turbine, Strategy "a"

80-Acre Alfalfa Farm in Cochise County, Arizona

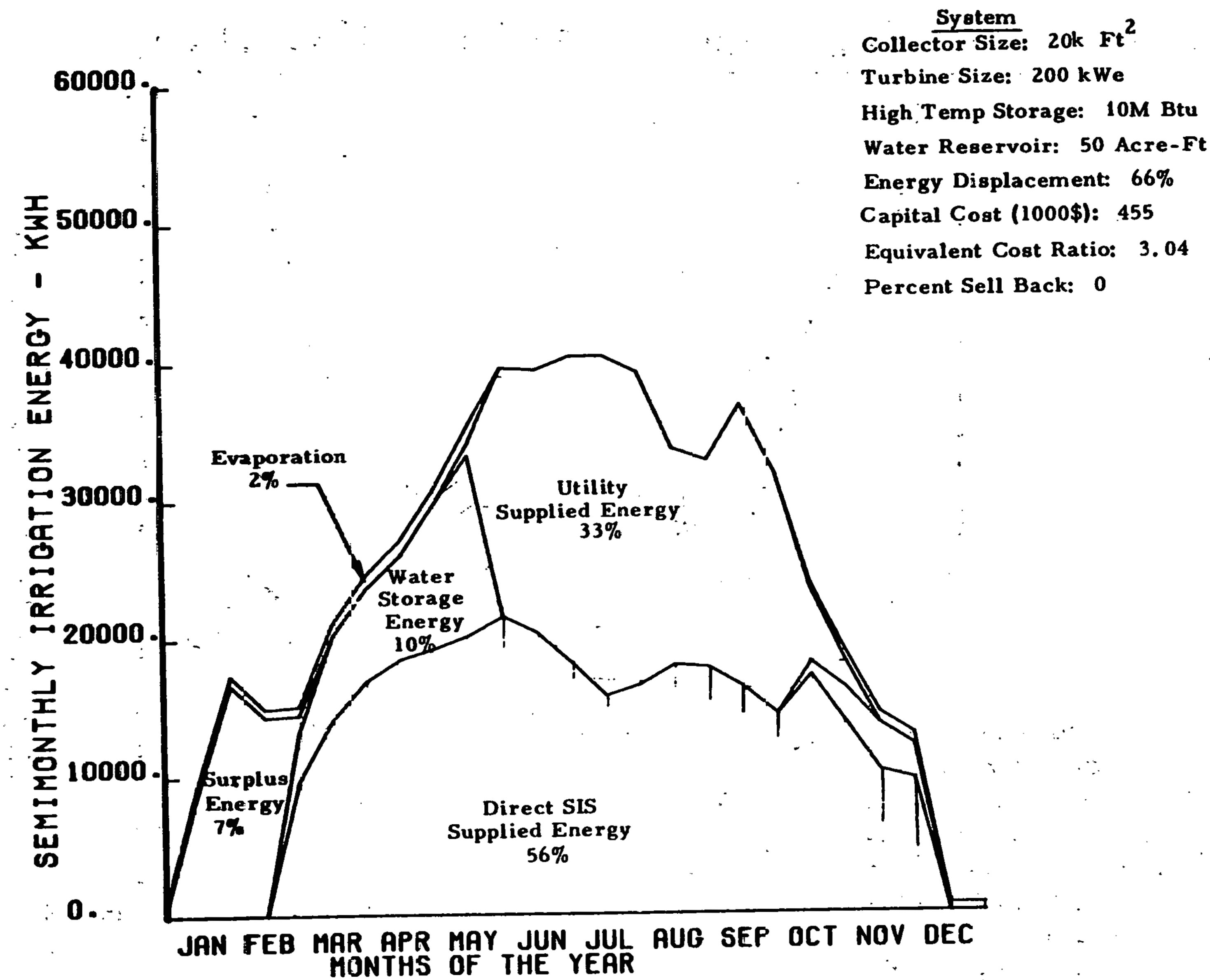


Figure 10-12. SIS Energy Balance and System Economics, 200 kW$_e$ Turbine, Strategy "b"

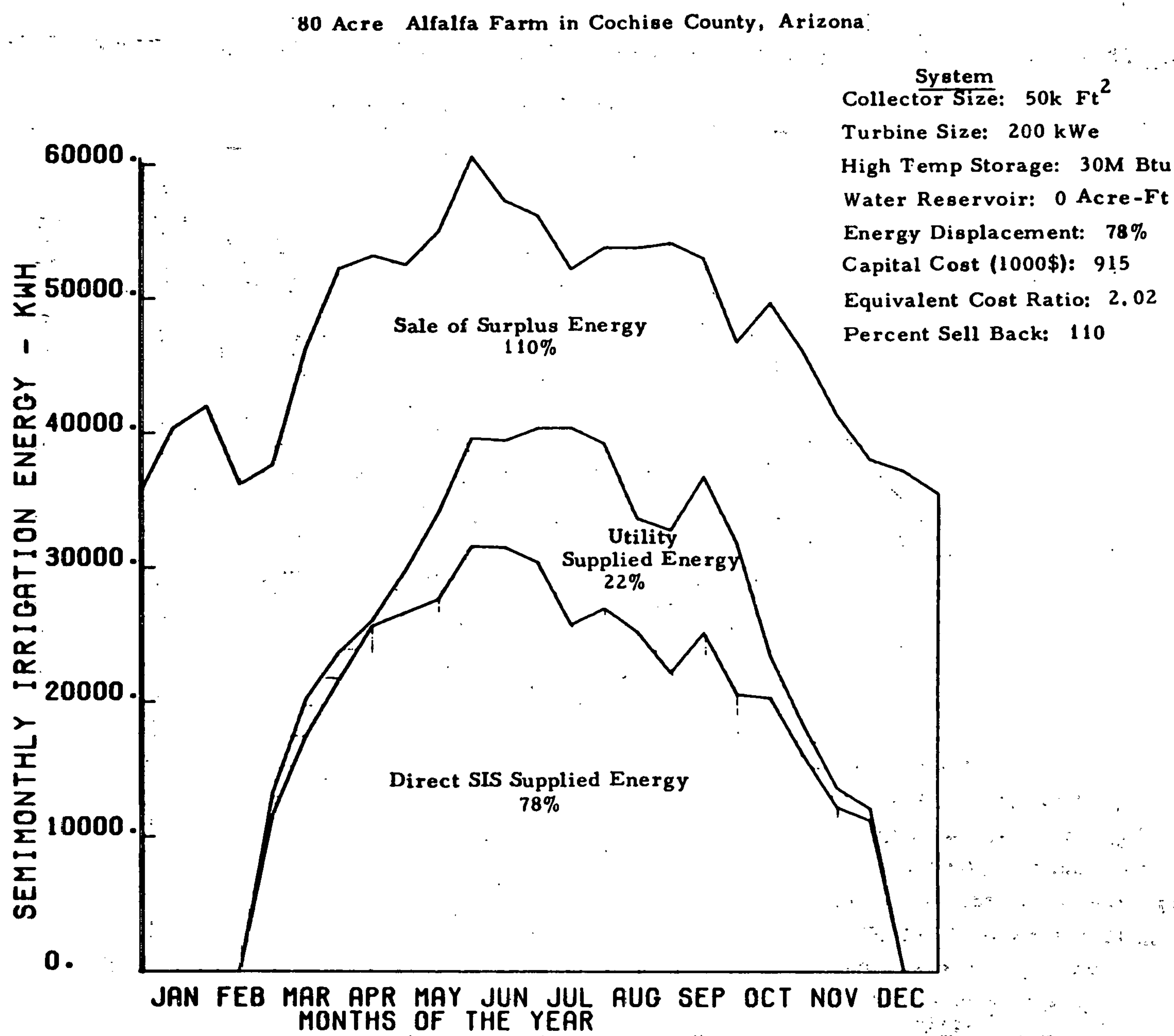


Figure 10-13. SIS Energy Balance and System Economics, 200 kW_e Turbine, Strategy "c"

winter would reduce standby energy needs from the utility but, unfortunately, would also increase the ECR and evaporation losses (due to a larger reservoir). As an alternative, a farmer may be able to trade the excess unused 19 percent energy for the 15 percent utility energy thereby achieving in effect, 100 percent energy displacement.

As seen from examination of Figures 10-2 through 10-13, as expected, the equivalent cost ratio (ECR) for strategy (c) is lower than for strategy (b), which in turn is lower than for strategy (a). Water storage does permit more cost effective use of the SIS, but with an accompanying increase in capital investment. If sales of surplus energy are possible, then water storage is no longer necessary and the ECR is found to be independent of turbine size. However, it is noted that for the larger turbine sizes, the optimum ECR leads to a very large collector area. With turbine power levels greater than 100 kW, the farmer unintentionally becomes an energy producer, but faces the prospect of a larger capital investment than if he had selected a smaller turbine.

10.3.1.2 Idealized Energy Demand Schedule

Recognizing that the maximum use of SIS-generated energy throughout the year is most cost-effective, an idealized energy demand schedule was selected for evaluation. The idealized schedule is flat throughout the year, implying the availability of complementary energy needs on the farm that can be met outside the irrigation season. This schedule also obviates the need for selling excess energy to a utility.

An example of the energy balance and the ECR achievable with the idealized schedule is given in Figure 10-14 for an Arizona application. The idealized annual demand was set equal to the 550 MWh annual expenditure for the alfalfa farm described in Section 10.3.1.1. The low ECR shown is indicative of the importance of having a level energy demand profile throughout the year. In fact, the ECR closely matches the value achieved when sale of surplus energy to utilities was considered for the alfalfa farm. The capital cost is also low when considering the relatively high energy displacement of 78 percent.

80 Acre Alfalfa Farm in Cochise County, Arizona
(Idealized Demand)

Collector Size:	20 k Ft^2
Turbine Size:	60 kW_e
High Temp Storage:	13M Btu
Water Reservoir:	0 Acre-Ft
Energy Displacement:	73%
Capital Cost (1000$):	363
Equivalent Cost Ratio:	2.00

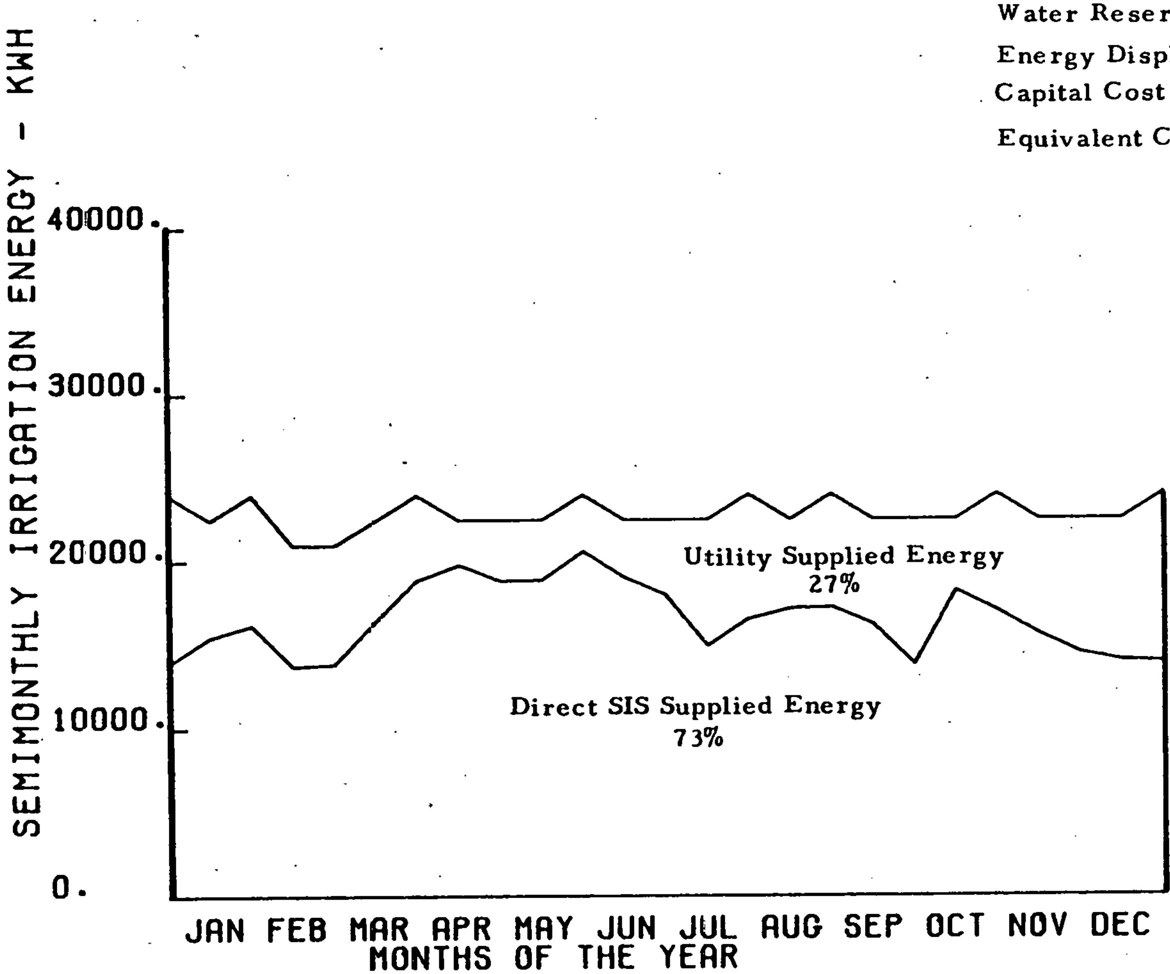


Figure 10-14. SIS Energy Balance and System Economics, 60 kW_e Turbine, Idealized Energy Demand

10.3.1.3 Sensitivity Analysis

Figure 10-15 shows the relationship of ECR to turbine size for the three operational strategies depicted in Section 10.3.1.1. The idealized energy demand case for a 60 kW_e turbine is also included. As seen from this figure, the ECR for strategy (c) is nearly the same for each turbine size and is comparable to the idealized demand case. ECRs for strategy (a) and (b) are approximately the same and invariant with turbine size up to 80 kW_e; thereafter, the ECR starts to increase gradually. This indicates that it does not pay to install water storage when using smaller turbines which produce lesser quantities of electricity.

System performance is shown in a plot of energy displacement as a function of turbine size in Figure 10-16. Energy displacement increases with turbine size for strategy (c); the idealized energy demand case also lies on this curve. (Energy displacement for strategy (c) includes energy displaced on-farm as well as at the utility.) Energy displacement for strategy (a) is lower than strategy (b), which in turn is lower than strategy (c). Energy displacement for strategy (a) peaks out at 80 kW_e whereas, for strategy (b), it lies between 80 and 112 kW_e. The above information, when used in conjunction with the data given in Figure 10-15, indicates that the optimum SIS turbine size for strategy (a) is about 80 kW_e and for strategy (b) is somewhat larger. No optimum turbine size is indicated for strategy (c).

Relative performance of the three strategies can also be displayed in the form of system capital cost as a function of energy displaced. Figure 10-17 shows the linear relationships relating greater system performance to higher cost. The advantage of strategy (c) is clearly indicated by the greater amount of energy displaced compared to strategy (a) or (b) at the same capital cost. The idealized energy demand case lies on the curve for strategy (c).

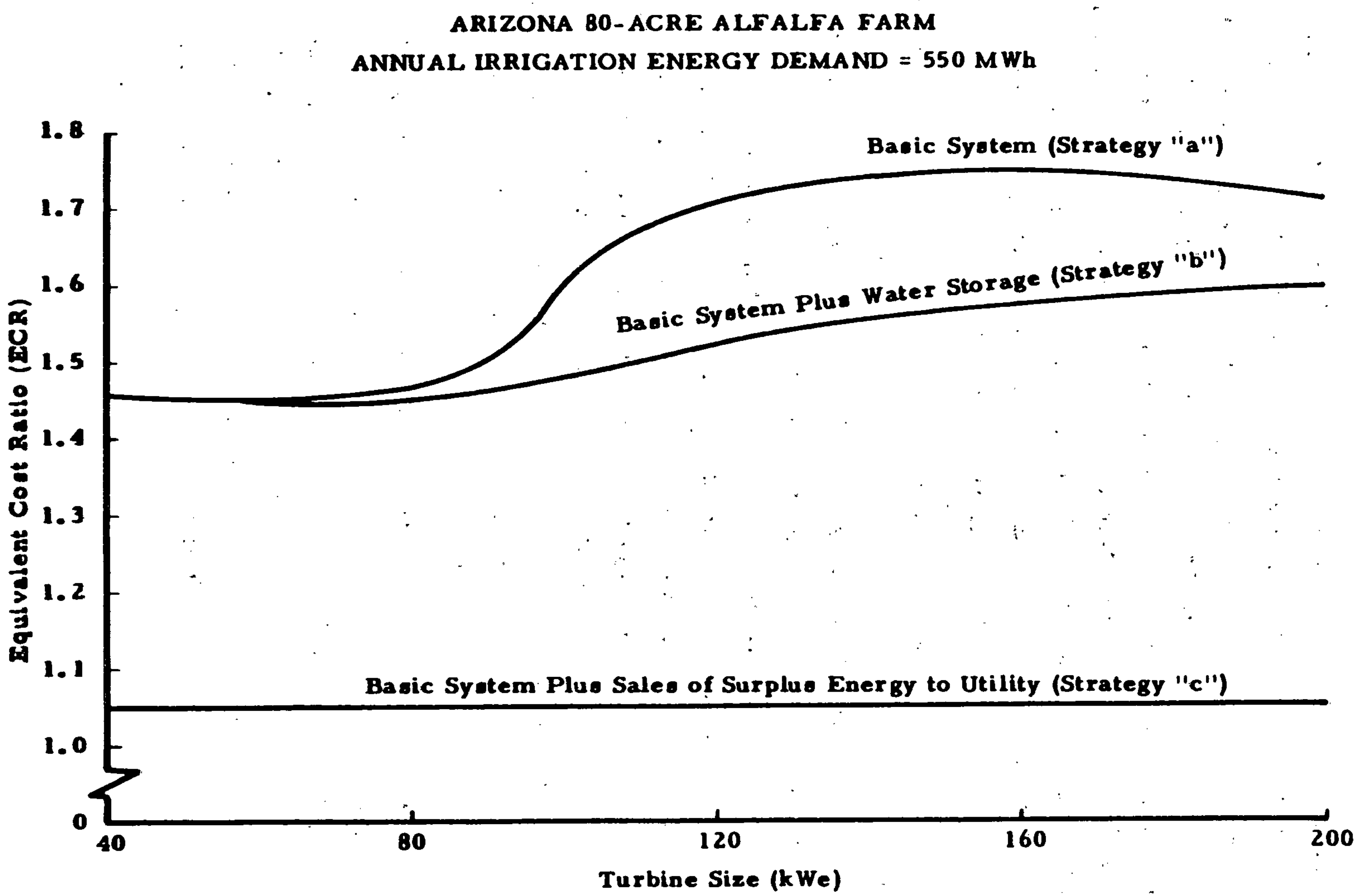


Figure 10-15. Effect of Turbine Size on ECR

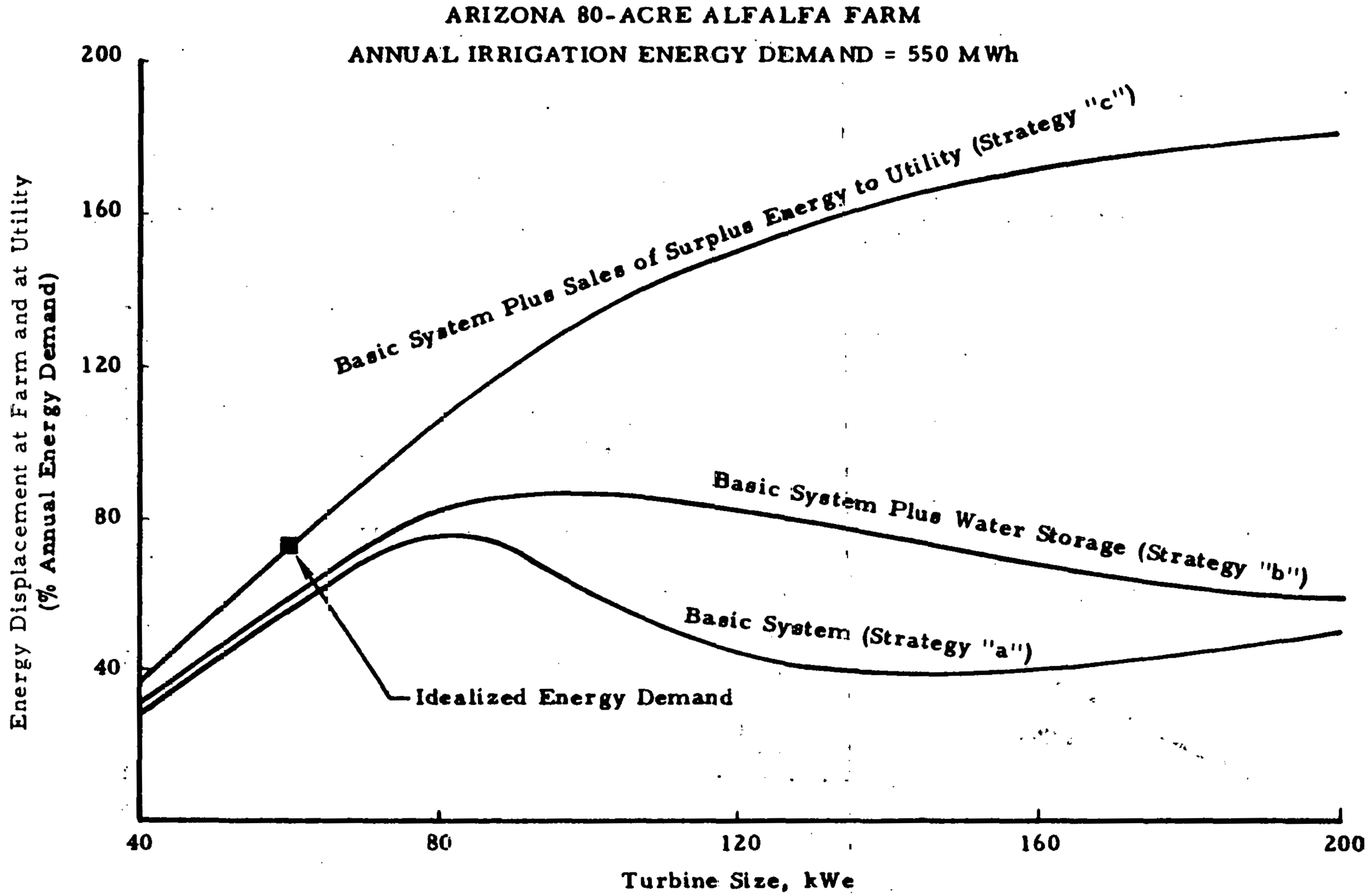


Figure 10-16. Effect of Turbine Size on Energy Displacement

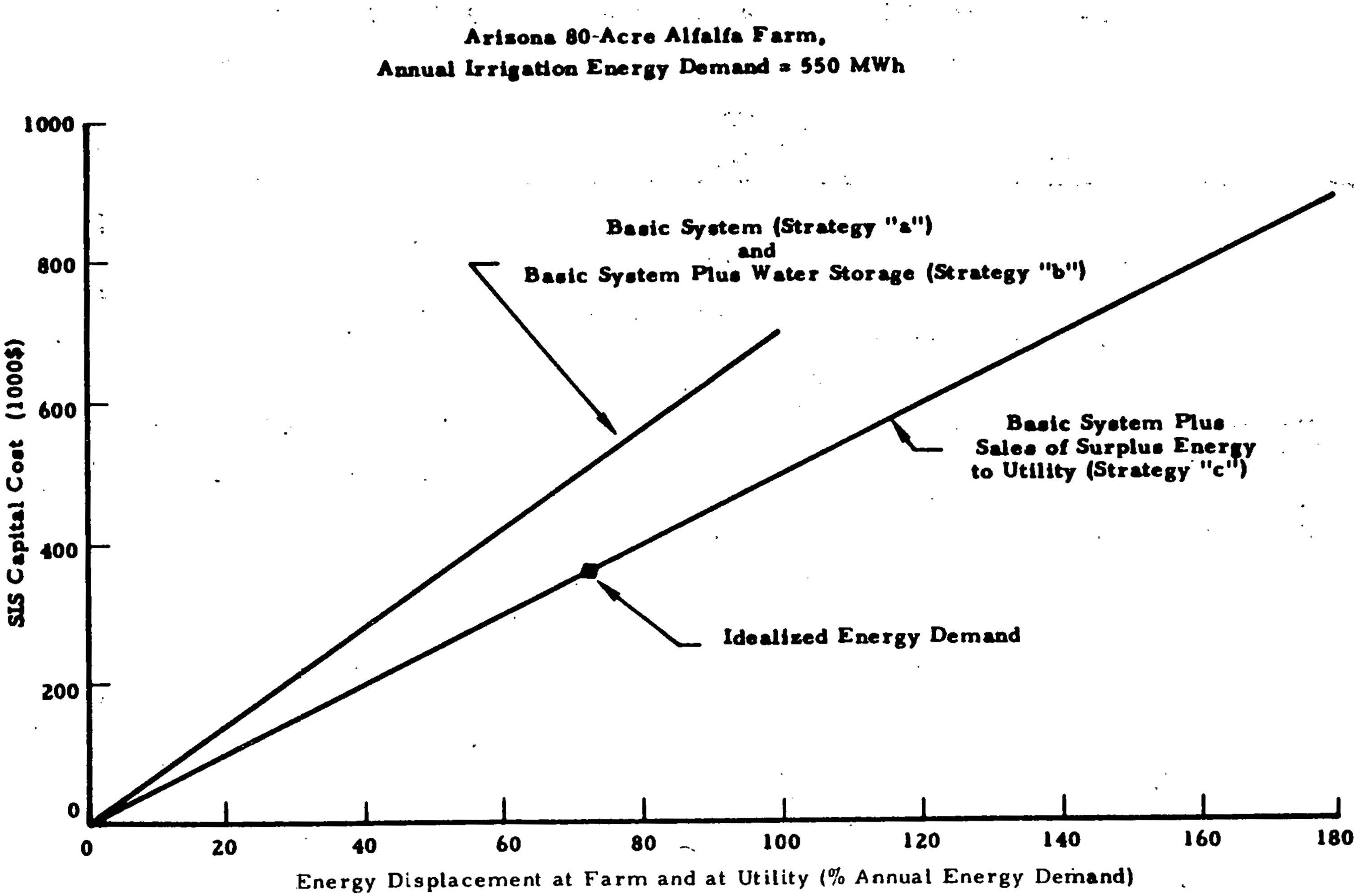


Figure 10-17. Effect of Energy Displacement on SIS Capital Cost

As noted in Section 10.3.1.1, under Strategy (c), excess solar energy is assumed to be sold back to utilities at the same cost at which standby energy is purchased from them. However, if the utility agreed to purchase this energy at a rate reduced from that at which it charged the farmer for energy he purchased to supplement solar-generated energy, then there would be a noticeable increase in the equivalent cost ratio. The effect of this form of utility policy on ECR for an 80 kW_e SIS is shown in Figure 10-18. A ratio of 1.0 on the abscissa corresponds to the initial assumption of parity in utility buy-sell rates, resulting in an ECR of 2.01. The ECR continues to rise as the ratio declines until, at a ratio of zero, the ECR has increased 40 percent to a value of 2.81, matching the ECR for Strategy (a) which has no sales of surplus energy.

10.3.1.4 Impact of Conventional Energy Costs and SIS Financial Parameters on Collector Cost Goals

It is of interest to evaluate how the annualized costs of competing conventional energy and SIS financial parameters might affect collector cost goals for achieving an ECR of unity. Figures 10-19 through 10-21 give breakeven requirements (ECR=1) for Strategies (a), (b) and (c) for different combinations of annualized unit costs of competing conventional energy and solar irrigation systems when collector costs are varied. It can be seen from Figure 10-19 that at 100 mills/kWh and 10 percent annualized cost rate, the breakeven collector cost is $\$10/ft^2$. Although not shown in Figure 10-21, the breakeven collector cost for Strategy (c) under similar conditions would be $\$16/ft^2$. These figures can also be used for determining SIS breakeven annualized cost rates for different expected combinations of collector system costs and competing energy prices.

10.3.2 Nebraska Farm Application Site

(This Section in Preparation)

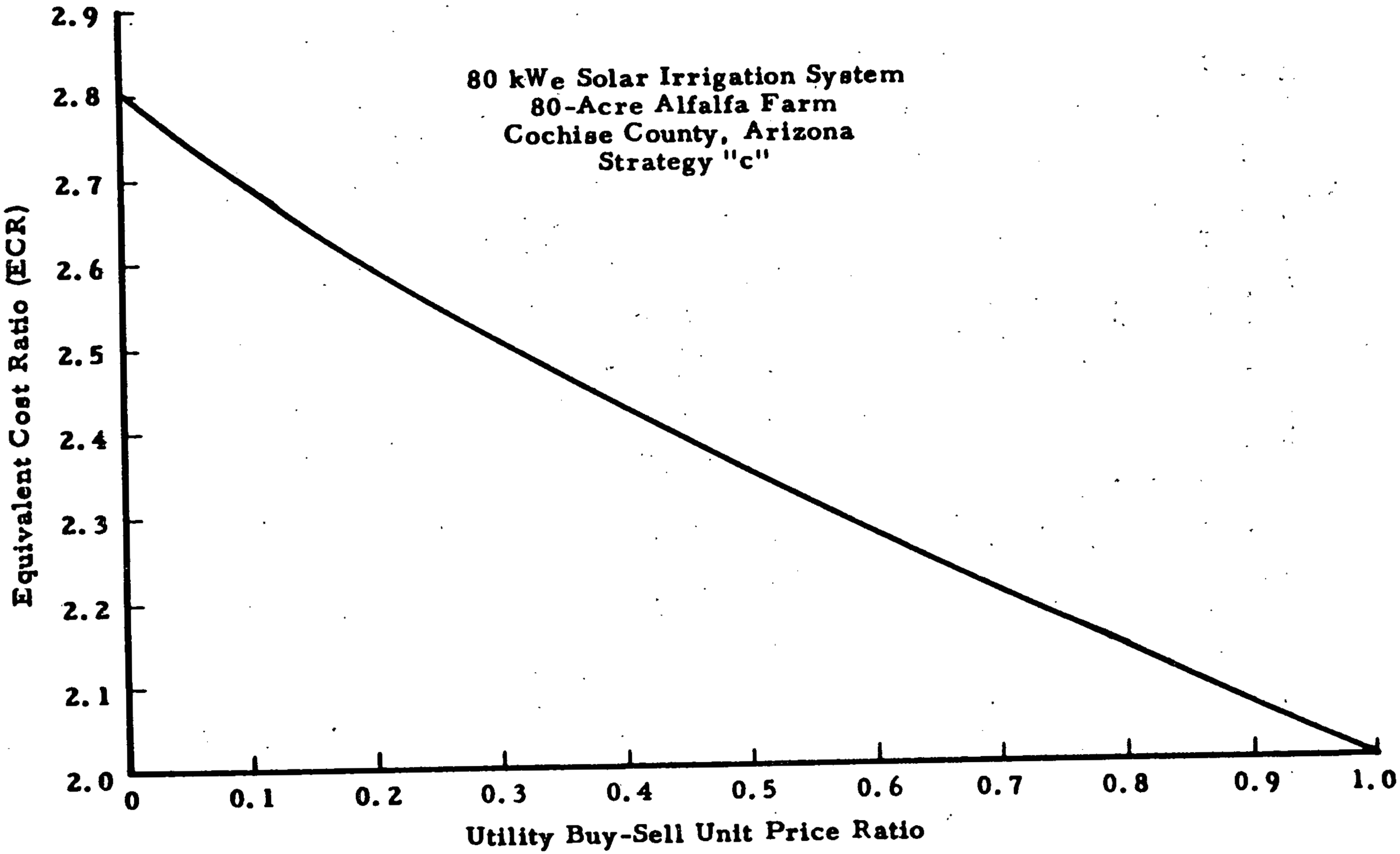


Figure 10-18. Effect of Utility Buy-Sell Rates on Solar Irrigation System ECR

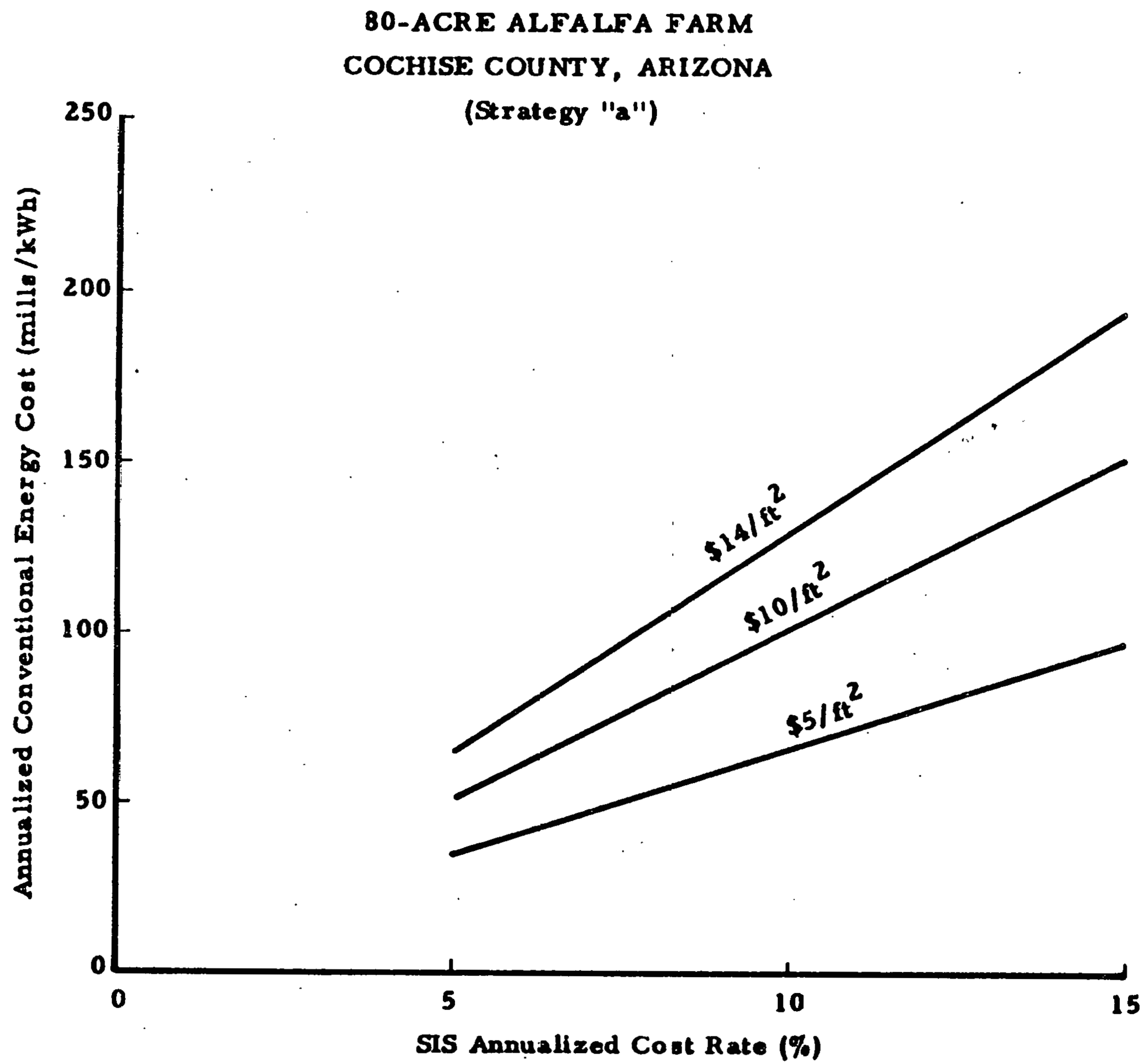


Figure 10-19. Collector Costs to Achieve ECR = 1 for Strategy "a"

80-ACRE ALFALFA FARM
COCHISE COUNTY, ARIZONA
(Strategy "b")

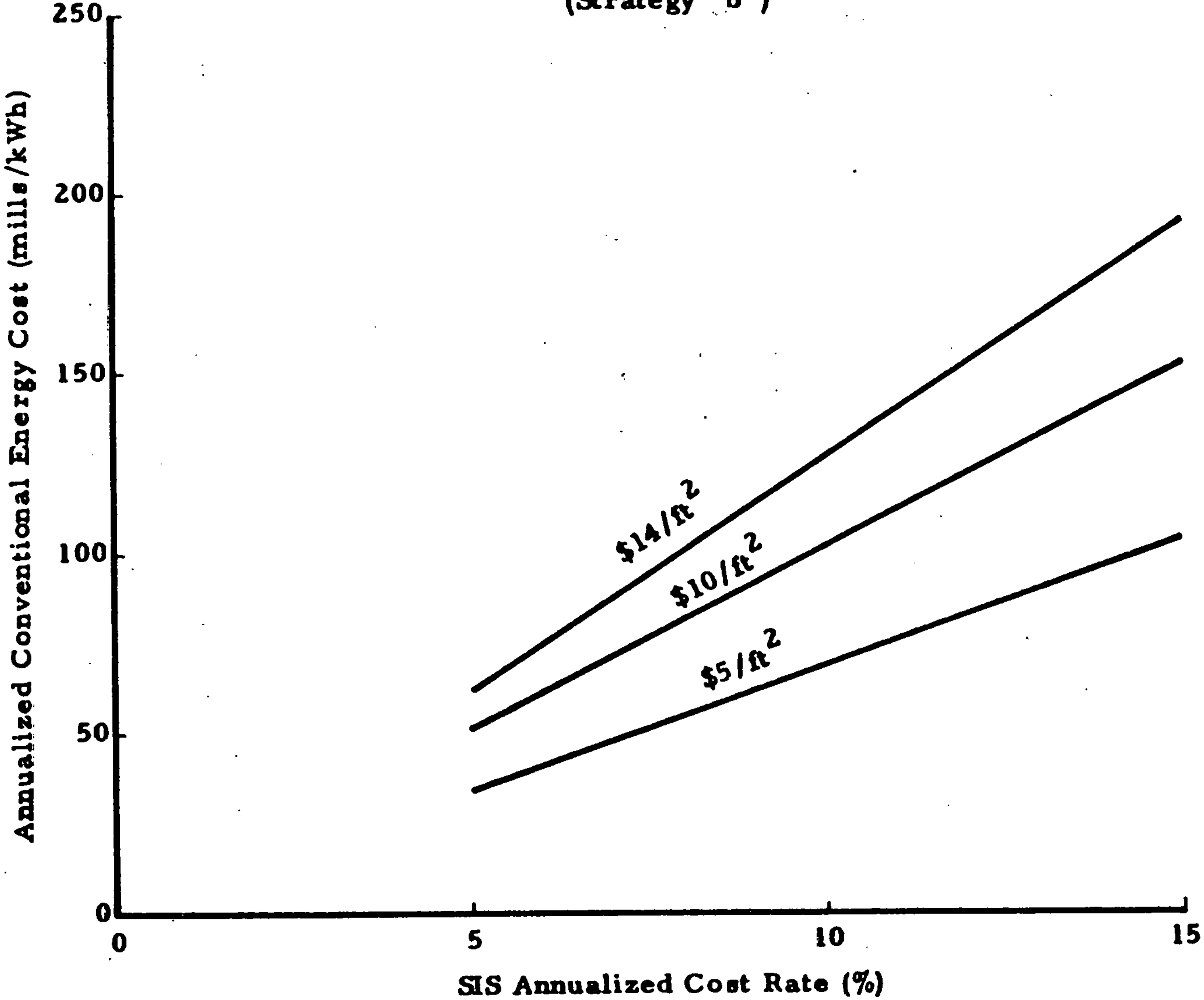


Figure 10-20. Collector Costs to Achieve ECR = 1 for Strategy "b"

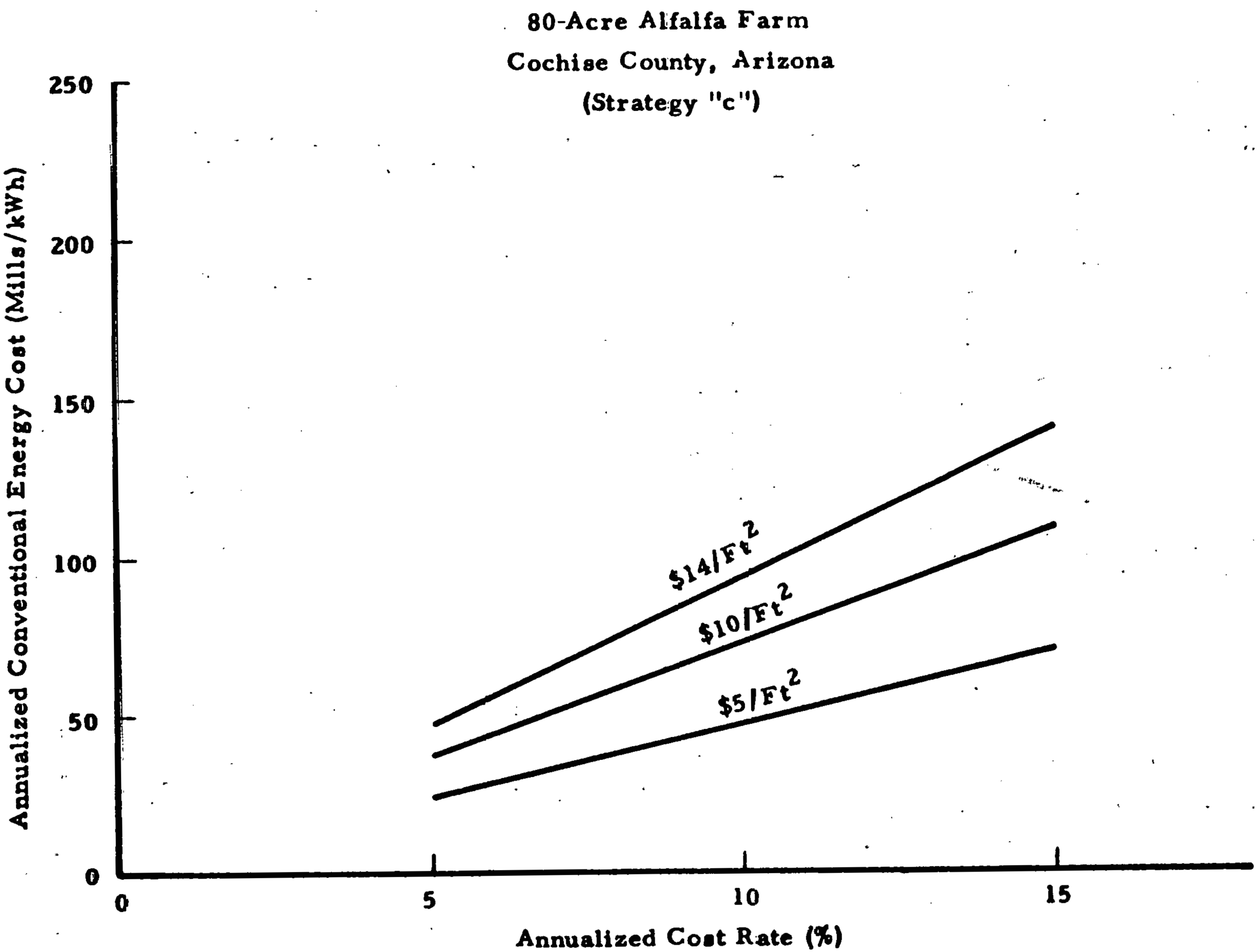


Figure 10-28. Collector Costs to Achieve ECR = 1 for Strategy "c"

10.3.3 ECR Correlation Analysis for Farms in the 17 Western States

To enable a simple assessment of the ECRs for all 17 western states without engaging in extensive analysis, calculations were performed for a few states, resulting in a useful correlation between the ECR and direct daily insolation (DDI) at each locale. It was assumed in the analysis that an idealized energy demand profile was available at all possible geographic locations. (If this is not possible, then sales of surplus energy to utilities could be considered; it would offer nearly the same ECR.) Fuel displacement was considered to be complete. The resulting correlation curve is given in Figure 10-22. The direct daily insolation needed to enter this curve has been summarized for each state in Figure 13-2. Because this curve was constructed for a fixed value of conventional energy cost, the resulting ECR must be modified by the particular annualized conventional fuel cost for each state, as given in Figure 13-3. An example of the ECR determination for New Mexico is shown in Figure 10-22.

Although the scenario assumed here is optimistic, it is useful in depicting the maximum market potential described in Section 13. Other scenarios can be ascribed to SIS applications with alternative correlations.

10.3.4 SIS Analysis for Farm Power Cooperative Application

Although the comparative evaluation places primary emphasis on solar irrigation systems sited on individual farms, an alternative consideration is the application of solar energy to agricultural power cooperatives that distribute grid power.* Such systems could serve the energy needs of many irrigation farmers as well as supply power needs for other farm operations or for surrounding municipalities when excess power was available outside the irrigation season. This excess power could also possibly be sold to the area power grid if the solar power unit could match the required line voltage.

*i.e., These co-ops do not generate their own power, they merely purchase power generated elsewhere and distribute it to farm communities.

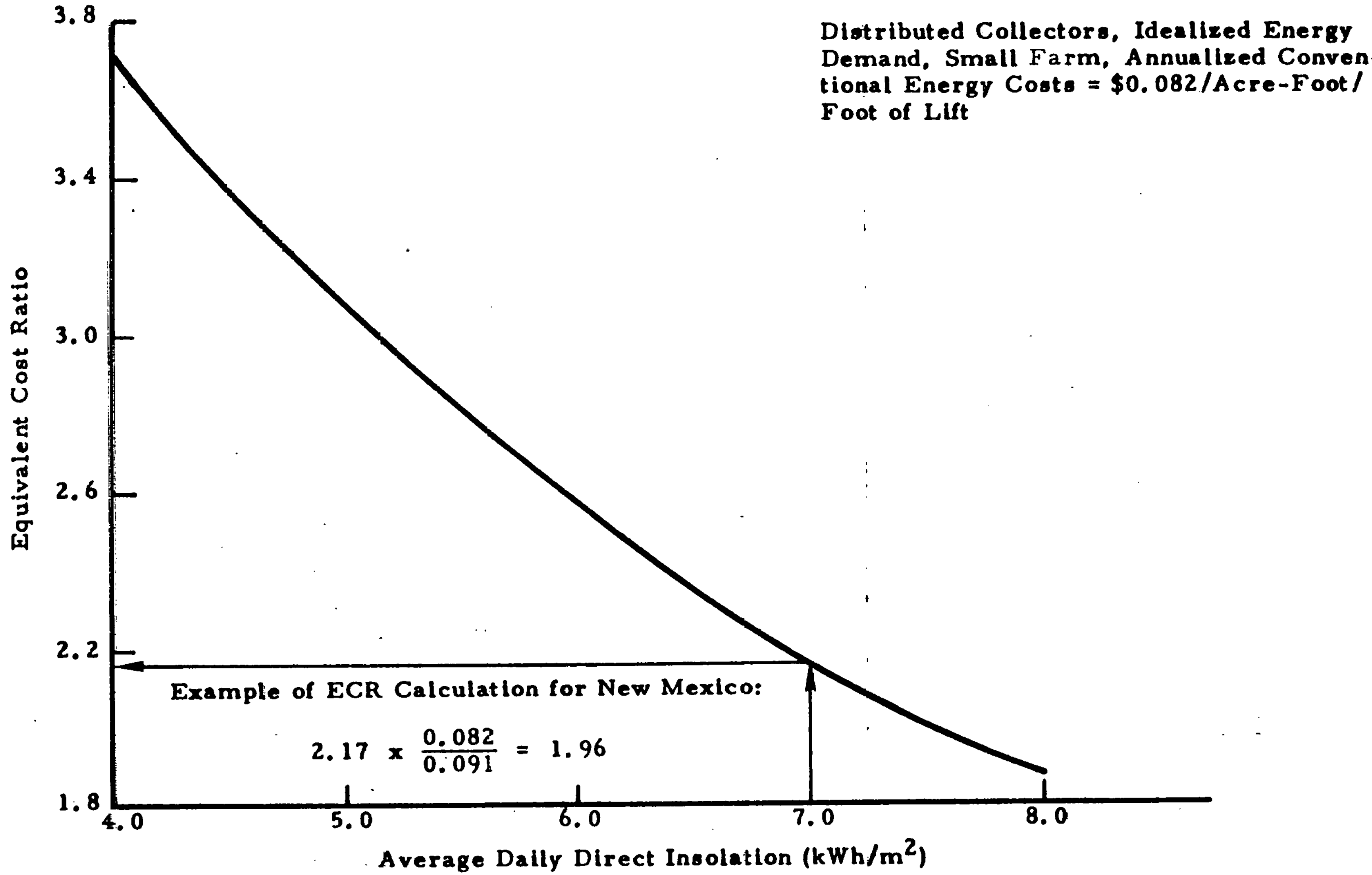


Figure 10-22. Effect of Insolation on ECR

Analysis of a co-op system was performed for the three strategies discussed in Section 10.3.1. Figures 10-23 through 10-25 give the energy balance and ECR results for a 25 MW_e central receiver solar irrigation system located in Cochise County, Arizona. This system was evaluated against the total irrigation energy requirement for the entire county. As seen, there are major reductions in ECR compared to the smaller on-farm systems that were depicted in Figures 10-2 through 10-13. An example of the economic advantage of a co-op system is afforded by comparison with an 80 kW_e on-farm system. The largest reduction was for operational strategy (c), where a reduction of 45.8 percent was achieved when surplus energy is sold to a utility, resulting in an ECR of 1.09. The smallest reduction of 34.5 percent was for operational mode (a). This lower reduction in ECR was mainly due to the fact that the shape of total irrigation energy demand for Cochise County has a significant summer peaking requirement compared to the 80 acre alfalfa farm energy demand schedule. In the surplus energy sales mode, the shape of the energy demand schedule is not an influencing factor for ECR, since anytime the SIS-generated electric energy exceeds the required demand, it can conceivably be sold back to the utility grid. As water storage tends to somewhat compensate for the effect of sharp peaking energy requirements, the results for operational strategy (b) indicate a large reduction of 45.7 percent in the corresponding values of ECR. Water storage remains at each farm as for the on-farm SIS application. If water were stored at the power co-op, an extensive pipe distribution system would be required to deliver water to each farm. The co-op distribution system is simply the existing electrical network.

The overall large reduction evident in ECR is due to SIS operation at higher efficiencies resulting in relatively smaller collector areas for a given power output when compared to the small on-farm system. The large co-op system permitted consideration of a heliostat/central receiver design with peak operating temperature of about 900°F. The higher cycle temperature combined with scaling effects results in increased system efficiency.

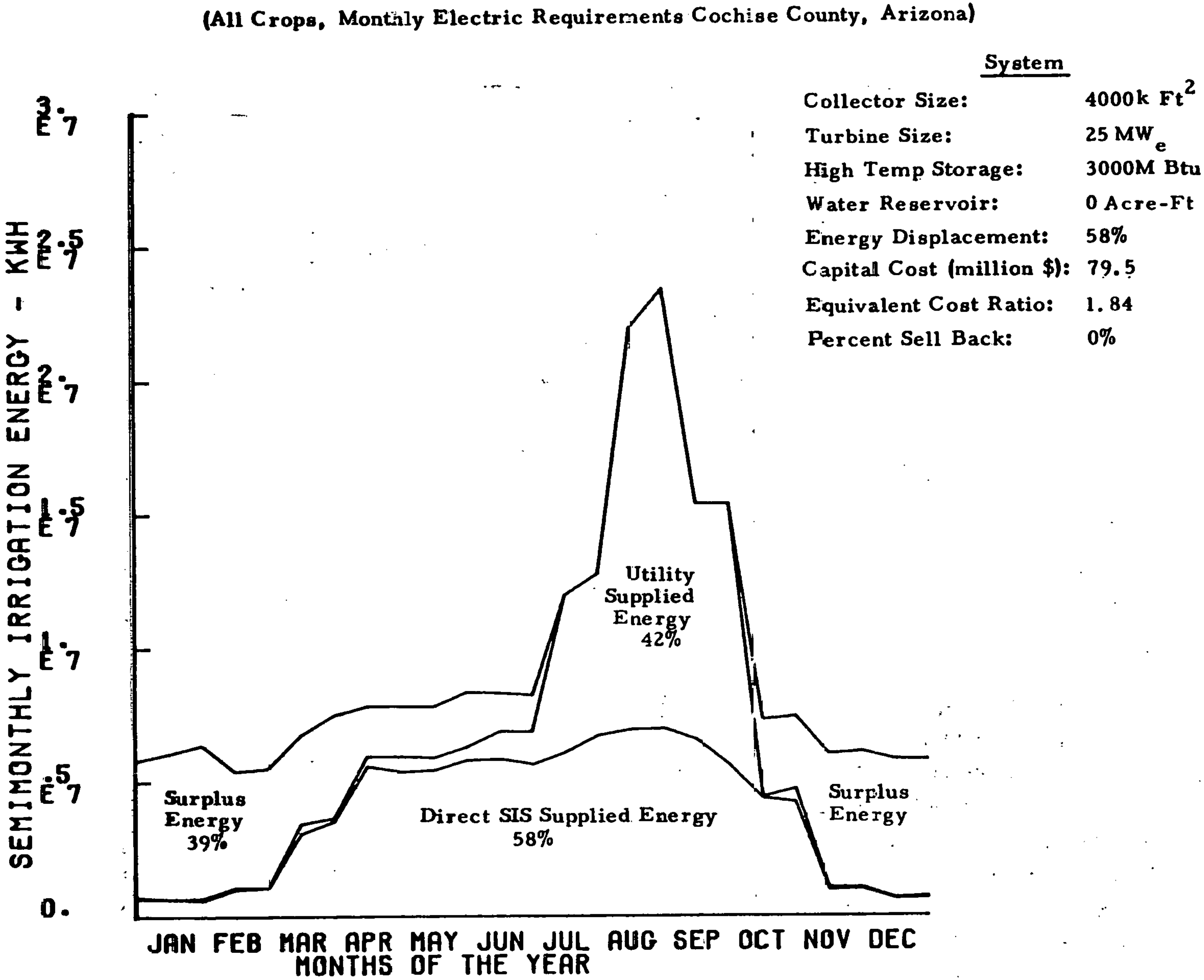


Figure 10-23. SIS Energy Balance and System Economics, Arizona 25 MWe Power Cooperative, Strategy "a"

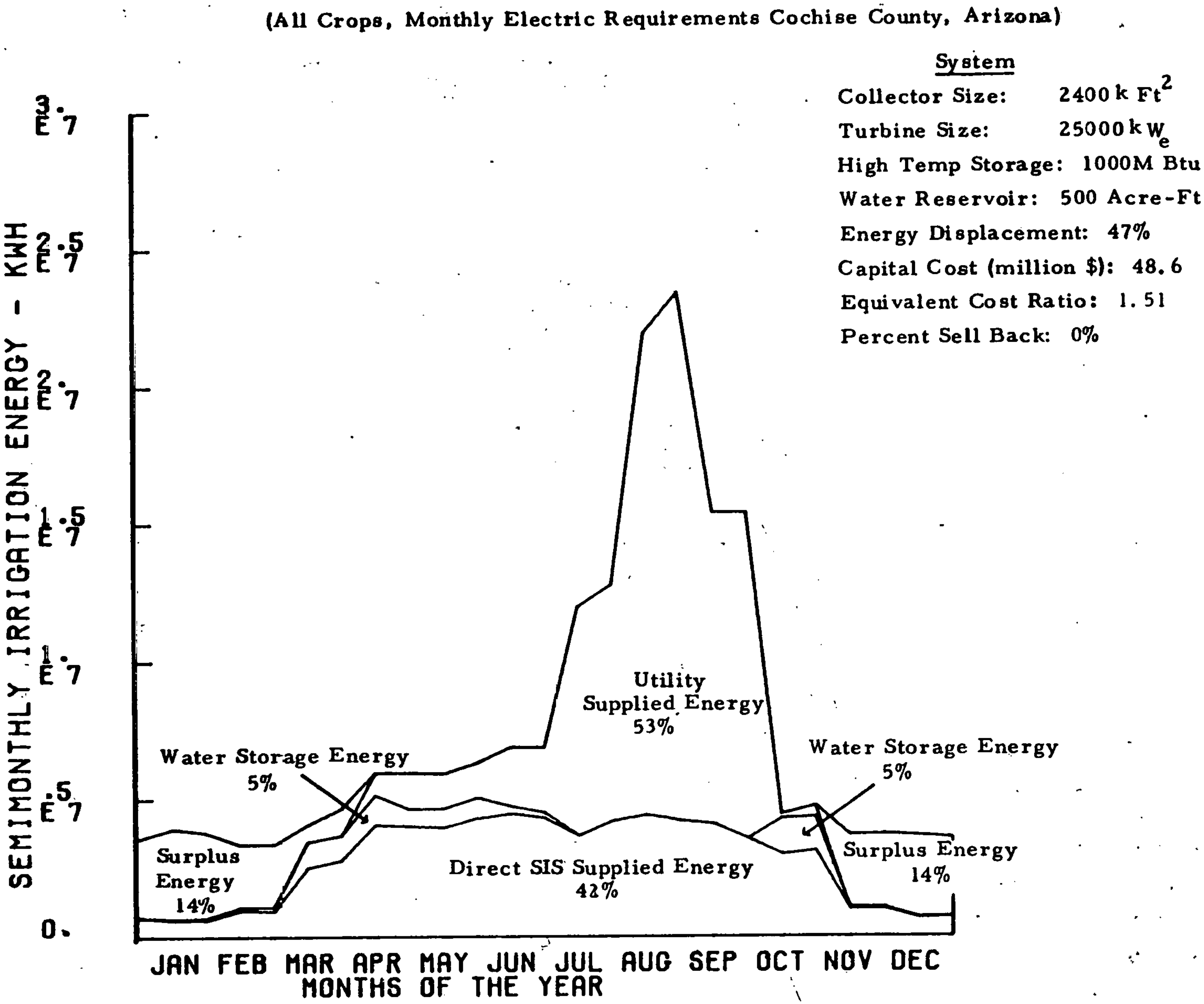


Figure 10-24. SIS Energy Balance and System Economics, Arizona 25 MWe Power Cooperative, Strategy "b"

(All Crops, Monthly Electric Requirements Cochise County, Arizona)

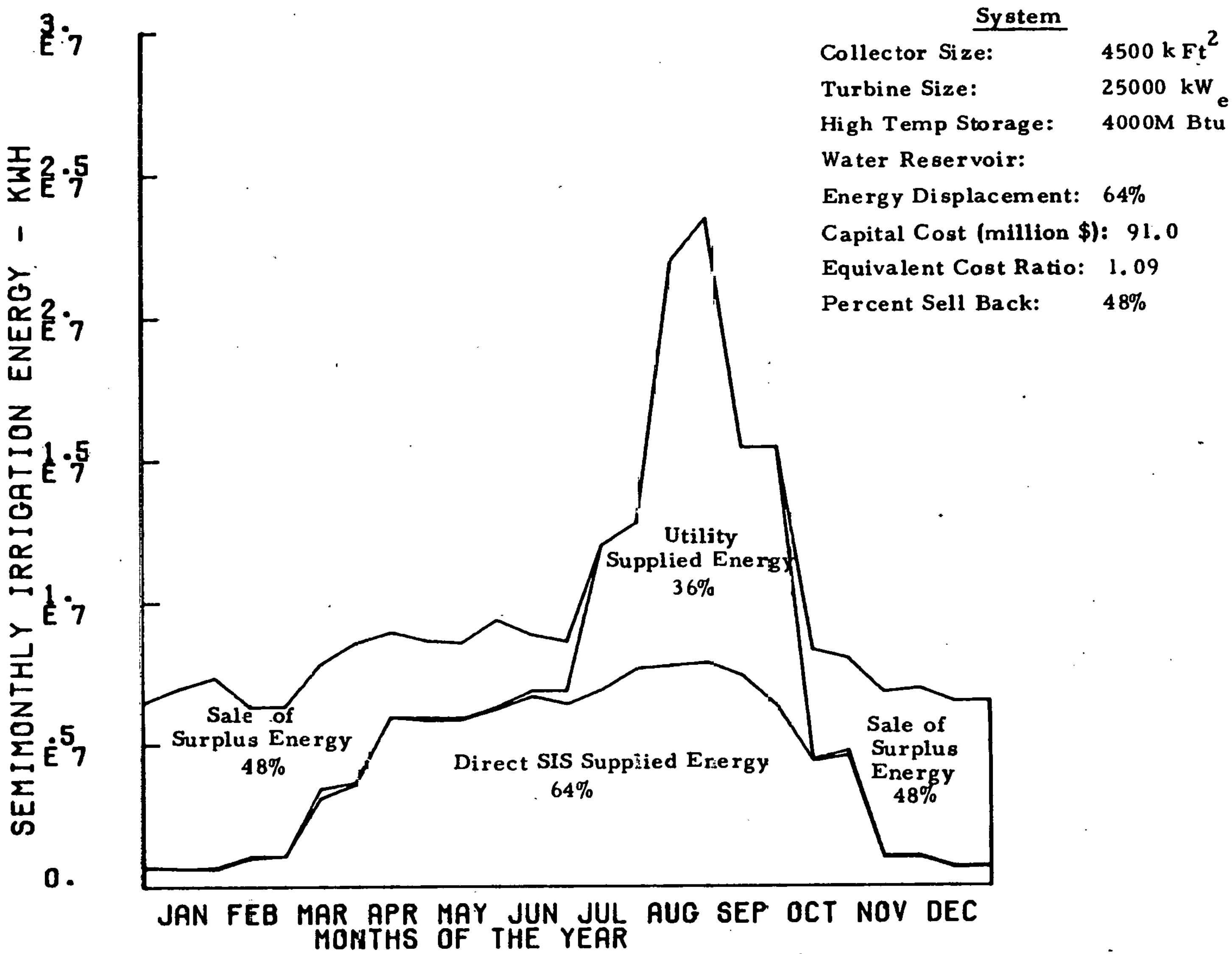


Figure 10-25. SIS Energy Balance and System Economics, Arizona 25 MWe Power Cooperative, Strategy "c"

Improvements in efficiency for large co-op systems are offset somewhat by the reduced cost of conventional energy purchased by a power distribution co-op compared to the cost of energy purchased by an individual farmer. These reduced costs were considered in calculation of the ECR for a co-op. Nonetheless, the low values for ECR show that co-ops may be the first market applications of SIS to be penetrated.

10.4 SIS INSTALLATION CONSTRAINTS

(This Section in Preparation)

11. FARM CASH FLOW ANALYSIS

11.1 METHODOLOGY USED FOR ANALYSIS

(This Section in Preparation)

11.2 BASE CASE ANALYSIS RESULTS

(This Section in Preparation)

11.3 EFFECT OF GOVERNMENT POLICIES

(This Section in Preparation)

12. FARM BUDGET ANALYSIS

12.1 COMPARISON OF CROP AND ENERGY PRICE INDICES

Since 1973, energy prices paid by farmers have increased much more than the crop prices paid to farmers. The national index for energy prices paid by farmers climbed steadily from a value of 100 in 1973 to 161 in 1976 while crop prices received by farmers varied within a narrower range, from 100 in 1973 to 113 in 1976 with a high of 128 in 1974. This effect is illustrated in Table 12-1 which shows the ratio of crop price index to energy cost index, both normalized to a value of 100 in 1973. The impact on farm operating budgets has been to reduce the already narrow margin of profit for successful farmers, and to drive unsuccessful farmers further into debt. Many farmers have been forced to refinance their land, taking advantage of rising land values, in order to offset negative cash flows.

While the national picture in itself appears discouraging to farmers, escalation in energy prices in parts of the southwestern United States poses even more serious problems for farm enterprises. For example, in Cochise County, Arizona, between the years 1973 and 1977, electricity prices increased by a factor of 2.54. Natural gas prices in this same period rose even more dramatically by a factor of 3.85. These figures translate to annual increases of 26.3 percent and 40 percent, respectively. This rapid escalation in energy prices has increased the cost of pumping irrigation water dramatically and has, at the same time, impaired the ability of Cochise County farmers to remain competitive with other areas in the country.

Energy cost increases can be expected in the future, and the viability of farming may eventually disappear for those farming regions dependent on irrigation. The impact of rising energy prices on future crop budgets is examined in the next section.

Table 12-1

COMPARISON OF NATIONAL CROP AND ENERGY PRICE INDICES, 1973-1976

Year	(1) Index of Crop Prices Received by Farmers (1973=100)	(2) Index of Energy Prices Paid by Farmers (1973=100)	Crop-Energy Price Index Ratio
1976	113	161	0.70
1975	115	153	0.75
1974	128	137	0.93
1973	100	100	1.00

12.2 ENERGY PRICE IMPACT ON FUTURE CROP BUDGETS

Future crop budgets will be affected by rising energy prices. This effect will be most severe for irrigated crops in areas where water must be pumped from deep wells. Some examples of the increasing share of crop budget devoted to irrigation fuel in 1975, 1985 and 2000 have been prepared for Arizona, Texas and Kansas. Two representative major irrigated crops in each of these states were selected from those on which the Economic Research Service of the U.S. Department of Agriculture (USDA) has published estimated 1975 crop budgets called Firm Enterprise Data System (FEDS) budgets. These FEDS budgets were compiled for USDA by the Department of Agricultural Economics at Oklahoma State University. Selected crops were: (1) alfalfa and cotton in Arizona, (2) sorghum and cotton in Texas, and (3) wheat and corn in Kansas.

The average amount of fuel required to irrigate one acre of the selected crops for one year was calculated from data provided by the Irrigation Market Energy Demand Computer Program (see Section 7). Table 12-2 shows the calculation of fuel required for each crop. The cost of fuel per unit, i.e., kilowatt hour (kWh) of electricity, thousand cubic feet (mcf) of natural gas, and gallons (gal) of diesel fuel is given in Table 12-3. All costs are in noninflated 1977 dollars and derived from the data base described in Section 5.

Tables 12-4, 12-5, and 12-6 show the major elements of crop budgets for the two example crops in each of the three states. The estimated annual cost expressed in terms of dollars per acre is shown along with the percent of total cost represented by each entry, which designates the resultant percentage of crop budget devoted to: (1) irrigation fuel, (2) other variable costs, (3) fixed irrigation costs, and (4) other fixed costs. These percentages were used in plotting the bar chart shown in Figure 12-1. Note that changes in budget elements with time are the result of increased fuel cost only. These fuel costs apply to all energy-consuming crop production operations, but have been isolated in Figure 12-1

Table 12-2

IRRIGATION FUEL REQUIRED

State	Arizona		Texas[1]		Kansas	
Crop:	Alfalfa	Cotton	Sorghum	Cotton	Wheat	Corn
Crop Thousand Acres	157.9	292.8	163.8	109.7	271.9	380.0
Annual Irrigation Energy (kWh)	879400	901279	102990	93081	200831	383615
Electricity (kWh) per acre	5569	3078	629	849	739	1010
Gas (MCF) per acre	- -	- -	9.64	13.02	11.33	15.49

(1) Hale County, Texas

Table 12-3

FUEL COSTS

(1977 DOLLARS)

State:	Arizona	Texas	Kansas
1975 Fuel cost $ per unit			
Electricity (KWH)	0.028		
Gas (MCF)		1.265	0.733
Diesel (GAL)	0.422	0.389	0.411
1985 Fuel cost $ per unit			
Electricity (KWH)	0.034	0.040	0.043
Diesel (GAL)	0.580	0.556	0.561
2000 Fuel cost $ per unit			
Electricity (KWH)	0.046	0.050	0.053
Diesel (GAL)	0.780	0.759	0.757

Table 12-4

ANNUAL CROP BUDGETS PER ACRE - ARIZONA
(1977 DOLLARS)

Crop:	Alfalfa			Cotton		
Year:	1975	1985	2000	1975	1985	2000
Irrigation Fuel						
(dollars)	154	189	256	85	105	142
(percent)	32	36	43	17	20	26
Other Variable						
(dollars)	272	273	275	291	295	300
(percent)	56	53	47	60	58	54
Total Variable						
(dollars)	426	462	531	376	400	442
(percent)	88	89	90	77	78	80
Fixed Irrigation						
(dollars)	54	54	54	40	40	40
(percent)	11	10	9	8	8	7
Other Fixed						
(dollars)	6	6	6	73	73	73
(percent)	1	1	1	15	14	13
Total Fixed						
(dollars)	60	60	60	113	113	113
(percent)	12	11	10	23	22	20
Grand Total						
(dollars)	486	522	591	489	513	555
(percent)	100	100	100	100	100	100

Table 12-5
ANNUAL CROP BUDGETS PER ACRE - TEXAS
(1977 DOLLARS)

Crop:	Sorghum for Grain			Cotton		
Year:	1975	1985	2000	1975	1985	2000
Irrigation Fuel						
(dollars)	12	25	31	17	34	42
(percent)	7	14	17	10	18	22
Other Variable						
(dollars)	95	97	100	91	94	97
(percent)	57	53	51	54	50	48
Total Variable						
(dollars)	107	122	131	108	128	139
(percent)	64	67	68	64	68	70
Fixed Irrigation						
(dollars)	39	39	39	29	29	29
(percent)	23	21	20	17	15	15
Other Fixed						
(dollars)	22	22	22	32	32	32
(percent)	13	12	12	19	17	15
Total Fixed						
(dollars)	61	61	61	61	61	61
(percent)	36	33	32	36	32	30
Grand Total						
(dollars)	168	183	192	169	189	200
(percent)	100	100	100	100	100	100

Table 12-6

ANNUAL CROP BUDGETS PER ACRE - KANSAS
(1977 DOLLARS)

Crop:	Wheat			Corn for Grain		
Year:	1975	1985	2000	1975	1985	2000
Irrigation Fuel						
(dollars)	8	32	39	11	43	54
(percent)	6	21	24	5	18	21
Other Variable						
(dollars)	64	65	67	135	138	143
(percent)	50	42	41	66	57	56
Total Variable						
(dollars)	72	97	106	146	181	197
(percent)	56	63	65	71	75	77
Fixed Irrigation						
(dollars)	39	39	39	34	34	34
(percent)	30	25	24	17	14	13
Other Fixed						
(dollars)	17	17	17	26	26	26
(percent)	14	12	11	12	11	10
Total Fixed						
(dollars)	56	56	56	60	60	60
(percent)	44	37	35	29	25	23
Grand Total						
(dollars)	128	153	162	206	241	257
(percent)	100	100	100	100	100	100

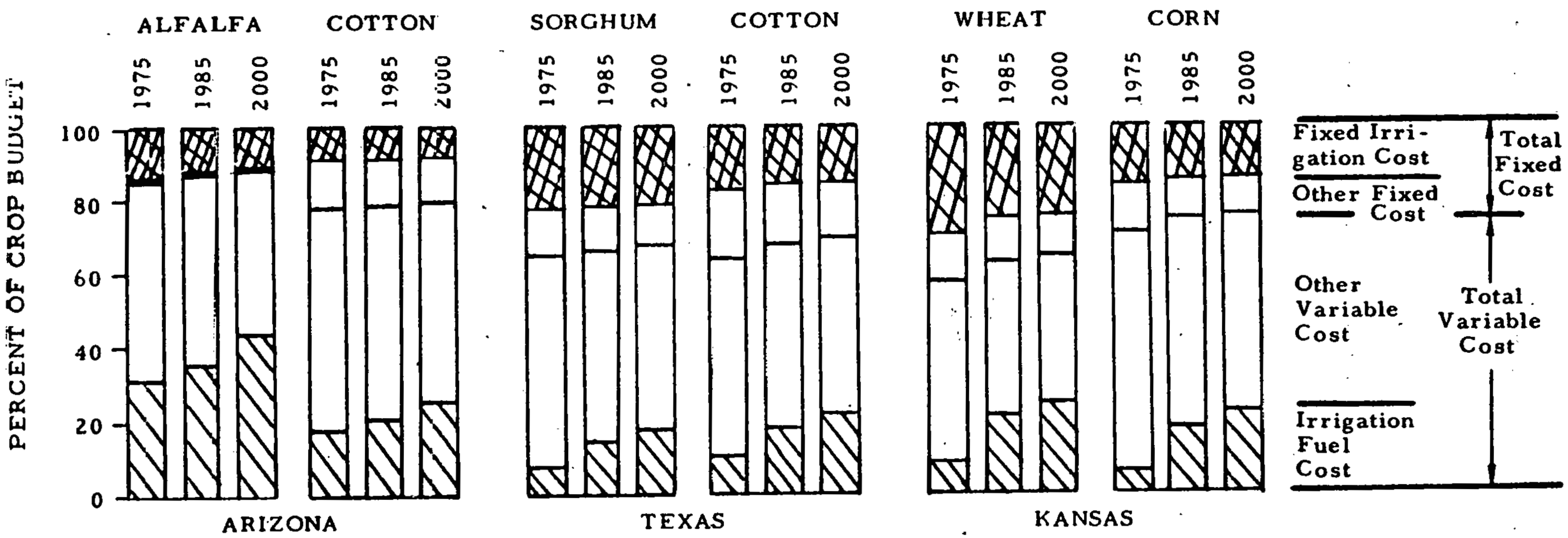


Figure 12-1. Crop Budgets - Effect of Irrigation Fuel on Percentage Distribution

just for irrigation operations. Tilling, seeding, harvesting and other operations fuel costs have been aggregated as a portion of "Other Variable Costs".

Examination of Figure 12-1 reveals some interesting comparisons and trends. Arizona presently dominates in allocation of costs to irrigation fuel costs, particularly for high water demand crops such as alfalfa. Between 1975 and 1985, small increases in irrigation fuel budget allocations are evident for Arizona, but Texas and Kansas show these percentage costs increasing by a factor of 2 to 3. By 2000, combined fixed and variable irrigation costs are expected to exceed 50 percent of crop budgets in some cases.

When irrigation fuel costs become a dominant factor in crop budgets, small changes from the estimated unit fuel costs could easily shift farm cash flows from positive to negative, particularly for crops that are prone to production yield variations from year-to-year. This factor could prove to be a major inducement to farmers to introduce solar irrigation systems in order to help stabilize their net farm income.

13. MARKET ANALYSIS

Because new technology typically does not achieve immediate total market penetration, even if an economic advantage is demonstrated, a market penetration model must be used to estimate annual percent of market potential captured by solar energy. The current study effort did not permit a complete assessment of market capture by solar irrigation systems. Rather, the analysis focused on market potentials; the number of solar units which might be sold to farmers from 1985 through 2015 remains to be estimated.

Some of the factors which could cause farmers to hesitate purchasing solar energy systems have already been discussed in Section 9. Not only do farmers as a group tend to be cautious in their purchases, but the financial institutions serving agricultural communities tend to be relatively conservative. Farming, in any event, is associated with risks, both on the production side, due to the constant possibility of crop failure, and on the marketing end, due to continual uncertainty about commodity prices. From year to year, farmers can never be sure about the prospects for positive cash flows. If the reliability of the solar system is in question, this would be an additional factor weighing against purchase of the solar systems. The likelihood of constantly increasing prices for conventional energy may only partially offset the uncertainties connected with solar energy.

Many of these uncertainties might be overcome through specific government programs involving low cost loans, loan guarantees, price supports, etc. If such uncertainties are assumed to be reduced through some form of government action, it is of interest to make a determination of when and where solar energy could become economically viable, and to estimate the magnitude of the market potentials which would then open up to solar systems. The following discussion briefly describes how this was accomplished.

13.1 SCENARIO DEFINITIONS

(This Section in Preparation)

13.2 SELECTION OF MARKET PENETRATION FACTORS

A detailed economic analysis of a solar-powered irrigation system has been completed previously, and is described in Section 10. The purpose of this section is to generalize results of that analysis for application of small on-farm solar irrigation systems in the 17 western states*. Since more than 92 percent of all energy consumed in crop irrigation occurs in these states, this area constitutes the major future market for solar irrigation systems. Geographic factors which influence the potential economic competitiveness of solar systems have been identified and quantified where possible. To test the market analysis methodology, an energy demand scenario has been specified and solar system cost goals have been estimated which will allow those systems to begin penetrating increasing portions of the market.

The measure of marketability of solar energy systems used in this section is the Equivalent Cost Ratio (ECR), which was discussed in Section 9. It is assumed that a value of ECR less than or equal to unity is a necessary condition for market penetration to begin. That fraction of the total market where ECR is less than or equal to unity under various conditions will be called the Market Potential for solar energy. Once a Market Potential is established, market penetration is postulated to occur in total. More sophisticated analyses are being considered where solar energy captures an increasing market share over time. Techniques necessary to estimate that time path are not currently well developed, and further efforts in that direction are beyond the scope of this present effort. Most studies conclude that an S-shaped curve best describes the time path of market penetration by successful new technologies. The applicability of this pattern to future technologies whose success is

*Large co-op solar irrigation systems will be considered in future analyses uncertain is questionable, however. Several articles on this topic can be found in Reference 13-1.

Many of the factors which affect ECR are those which vary from one application and location to another. The most important of these factors have been identified as the average daily direct insolation (DDI) and the expected costs of conventional fuels (AFC). A simulation analysis has been previously described in Section 10 in which the ECR of an optimized solar system was generated under various insolation conditions for an idealized energy demand profile. The relation between ECR and its major argument can be approximated by the equation:

$$ECR = (6.488 - 0.9973 \times DDI + 0.04912 \times DDI^2) \frac{ACR}{AFC} \qquad (13\text{-}1)$$

The expression will be used to estimate the ECR for each of the regions comprising the 17 state markets.

The individual regions which have been delineated for this analysis are shown in Figure 13-1. In most cases, an entire state is taken to be one region. The analysis described in Section 6 resulted in preliminary rankings of the states according to the likelihood of markets for solar irrigation systems. Based on those rankings, six states were selected for detailed study, namely: Arizona, California, Kansas, Nebraska, New Mexico, and Texas. As Figure 13-1 shows, four of these states have geographic divisions that are based on significant differences in projected conventional energy costs, insolation levels, and farming patterns. The specific outlines of the substate divisions follow those of the areas used in the Firm Enterprise Data System of the U.S. Department of Agriculture. Irrigation in Kansas is limited to the western third of the state, which is quite homogeneous. In New Mexico, much of the irrigation occurs along the border with Texas, and in Arizona, almost all irrigation is found in the southern part of the state.

The estimated average daily direct solar insolation (DDI) isoquants for the study area were derived from Reference 13-2 and are

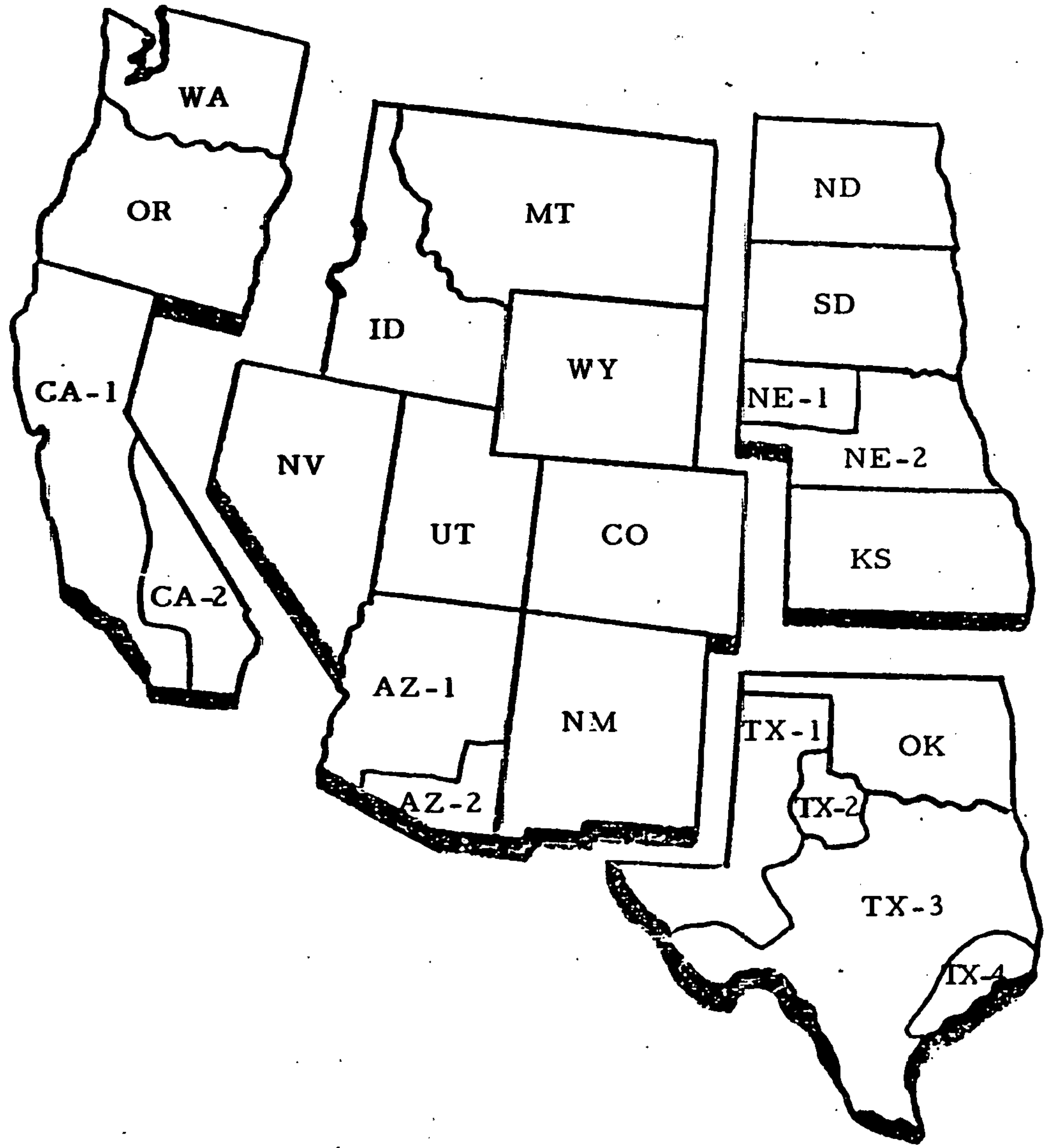


Figure 13-1. Solar Irrigation System Study Regions

shown in Figure 13-2. These values are expressed as intervals and include visual geographical weightings based on areas of concentrated energy use for irrigation. As shown, the values range from a low of 3.5 kWh/m^2 per day in Washington to a high of 8.0 kWh/m^2 per day in parts of Arizona and the desert areas of Southern California.

In all cost comparisons involving solar powered systems, the cost of solar energy is compared over a 30-year period to that of the least costly conventional energy source on the assumption that sufficient supplies of those sources will be available at the projected prices. Costs for pumps and wells were not included in the analysis because these costs are common to both solar power and conventional power systems. Costs for pump drive units were also excluded from the present analysis because it was assumed that existing electric motor drives would be compatible with a solar thermal/ electric power unit, and no additional costs would be entailed. For the case of existing mechanical engine drives, it was assumed that conversion to lower cost conventional electric power (see discussion in Section 5) would take place prior to the introduction of solar power and, again, the electric motor drive would be available for use at no additional cost. Solar power system capital costs always include costs for an electric generator linked to the power turbine subsystem.

13.3 ANALYSIS RESULTS FOR BASE SCENARIO

The methodology used to calculate the annualized conventional fuel cost (AFC) was described in Section 9. The AFC for each of the study regions has been calculated and displayed in Figure 13-3. These values are expressed as constant 1977 dollars per acre-foot per foot of life, and were annualized for a 30-year period using a 5 percent discount rate. The AFCs were also calculated using a 2.5 percent discount rate, but they are higher than the values shown by only about 3 percent. As shown, the values range from a low of \$0.056 in Idaho to a high of \$0.124 in southeastern Arizona. Much of the variation in the values is due to differences in the availability of low cost hydropower for electricity. For example, much of

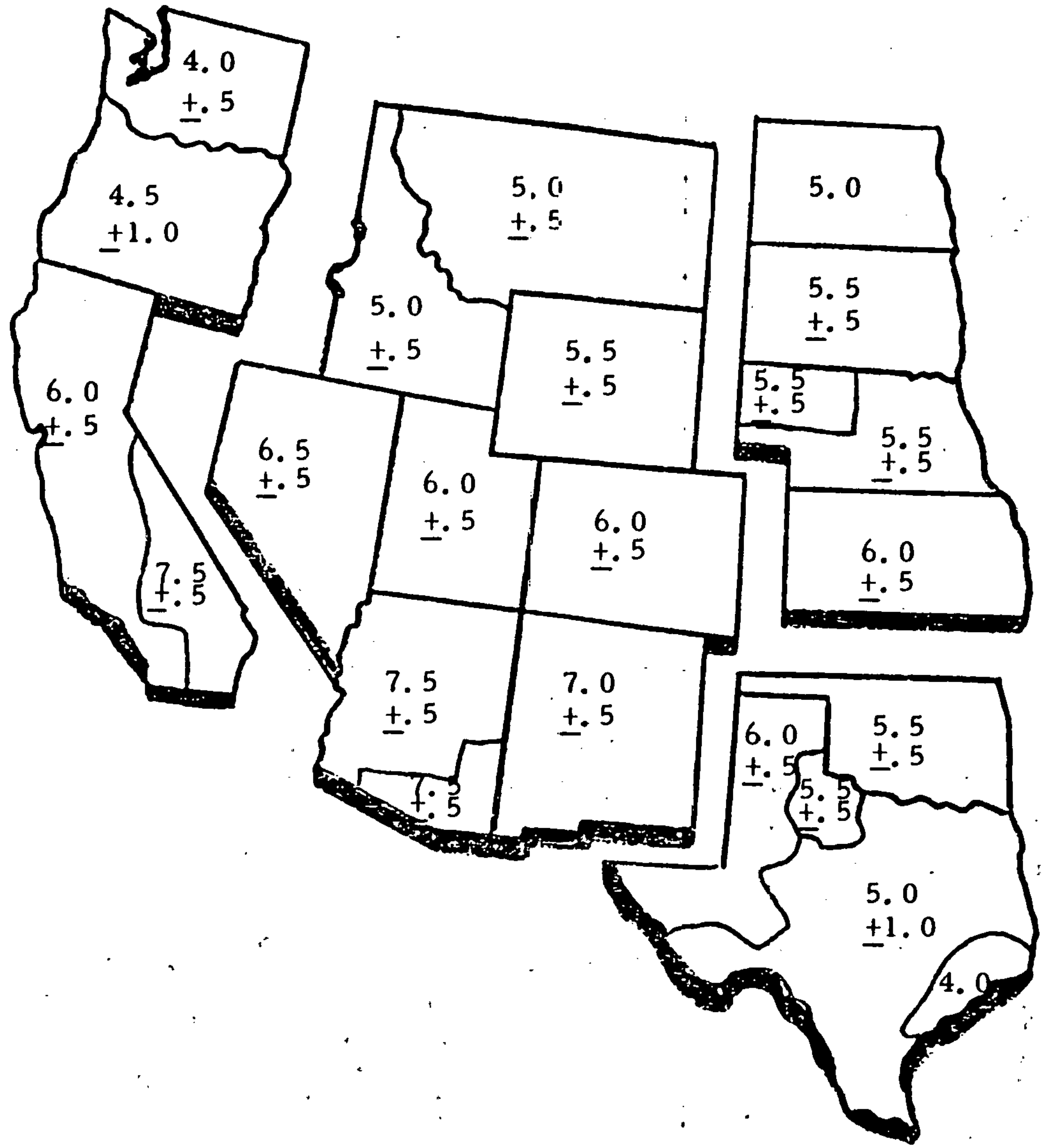
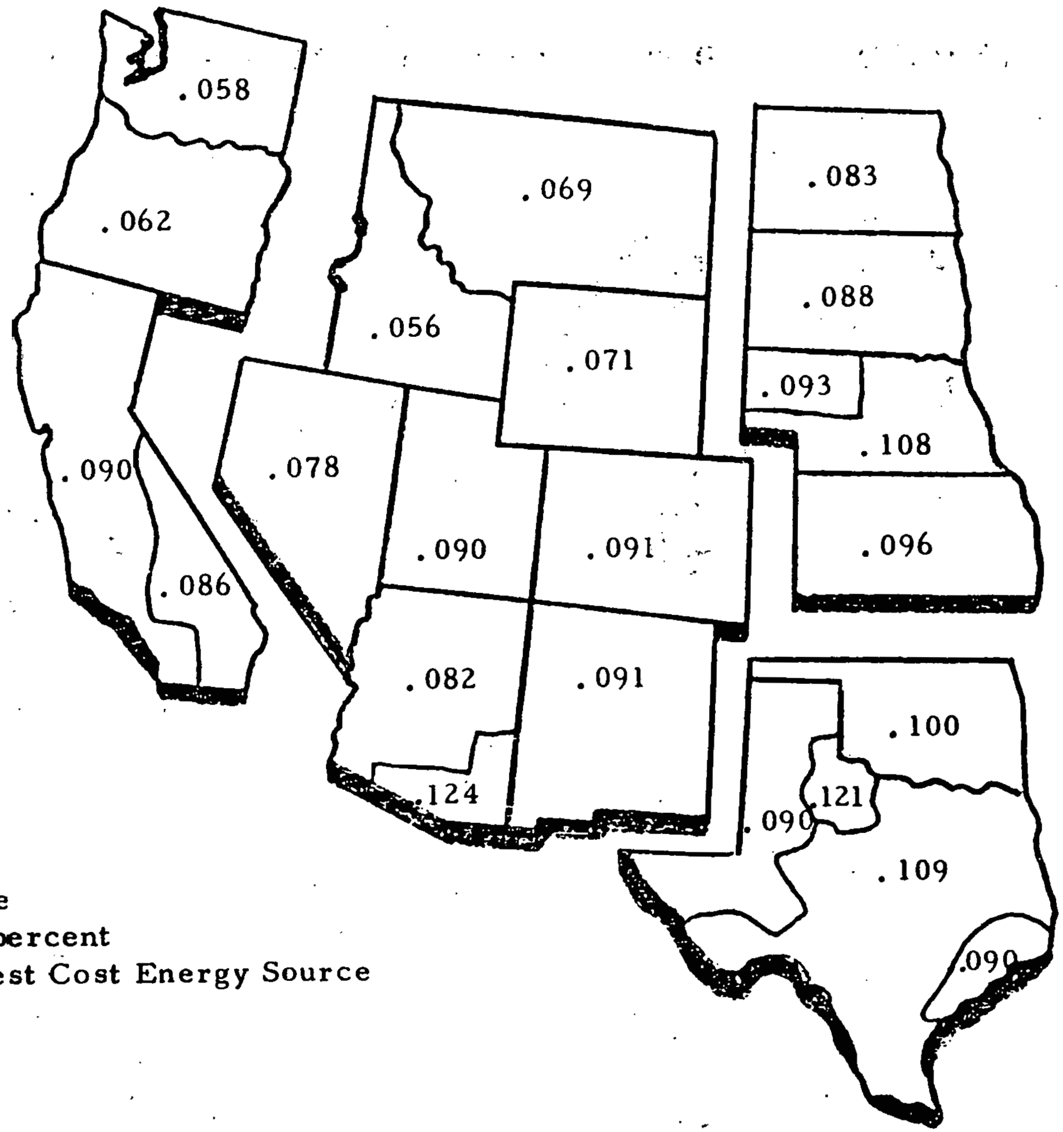


Figure 13-2. Average Daily Direct Solar Insolation (kWh/m^2 Day)



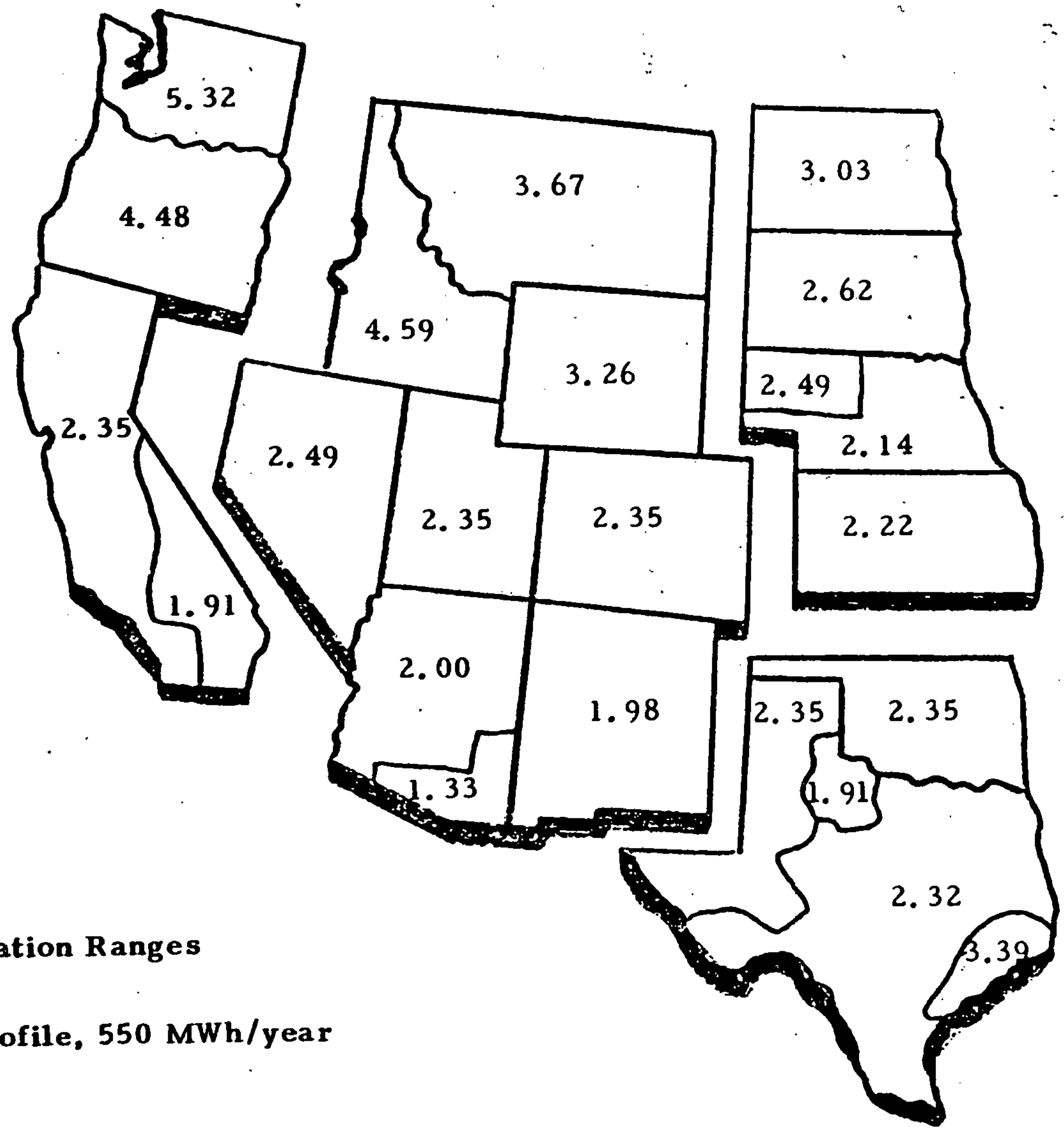
Smallest Farm Size
Discount Rate = 5 percent
Costs are for Lowest Cost Energy Source

Figure 13-3. Annualized Conventional Energy Costs, 1985-2015
(1977 $/Acre-Foot Per Foot of Lift)

the Arizona irrigated land has access to electricity generated by federally-sponsored hydropower projects along the Colorado and Salt Rivers. This is reflected in an AFC of $0.082 which is much lower than the AFC for the southeastern part of the state served by investor- or municipally-owned electric power utilities competing with increasingly higher-priced and scarce natural gas energy sources. All of the values shown are for the least costly conventional energy source which, in most states, was found to be electricity when annualized over the 30-year period.

Using the methodology described previously, Equivalent Cost Ratios (ECRs) have been calculated for each of the study regions. These ECRs have been expressed as intervals, with the endpoints given by the ranges of insolation values within a region. The values for a system purchased in 1985 and operated until 2015 are shown in Figure 13-4 for farms of the smallest size, for which the annualized cost rate (ACR) is 0.093. Larger farms and electric co-ops will have ECRs which are smaller in proportion to their ACR. The ECRs shown vary from a low of 1.33 in southeastern Arizona to a high of 5.32 in Washington. As may have been expected, the most favorable regions for solar energy are in the southern group of states, where insolation levels are high and low-cost energy sources are less common. By way of comparison, more favorable results are obtained for the largest farms, (e.g., the ECR for large farms in southeastern Arizona is very close to 1.00).

The ultimate significance of a low ECR value depends on the amount of energy consumed for irrigation pumping within a given region. That energy use has been previously estimated by Aerospace for each county in the 17 western states, and is shown distributed by region in Figure 13-5. If the current mix of pump drive units were to be converted to electric motor drives prior to introduction of solar power units, the energy used for irrigation from groundwater sources is estimated as 27.3×10^9 kWh



Mean Value of Insolation Ranges
Smallest Farm Size
Leveled Demand Profile, 550 MWh/year

Figure 13-4. Equivalent Cost Ratios For 1985 Solar Irrigation System

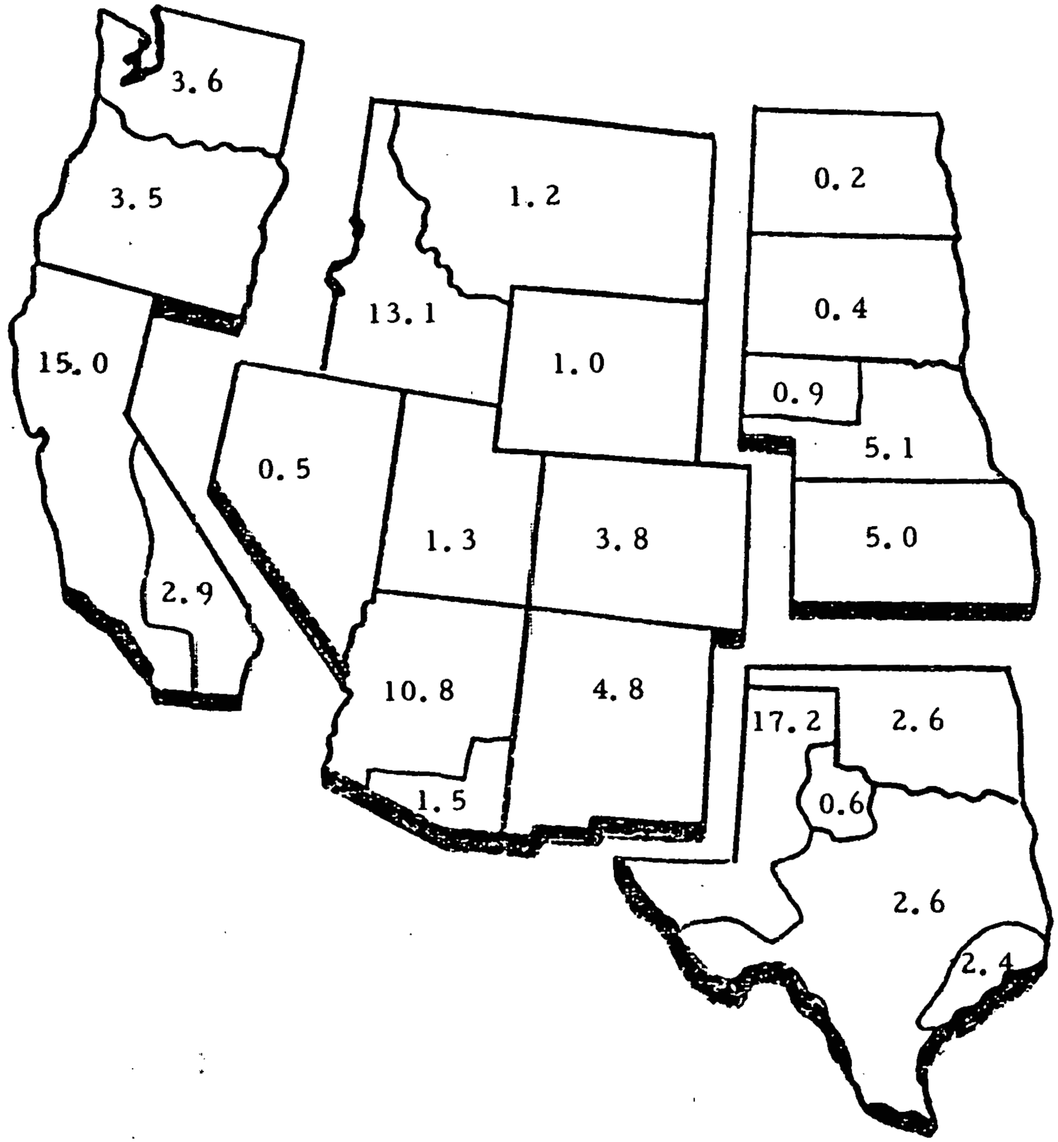


Figure 13.-5. Distribution of Energy Consumption For Irrigation From Groundwater, 1969 (Percent of 17 State Total)

for 1969*. Because the amount of irrigated acreage has increased significantly since 1969, energy consumption can be assumed to have also increased. For purposes of this analysis, however, only the regional fractions of the 17-state energy total will be used.

While values for ECRs are greater than unity everywhere, several factors could lower those estimates. For example, the system capital cost per kilowatt could be expected to decrease over time because of improved production/installation efficiencies or improved design efficiencies. The cost reductions necessary to produce an ECR equal to unity are best shown by recalling the formula for ECR:

$$ECR = \frac{ACR \times CC}{FD \times AFC} \qquad (13\text{-}2)$$

Any change in system capital costs (CC) will have a proportionately equal effect on ECR, viz:

$$\frac{CC_{rev.}}{CC_{orig.}} = \frac{ECR_{rev.}}{ECR_{orig.}} \qquad (13\text{-}3)$$

Hence,

$$CC_{rev.} = \frac{CC_{orig.}}{ECR_{orig.}} \quad \text{for } ECR_{rev.} = 1 \qquad (13\text{-}4)$$

Regions for which the current estimates of ECR are relatively low will require only small decreases in capital costs to achieve solar system cost parity. Alternatively, regions with high ECRs will require larger capital cost decreases. The cost reduction factor, $(\frac{1}{ECR})$, thus represents goals at which each region becomes part of the market potential for solar energy systems. As the solar system costs fall, more and more regions achieve cost parity and the market potential grows.

The effect of capital cost decreases on the ultimate (complete fuel displacement by solar system) market potential for solar irrigation

*More recent 1974 data have just recently been summarized by the U.S. Bureau of the Census and were not available when Aerospace completed the Irrigation Market Energy Demand Computer Program.

systems is shown graphically in Figure 13-6. The capital cost goals required for each level of market potential are expressed as a percent of system baseline capital cost which is shown in the figure. The baseline cost was estimated for 1985 system installation and is based on collector costs of $14 per square foot, high temperature storage costs of $4500 per million Btu's, and combined turbine and generator costs of $400 per kW_e. The level of these baseline costs is illustrated by the example shown of an 80 kW_e system that costs $4700 per kW_e in constant 1977 dollars.

The potential market for solar power is expressed as a percent of the total energy consumed for irrigation by groundwater in the 17 western states. Two market potential curves are shown - one for small farms, and one for large farms. These curves represent bounding cases for impact of ownership on solar irrigation system market potential, because of the effect of farm size on income tax bracket and the resultant effect on economic attractiveness of these systems when compared to conventional energy sources. (Further work could result in refined estimates of market potential by considering the actual distribution of farm size within the various geographic regions.) Both curves exhibit similar characteristics, however. They show that the initial markets will be available on a small scale in certain geographic areas which are characterized by high insolation levels and expected high costs for conventional energy sources. Inroads by solar energy into larger markets will depend on major cost reductions for solar systems. However, once those lower cost goals are realized, the markets become accessible very rapidly. For example, the curve for large farms shows that as solar costs fall from 65 percent of the baseline values to 45 percent, the potential sales increase from only 5 percent to over 80 percent of the entire market. Thus, in this example, the 65 percent cost goal could be a demarcation point, after which rapid access to irrigation markets could be expected.

As is noted in Figure 13-6, the market potential curves shown assume that the individual solar-powered irrigation systems are able to

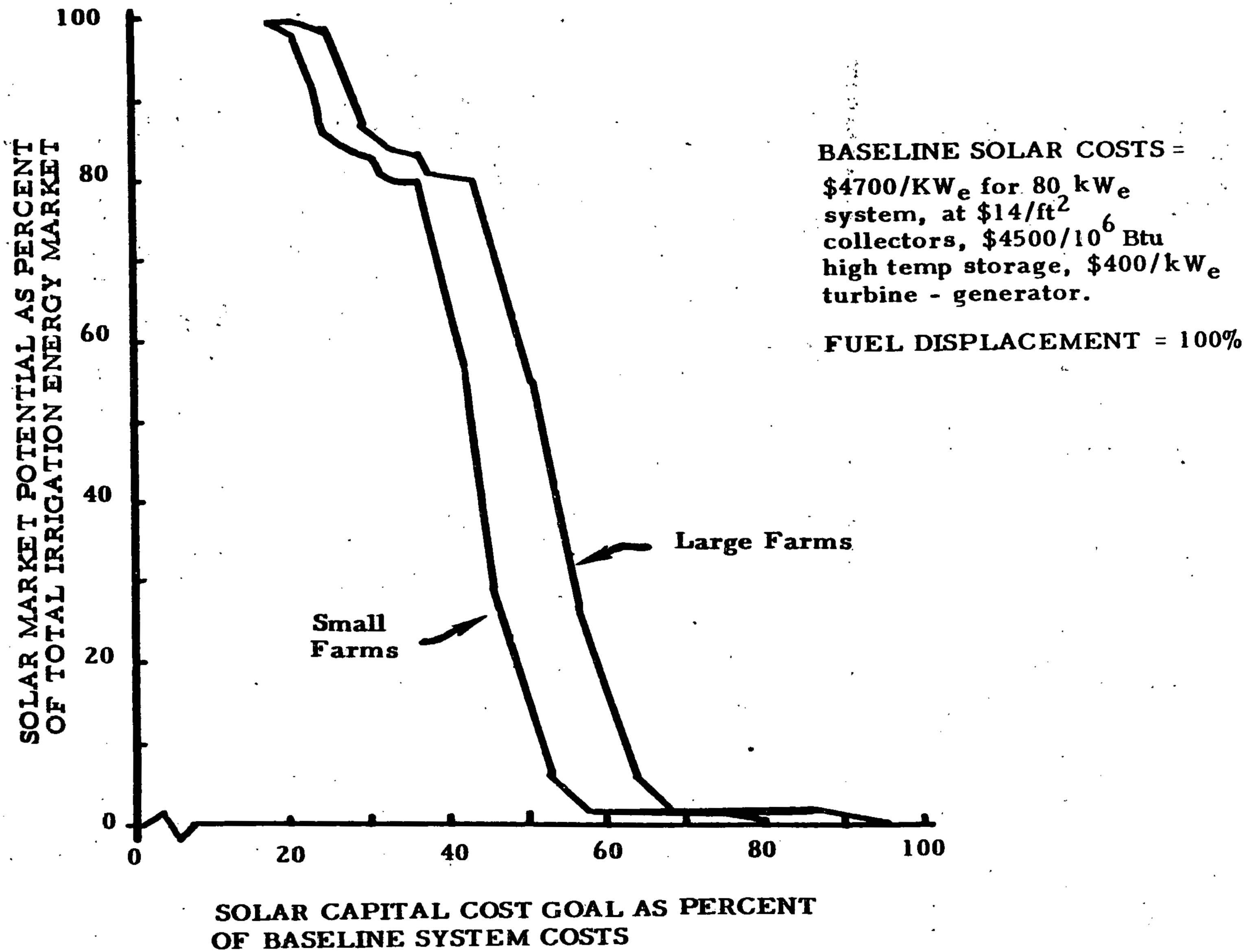


Figure 13-6. Solar Irrigation System Market Potential As a Function of 1985 System Capital Costs

displace all of the conventional energy. Detailed Aerospace analysis has shown, however, that it is often more cost effective (as judged by a minimum value for ECR) to design a solar system which displaces only a portion of the energy for irrigation. This is illustrated in Figure 13-7 where market potential curves are shown for different levels of fuel displacement (100%, 75% and 50%) which are assumed to apply uniformly to all markets. For clarity, only the curves for large farms are shown. The curve for 100 percent displacement is identical to the curve in Figure 13-6 for large farms. The curves for lower fuel displacement illustrate the lower market potential achievable at each capital cost goal. The capital cost goal required for initial market access and the goal required for major market access are unchanged, however.

For years beyond 1985, at least two factors will increase the economic attractiveness of solar energy systems for irrigation pumping. First, the costs of conventional energy sources are expected to increase, as shown previously in Section 5. Second, the capital cost of solar irrigation systems may be expected to decrease beyond the cost estimated for 1985. The effect of rising conventional energy costs is illustrated in Figure 13-8, where market potential curves are shown for both 1985 and the year 2000 for the large farm sector. To obtain the curve for the year 2000, solar costs were not modified between 1985 and 2000, nor were insolation levels and geographic distribution of irrigation energy consumption revised. The annualized conventional fuel costs were based on those costs which have been projected for the period 2000-2030. The solar cost goal required for establishment of an initial market potential relaxes from about 95 percent of the baseline costs in 1985 to over 110 percent of baseline costs in 2000. Similarly, the market potential achievable at any given cost goal is increased over time.

13.4 ANALYSIS RESULTS FOR ALTERNATIVE SCENARIO

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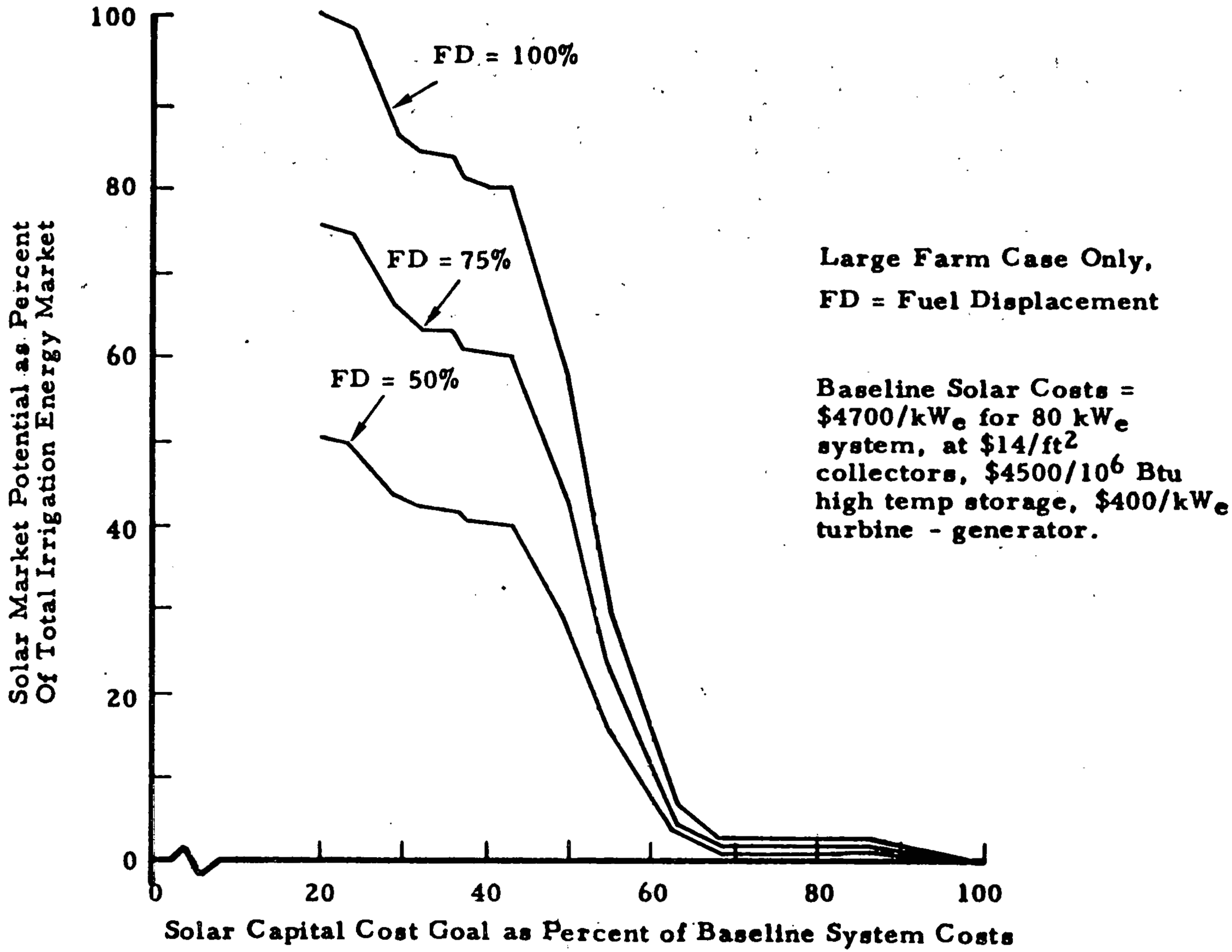

Figure 13-7. Effects of Fuel Displacement on Solar Energy Market Potential, 1985

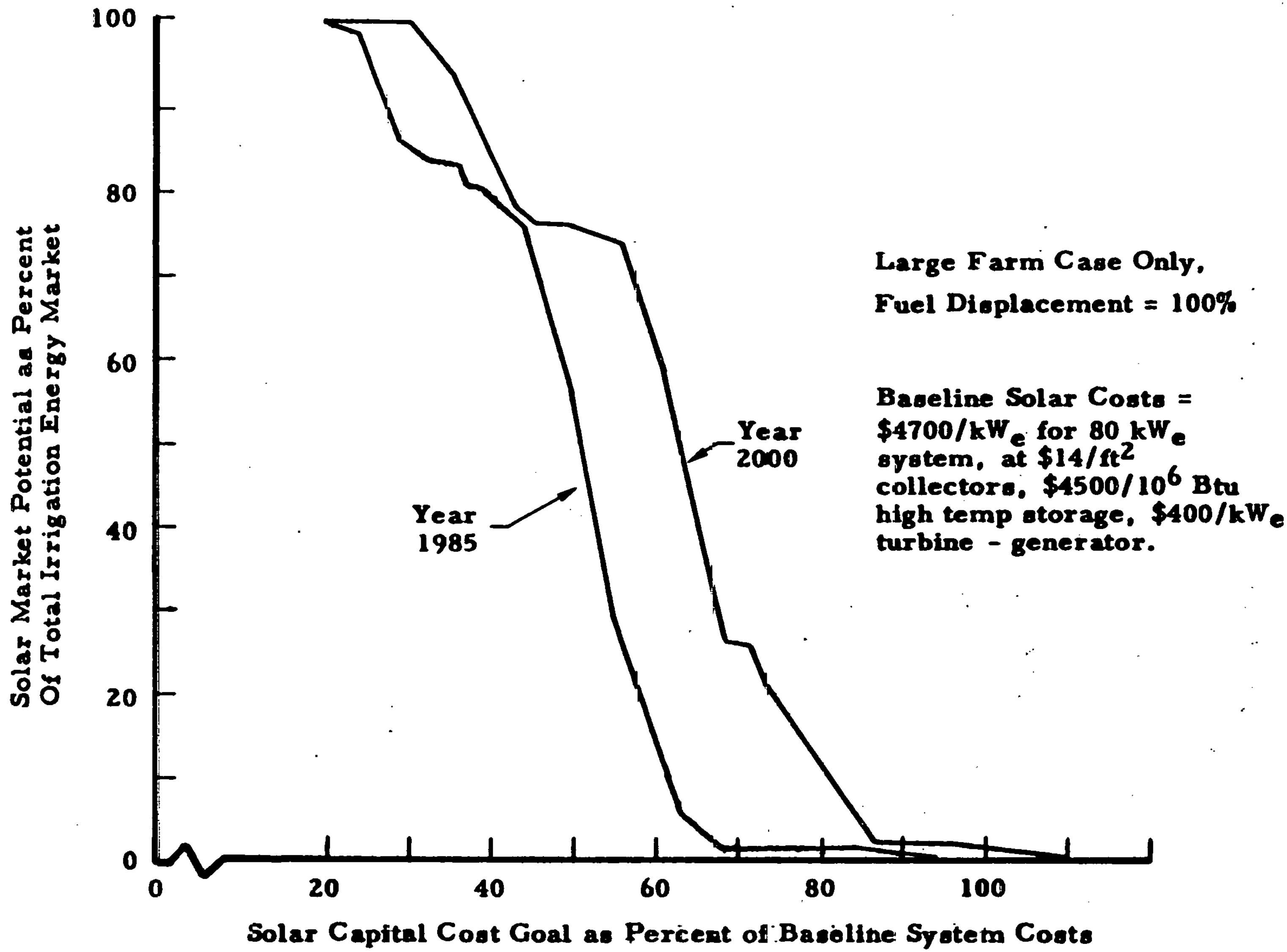

Figure 13-8. Effects of Time on Solar Energy Market Potential

14. ASSESSMENT OF STUDY RESULTS

14.1 PRINCIPAL STUDY FINDINGS

(This Section in Preparation)

14.2 NATIONAL BENEFITS AND COSTS ISSUES

(This Section in Preparation)

14.3 GOVERNMENT POLICY ISSUES

(This Section in Preparation)

14.4 IMPACT ON PROGRAM PLANS

(This Section in Preparation)

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