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Preliminary Economic Analysis of Solar Irrigation Systems (SIS) for Selected Locations

Laurance L. Lukens, Audrey M. Perino, Sharla G. Vandevender

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PRELIMINARY ECONOMIC ANALYSIS OF SOLAR IRRIGATION SYSTEMS (SIS) FOR SELECTED LOCATIONS

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ABSTRACT

This paper describes a preliminary analysis of the economic feasibility of stand-alone solar irrigation systems (SIS) for certain applications in various locations. The economic feasibility was determined by comparing the life cycle cost (LCC) of the solar system to the LCC of conventional systems. The systems analyzed in this paper were point studies and do not represent either worst case or best case conditions. Therefore, general conclusions should not be drawn on the results presented here. The results show that for these cases, economic feasibility is dependent on utilization of the SIS for production of energy in addition to that required to water crops. In Southern Arizona, the LCC of the SIS, when used only to pump water, ranges from 3 to 1.7 times that of a conventional electric system for start-up dates of 1980 and 1990. For the same system, the LCC ratio ranges from 1.6 to 0.9 when 100% utilization of the system capacity is achieved. The feasibility of a hybrid system was also examined for Arizona. This system purchased 21% of the required power, yet the hybrid LCC was only 90% of that of a conventional electric system with a 1990 start-up date. Future studies will include a broad-scale parameter sensitivity analysis to determine which parameters most effect the SIS economic feasibility. Hybrid SIS will be examined in more detail. Alternative uses will be sought which will provide greater utilization of the SIS capacity. The effects of government incentives will be determined.

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PRELIMINARY ECONOMIC ANALYSIS OF SOLAR IRRIGATION SYSTEMS (SIS) FOR SELECTED LOCATIONS

SUMMARY

This paper describes a preliminary analysis of the economic feasibility of stand-alone solar irrigation systems for certain applications in various locations. The system configuration used was similar to that being used in the ERDA/NM solar irrigation experiment. Locations were chosen on the basis of the 1969 Census of Agriculture and on the irrigation energy weight ranking of the western states. The crops considered were chosen from the principal crops in each region. System costs were based on industry estimates of production costs. The system components were sized to minimize capital cost and meet the specific crop water demand identified for each location. The economic feasibility was determined by comparing the life cycle cost (LCC) of the solar system to the life cycle cost of conventional systems.

Based on the above assumptions, the results show the economic feasibility of a stand-alone solar irrigation system for open-ditch irrigation in each location. In southern Arizona the LCC of a stand-alone SIS is 1.5 to 3 times greater than that of a conventional electric system when used only for irrigation and operation is begun between 1980 and 1990. However, the SIS becomes competitive when 100% of the system capacity is utilized throughout the year. This indicates that solar irrigation can be made feasible if the systems can be incorporated into the farm as a power or heat source rather than solely as an irrigation energy source. If government incentives are established, this SIS can be made competitive even earlier. One incentive was examined which would make the SIS less costly than a conventional electric system by 1990. The combination of 100% utilization and the incentive brought the system life cycle cost to less than half that of electricity.

SIS were also designed for five other areas. In the San Joaquin Valley of California, the SIS LCC is 2 to 4 times that of electricity. In northwestern Nebraska, the LCC is 3.5 to 6.5 times higher than electricity or diesel powered systems. In central New Mexico the LCC is 2.5 to 5 times higher than electricity or natural gas. The case study in southeastern Oregon demonstrates the difficulty of competing against inexpensive hydroelectricity--the LCC of the SIS is 4.5 to 9 times higher. Comparison against electricity for a double crop in the southern High

Plains of Texas showed the SIS to have an LCC 2 to 4 times higher than electricity.

The feasibility of a "hybrid" system was examined for southern Arizona. This system was solar powered with an electrical backup capability. For the case considered, the hybrid becomes economical by 1990 without government incentives or utilization of total system capacity during the off-season. This indicates that where possible, SIS should not necessarily be designed to be self-sufficient.

The need for additional analysis should be emphasized. Sensitivity analyses are necessary to determine which parameters will control the feasibility of converting to solar power in the various irrigating regions of the U.S. In every case studied, the parameters considered were a "snapshot" of actual conditions; they do not represent either worst case or best case conditions. Therefore, general conclusions should not be drawn except for indications of future work which must be done to fully analyze the economic feasibility of solar powered irrigation.

DEFINITION

The locations and crops chosen were based on cropping patterns identified in the 1969 Census of Irrigated Agriculture and on the energy weight ranking of the states. Each of the locations* was shown in 1969 to be an area with a high density of irrigated acreage. Although the 1974 census is not yet available, other surveys have shown the density of irrigated acreage in these areas to be increasing significantly. The areas are important for consideration of alternatives to conventional energy sources because they all have high energy weight rankings. The energy rank was determined by the following weighting scheme:**

$$W = (A_S \times \bar{L}_S + A_G \times \bar{L}_G + A_{S+G} \times \bar{L}_{\max(S,G)})\ \bar{D}$$

where

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*Except central New Mexico.

**The weighting utilizes data from Sloggett, G., "Energy Used for Pumping Irrigation Water."

W = weight

A_S = acres irrigated by pumped surface water

A_G = acres irrigated by pumped groundwater

A_{S+G} = acres irrigated from both sources

$\bar{L}_S$ = average lift for pumped surface water in feet

$\bar{L}_G$ = average lift for pumped groundwater in feet

$\bar{L}_{max(S,G)}$ = maximum of average lifts

$\bar{D}$ = average water demand in acre-feet/acre.

Table I shows the energy-weight rank of the first 20 states for surface water pumping, groundwater pumping and the combined rank. Figure 1 shows a preliminary regionalization of the states based on irrigation density and energy priority. Table II shows the principal crops of each of the regions identified in Figure 1.

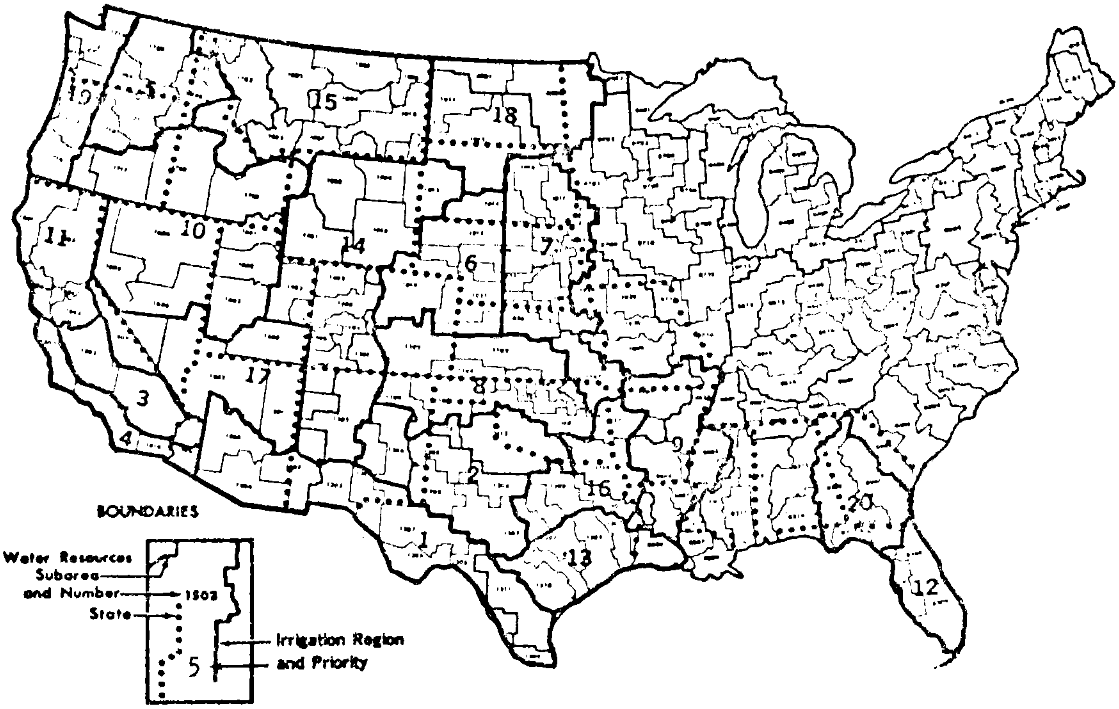


Figure 1. Map of Regions to be Considered in the Solar Irrigation Program, Showing Order of Priority (Preliminary Regionalization)

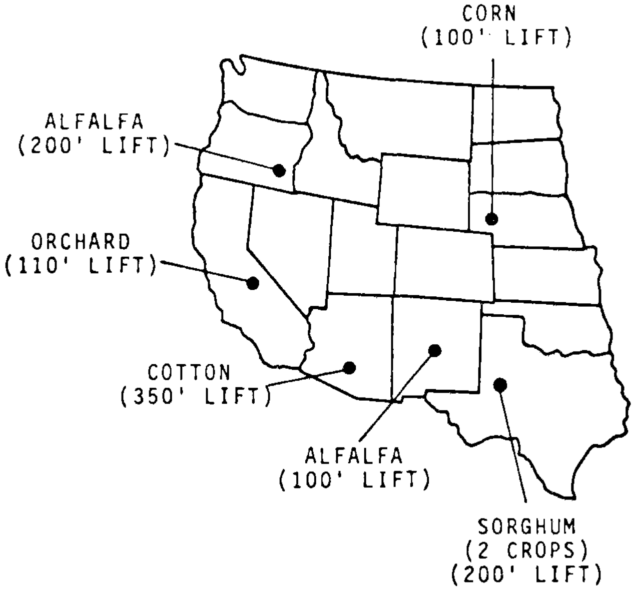
TABLE I

Energy-Weight Rank of States for Irrigation Pumping

	On-Farm Surface Water Pumping Only	On-Farm Groundwater Pumping Only	On-Farm Pumping of Ground or Surface Water
1	Washington	Texas	Texas
2	Oregon	California	Arizona
3	Mississippi	Arizona	California
4	Texas	Nebraska	Washington
5	Montana	Kansas	Nebraska
6	Nebraska	Idaho	New Mexico
7	South Dakota	New Mexico	Kansas
8	California	Hawaii	Idaho
9	Arkansas	Oklahoma	Oregon
10	Louisiana	Washington	Hawaii
11	Utah	Nevada	Mississippi
12	Florida	Arkansas	Oklahoma
13	Wyoming	Colorado	Colorado
14	Nevada	Utah	Nevada
15	North Carolina	Oregon	Arkansas
16	Kansas	Florida	Utah
17	Oklahoma	Louisiana	Louisiana
18	Georgia	Mississippi	Florida
19	Wisconsin	Wyoming	Montana
20	North Dakota	Georgia	Wyoming

Figure 2 shows the areas considered in this preliminary analysis, along with the crops, well lifts and the field description used in determining the irrigation demand on the solar power system. The well lifts chosen were averages for the areas considered. In each case, only an area within a state was considered, not the entire state. This should be emphasized because of the variability of climate, particularly rainfall and insolation, across each state. The areas included were southeastern Oregon, San Joaquin Valley of California, southern Arizona, central New Mexico, southern High Plains of Texas, and northwestern Nebraska.

The use of a common field description allowed the analysis to consider the effects of various utility rate structures and crop demands on



FIELD SIZE:	120 ACRES
SOIL TYPE:	DEEP, SANDY LOAM
SLOPE:	0.33%
READILY AVAILABLE MOISTURE:	1.5 IN/FT
IRRIGATION METHOD:	OPEN DITCH
DITCH EFFICIENCY:	80%
APPLICATION EFFICIENCY:	70%
LENGTH OF RUN:	1250 FT
FURROW STREAM SIZE:	30 GPM
FURROWS PER SET:	46
SETS PER FIELD:	30
SET TIME:	4-7 HOURS
WATER DELIVERY RATE:	1725 GPM

Figure 2. Study Areas and Field Parameters

a single management system. In each case a 120-acre field irrigated by an open-ditch, gravity-flow system was assumed. The field was divided into 30 sets of 4 acres each with 46 furrows (1250 feet long) per set. The irrigation system was designed to deliver 0.77 set-inches per hour. The water delivery rate to the ditch was 1725 gpm. The system was assumed to have an 80% ditch efficiency and a 70% application efficiency. The soil considered was deep sandy loam with a readily available moisture capacity of 1.5 inches per foot.

The crop water demand for the selected crops was based on average consumptive use data provided by irrigation specialists in each area. The irrigation schedule was determined by comparing the crop demand per day to the water stored in the active root zone. No more than 50% depletion of the readily available moisture was allowed. The average rainfall of the area was utilized to partially satisfy the crop water demand. Where soil moisture was expected to be low at planting time, preplant irrigations were scheduled to provide a full soil moisture profile in the root zone. The irrigation schedule defines the demand for energy from the SIS. The consumptive use data and irrigation demands are shown in Figures 3 through 14.

TABLE II

Regionalization of Irrigated Agriculture (1969 Census)

(Acres in Thousands)

Region	Acres[a]	Principal Crops	Acres	Second Crop	Acres	Third Crop	Acres	Fourth Crop	Acres
1	2125	Cotton	670	Sorghum	380	Hay	139	Barley	123
2	3981	Sorghum	1514	Cotton	1454	Wheat	384	Hay	68
3	2930	Orchard	605	Cotton	564	Barley	338	Hay	77
4	1106	Vegetables	307	Hay	250	Orchard	150	Barley	63
5	1533	Hay	482	Wheat	162	Orchard	156	Pasture[b]	95
6	2453	Corn	1119	Hay	404	Small Grain	80	Sorghum	20
7	1707	Corn	1311	Sorghum	114	Hay	74	Soybean	10
8	2999	Sorghum	1114	Wheat	780	Corn	493	Pasture	85
9	1300	Rice	600	Soybean	421	Cotton	247	Corn	37
10	1170	Hay	756	Pasture	295	Barley	62	Corn	19
11	3425	Orchard	693	Hay	688	Pasture	486	Grain	469
12	1300	Orchard	682	Pasture	309	Vegetables	280	Potatoes	26
13	1314	Rice	1176	Peanuts	31	Cotton	22	Pasture	17
14	2812	Hay	1535	Pasture	1002	Barley	162	Corn	133
15	2141	Hay	1528	Pasture	524	Grain	99	Barley	97
16	172	Cotton	62	Peanuts	29	Pasture	25	Hay	17
17	140	Hay	78	Pasture	64	Barley	4	Cotton	3
18	111	Hay	45	Corn	18	Grain	9	Wheat	5
19	346	Pasture	85	Hay	76	Sweet Corn	26	Beans	24
20	97	Tobacco	25	Peanuts	19	Corn	16	Vegetables	13

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[a] Cropland irrigated acres.

[b] Wherever "pasture" occurrs, it includes both "cropland pasture" and "other irrigated pasture" so that cropland acres is not necessarily the sum of all irrigated acres.

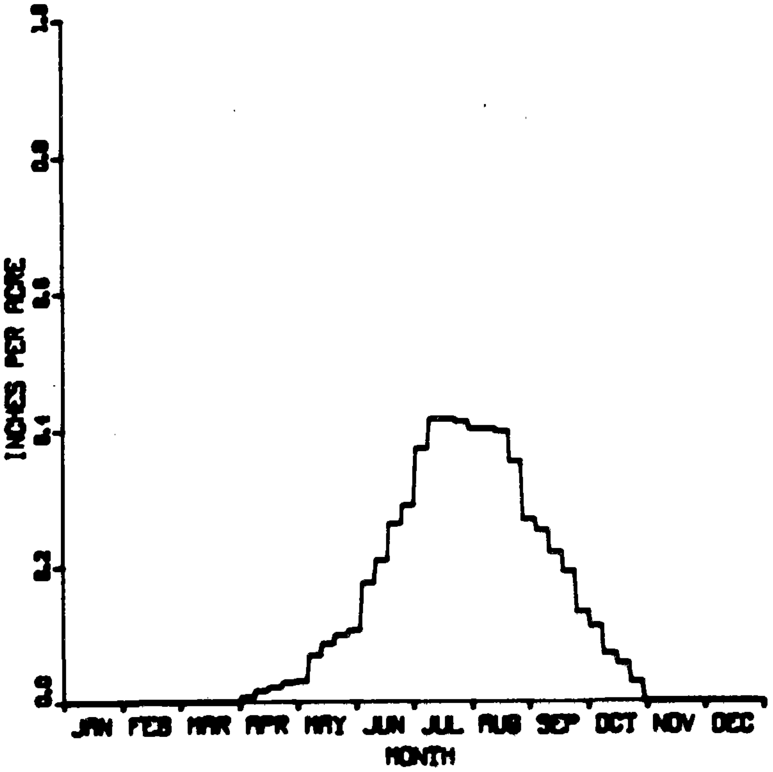

Figure 3. Consumptive Use of Water by Cotton in Southern Arizona

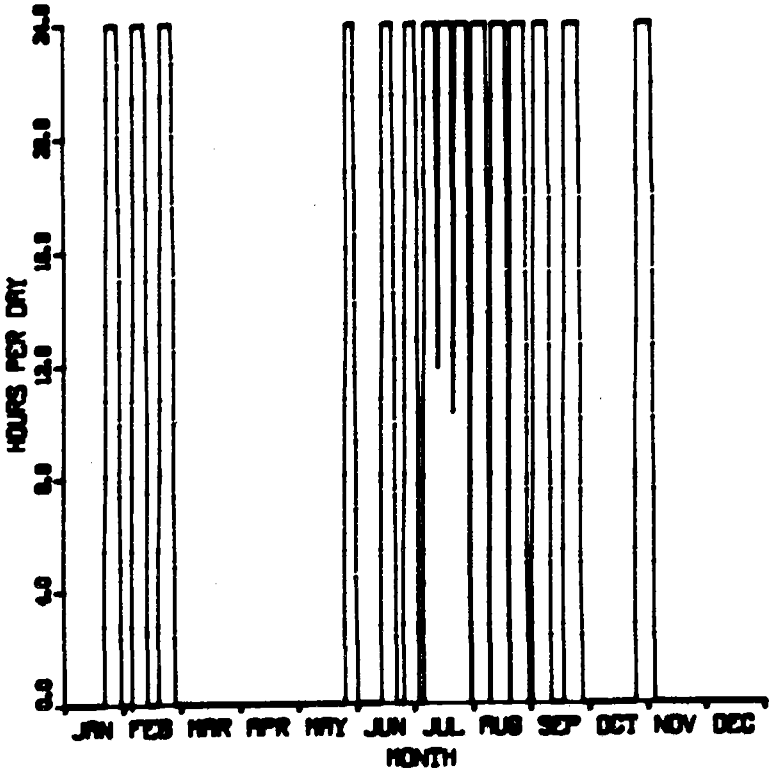

Figure 4. Solar Irrigation System Demand Southern Arizona

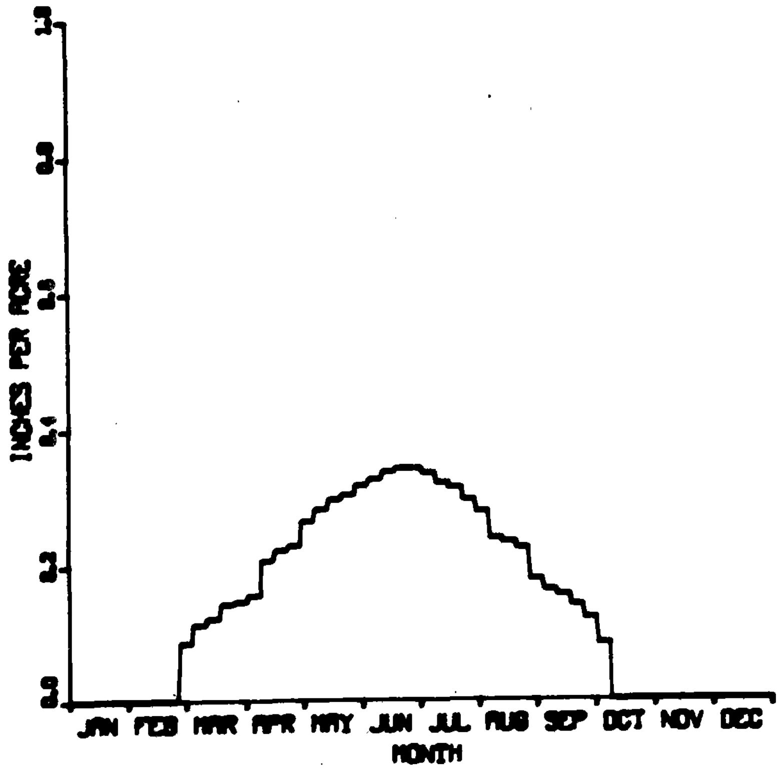

Figure 5. Consumptive Use of Water by an Orchard in the San Joaquin Valley, California

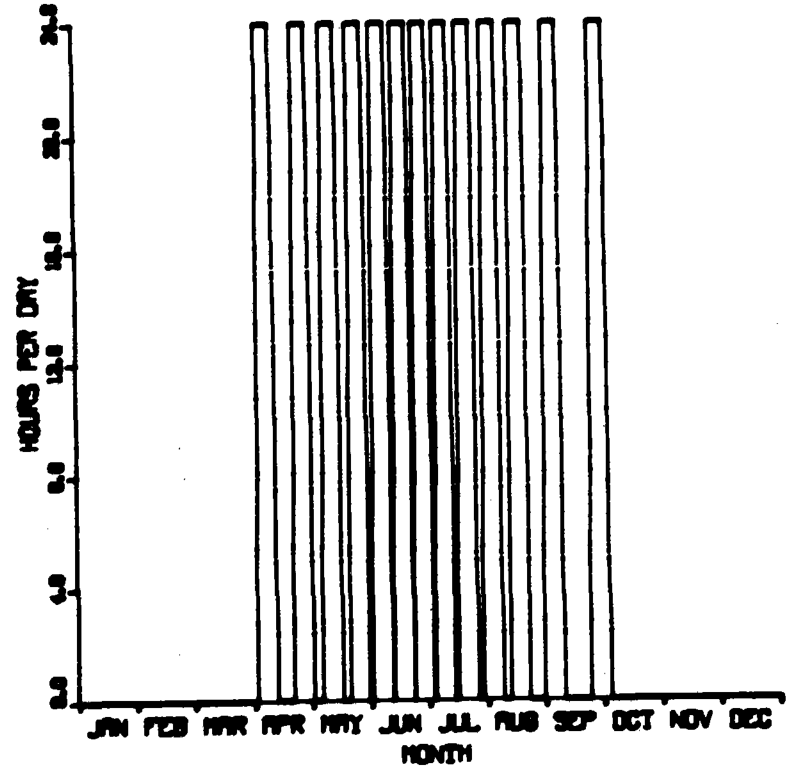

Figure 6. Solar Irrigation System Demand San Joaquin Valley, California

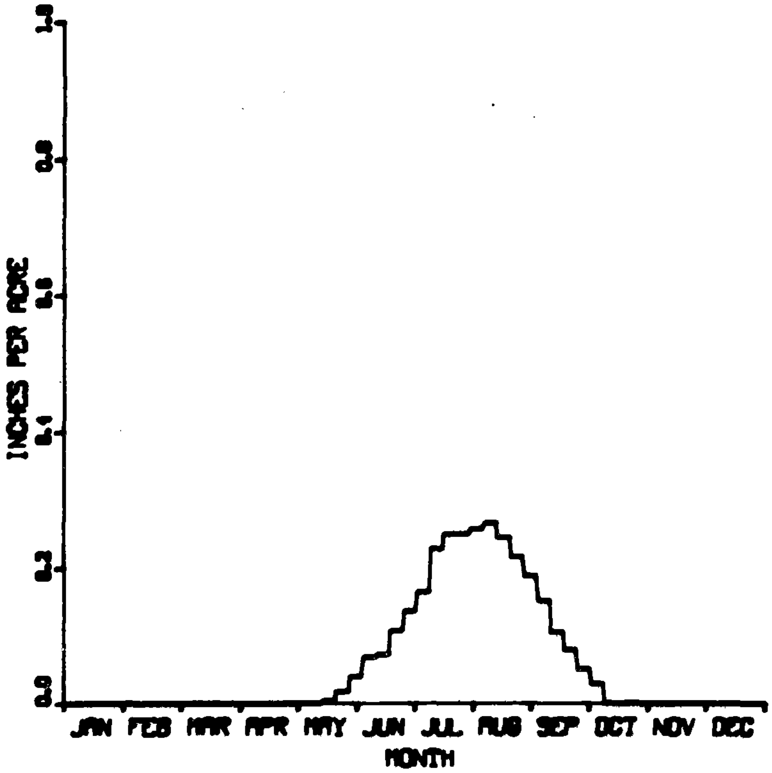

Figure 7. Consumptive Use of Water by Corn in Northwestern Nebraska

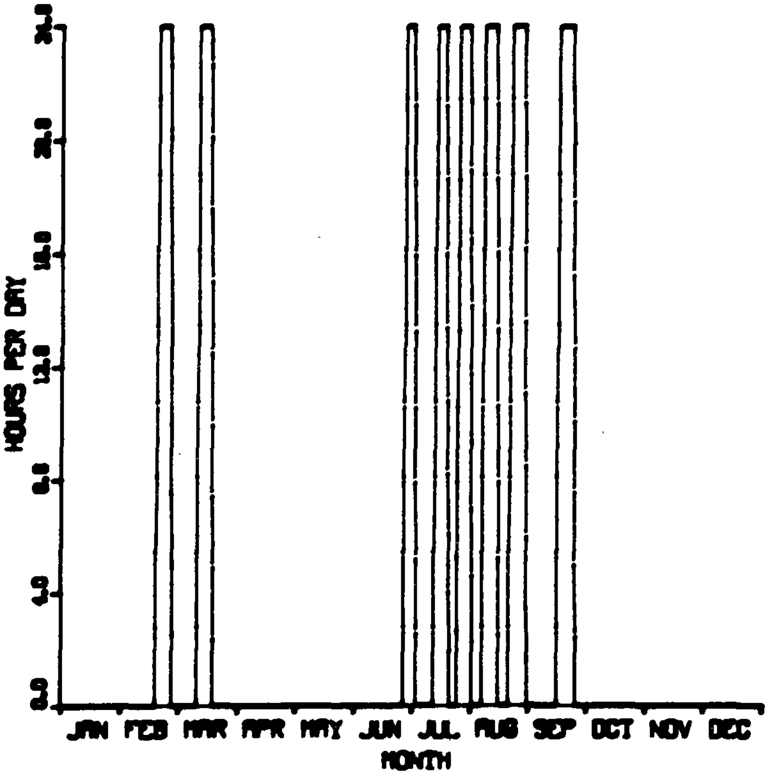

Figure 8. Solar Irrigation System Demand Northwestern Nebraska

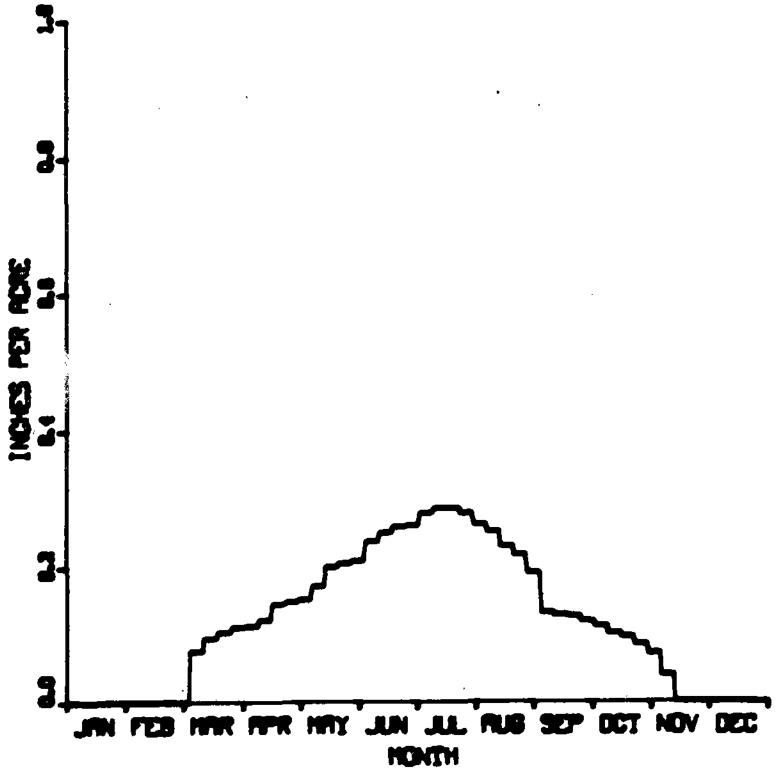

Figure 9. Consumptive Use of Water by Alfalfa in Central New Mexico

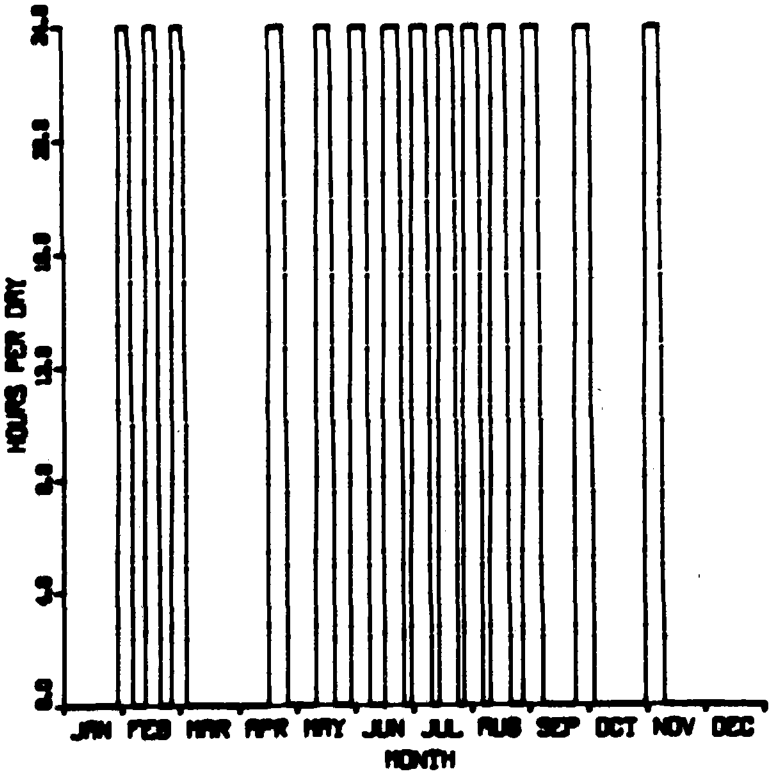

Figure 10. Solar Irrigation System Demand Central New Mexico

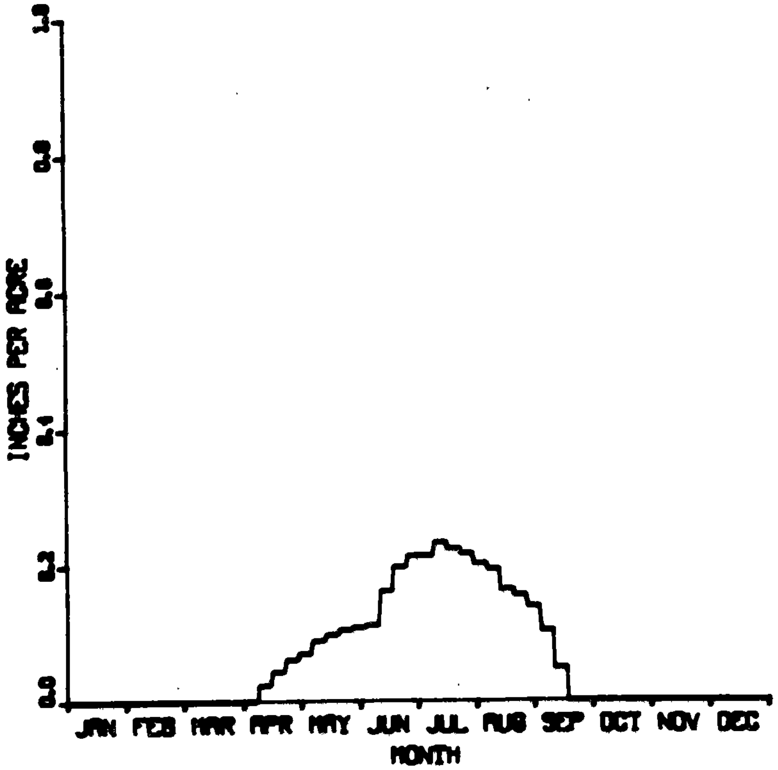

Figure 11. Consumptive Use of Water by Alfalfa in Southeastern Oregon

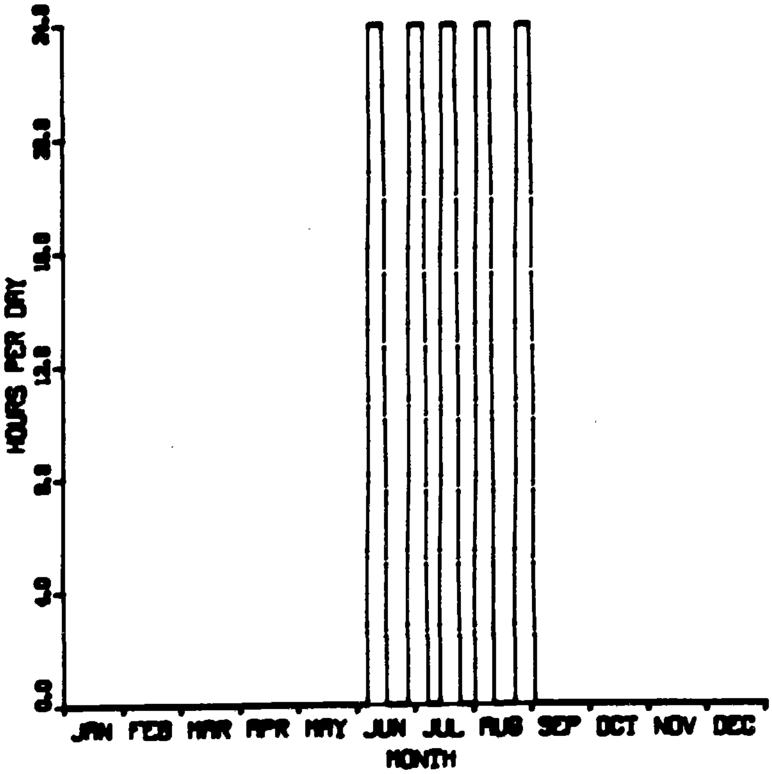

Figure 12. Solar Irrigation System Demand Southeastern Oregon

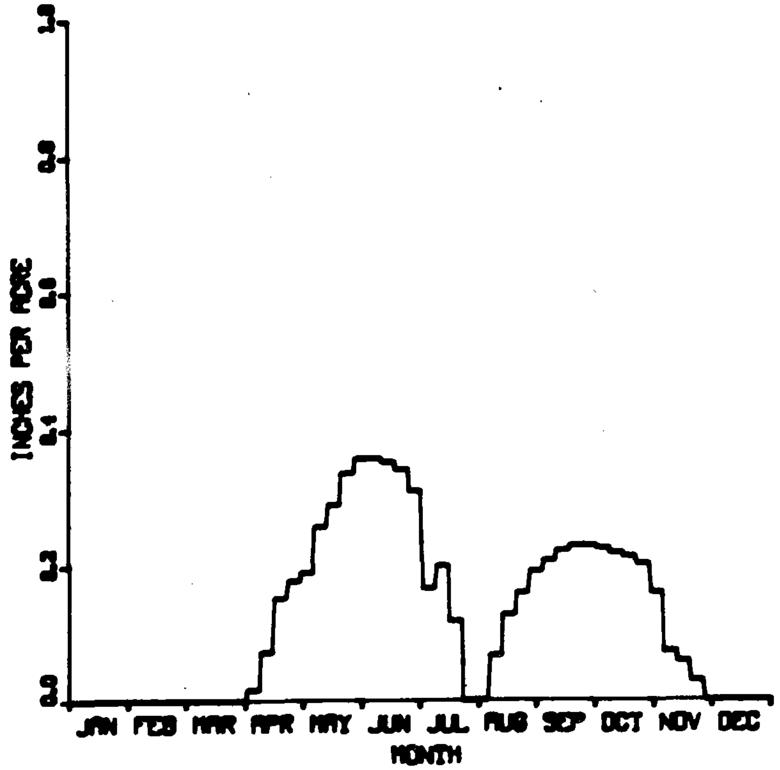

Figure 13. Consumptive Use of Water by Double-Cropped Sorghum in Southern High Plains, Texas

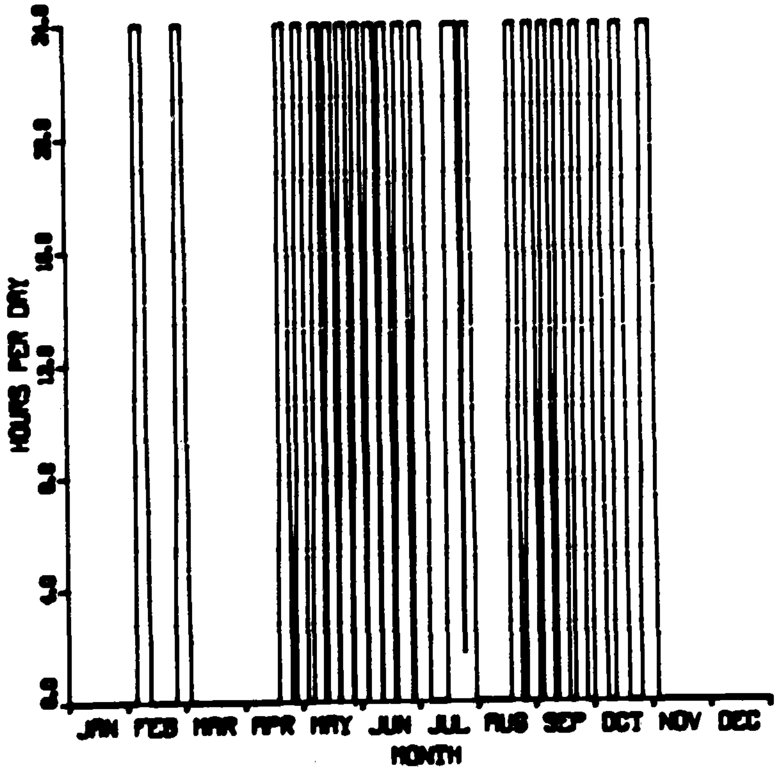

Figure 14. Solar Irrigation System Demand Southern High Plains, Texas

SOLAR IRRIGATION SYSTEM DESIGN

The solar irrigation systems (SIS) designed for this study were variations of a conceptual system. The conceptual design chosen for this study was very similar in its function and makeup to the system built for the ERDA/New Mexico Solar Irrigation Experiment. The systems were optimized to meet 100% of the irrigation energy demands of an area subject to the system parameters chosen and the solar insolation availability in that area.

An energy flow schematic of the SIS chosen for the system design is shown in Figure 15. Solar energy is captured by the collector field and converted to thermal energy. The thermal energy is delivered to one or both of the system's prime movers based on the system's needs or is stored in the thermal storage area for use when the amount of energy being collected is not sufficient to meet the demands of the prime movers. The prime movers convert thermal energy into mechanical energy which is used to pump water. One prime mover pumps water from a well into a water storage pond and the other prime mover pumps water from the pond to a field for irrigation use.

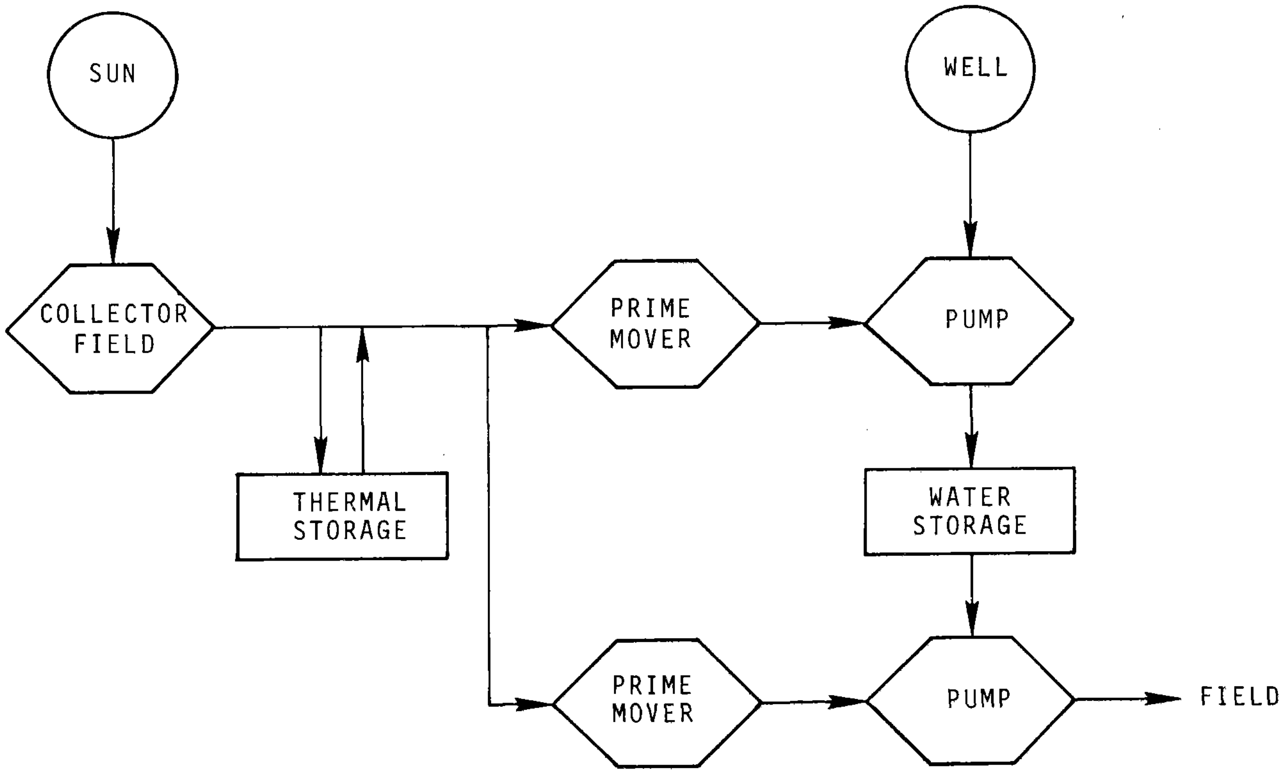

Figure 15. Stand-Alone Solar Irrigation System Energy Flow Schematic

The collector field used consisted of an array of parabolic trough concentrators. The collector efficiency was assumed to vary between 40.0 and 60.0 percent, as shown in Figure 16, for an output temperature of 420°F.

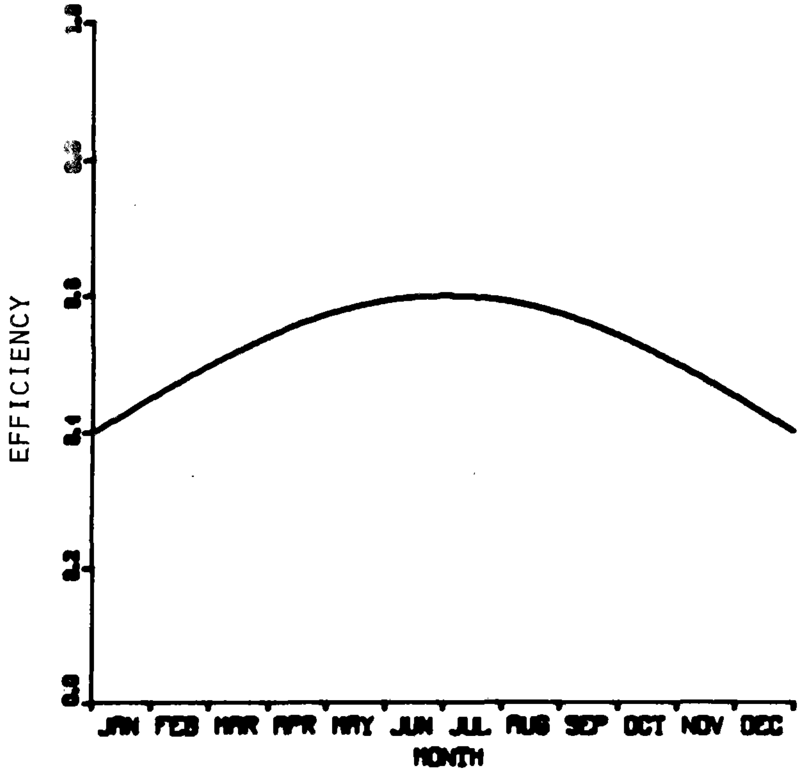

Figure 16. Collector Efficiency

Thermal storage for the system consisted of a thermocline fluid system in which the fluid, also used as the transfer fluid in the collector field, was assumed to be Caloria HT-43, a heat transfer oil. Any losses of energy from the thermal storage subsystem were considered negligible for the purposes of this study.

The prime movers used were organic Rankine cycle turbines using Freon 113 as a working fluid. They were assumed to have a thermal to mechanical energy conversion efficiency of 15 percent.

The pumping efficiency used was 70 percent, which is the combined efficiency of a pump and right-angle gear drive.

Water storage for the system was a fully lined pond approximately 20 feet in depth. Losses from a water storage pond consisted of seepage which was assumed to be zero due to the pond liner, and evaporation which was assumed to be approximately 6 feet per year for all of the regions studied.

A mathematical model of the SIS was developed for use in the optimization process. The model is run on an hourly energy flow basis and evaluates one full year of system operation. Input data for the model included pumping lift, irrigation water demand, and available direct normal solar insolation data for the region being studied. Solar insolation data for each region was approximated by applying monthly conversion factors derived for each region to an actual data tape of the hourly direct normal insolation for Albuquerque, New Mexico. The monthly conversion coefficients were the monthly fraction of the extraterrestrial radiation transmitted through the atmosphere for a city in the region being studied, divided by that of Albuquerque. These monthly fractions were obtained from Liu and Jordan.[***] The monthly conversion coefficients are shown in Table III. Irrigation demand for the model was in the form of hours of pumping per day, at the pumping rate and lift specified.

For optimization purposes four major parameters in the system model were varied: collector area, thermal storage capacity, water storage capacity, and the pumping rate from the well to the water storage pond. The optimization criteria were to minimize the system capital costs and satisfy the irrigation water demand. Total capital costs were the sum of the costs of the collector field, the thermal storage subsystem, the water storage subsystem and the two prime movers. Cost estimates used for this study were based on production cost estimates obtained indirectly from industry through work being done on the ERDA/New Mexico Solar Irrigation Experiment.[†] All system costs were held constant for this study with the exception of collector costs. Two values were used to bound expected collector costs. Table IV lists the unit costs used in this study.

The optimization methodology used involved a two-step procedure. The first part of the procedure required setting upper and lower limits on each of the four parameters outlined. Then through a random process, a parameter vector was chosen and input into the system model which would calculate the system capital costs and determine whether or not the irrigation demand was satisfied. This process would be repeated a given

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[***] Liu, B. H., and R. C. Jordan, "A Rational Procedure for Predicting the Long-Term Average Performance of Flat-Plate Solar Energy Collectors," Solar Energy, Vol. 7, No. 2, 1963.

[†] Private communication from R. L. Alvis, 5715.

number of times, retaining the parameter vector which had the minimum capital cost and still satisfied the demand. From this parameter vector, assumed to be in the region of the parameter vector of the optimal system, a pattern search was performed within a region around each parameter to find the optimal system.

TABLE III

Solar Conversion Coefficients
To be Applied to Albuquerque Data

City	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
Albuquerque	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Boise	0.634	0.771	0.762	0.823	0.868	0.856	0.984	0.932	0.901	0.827	0.722	0.628
Fresno	0.656	0.797	0.879	0.884	0.942	0.954	0.981	0.969	0.913	0.893	0.749	0.625
Midland	0.834	0.863	0.887	0.855	0.896	0.844	0.904	0.908	0.882	0.844	0.890	0.868
Phoenix	0.923	1.0	0.996	1.008	1.056	1.011	0.96	0.956	0.992	0.996	0.961	0.926
Rapid City	0.854	0.907	0.903	0.823	0.805	0.791	0.881	0.879	0.863	0.878	0.827	0.835

TABLE IV

Component-Subsystem Costs

Subsystem	Units	Unit Cost ($/Unit)	Fixed Cost (1978$)
Collector Field			
(Upper)	Ft^2	10.00	0.00
(Lower)	Ft^2	5.00	0.00
Collector Installation	Ft^2	1.20	0.00
Prime Movers	kW	223.95	11775.00
Thermal Storage	10^6 Btu	2500.00	0.00
Water Storage*	Gal	0.004	6750.00

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*$1303.40/ac-ft.

This optimization procedure was used to design two SIS for each region studied, one for each value of collector costs used. Tables V through XVI show the design results for each solar irrigation system.

TABLE V

Solar Irrigation System Design
Southern Arizona ($5/Ft^2 Collector)

Parameter	Unit	Size	Cost (1978$)
Collector Area	Ft^2	52,384	324,800
Thermal Storage Capacity	Btu	137,344,126	343,400
Water Storage Capacity	Gal	92,995,600	378,700
Well Prime Mover	kW	72	27,900
Irrigation Prime Mover	kW	14	14,900
Well Pumping Rate	gpm	766	
System Capital Cost			1,089,700

TABLE VI

Solar Irrigation System Design
Southern Arizona ($10/Ft^2 Collector)

Parameter	Unit	Size	Cost (1978$)
Collector Area	Ft^2	54,941	615,300
Thermal Storage Capacity	Btu	135,913,930	339,800
Water Storage Capacity	Gal	93,755,838	381,800
Well Prime Mover	kW	72	27,800
Irrigation Prime Mover	kW	14	14,900
Well Pumping Rate	gpm	762	
System Capital Cost			1,379,600

TABLE VII

Solar Irrigation System Design
San Joaquin Valley, CA ($5/Ft^2 Collector)

Parameter	Unit	Size	Cost(1978$)
Collector Area	Ft^2	26,367	163,500
Thermal Storage Capacity	Btu	37,802,744	94,500
Water Storage Capacity	Gal	17,844,593	78,100
Well Prime Mover	kW	36	19,700
Irrigation Prime Mover	kW	14	14,900
Well Pumping Rate	gpm	1,201	
System Capital Cost			370,800

TABLE VIII

Solar Irrigation System Design
San Joaquin Valley, CA ($10/Ft^2 Collector)

Parameter	Unit	Size	Cost(1978$)
Collector Area	Ft^2	27,070	303,200
Thermal Storage Capacity	Btu	36,977,631	92,400
Water Storage Capacity	Gal	20,795,796	89,900
Well Prime Mover	kW	35	19,600
Irrigation Prime Mover	kW	14	14,900
Well Pumping Rate	gpm	1,173	
System Capital Cost			520,000

TABLE IX

Solar Irrigation System Design
Northwestern Nebraska ($5/$Ft^2$ Collector)

Parameter	Unit	Size	Cost(1978$)
Collector Area	Ft^2	26,117	161,900
Thermal Storage Capacity	Btu	37,691,097	94,200
Water Storage Capacity	Gal	11,564,914	53,000
Well Prime Mover	kW	24	17,200
Irrigation Prime Mover	kW	14	14,900
Well Pumping Rate	gpm	902	
System Capital Cost			341,300

TABLE X

Solar Irrigation System Design
Northwestern Nebraska ($10/$Ft^2$ Collector)

Parameter	Unit	Size	Cost(1978$)
Collector Area	Ft^2	25,181	282,000
Thermal Storage Capacity	Btu	38,246,620	95,600
Water Storage Capacity	Gal	12,598,826	57,100
Well Prime Mover	kW	24	17,100
Irrigation Prime Mover	kW	14	14,900
Well Pumping Rate	gpm	887	
System Capital Cost			466,800

TABLE XI

Solar Irrigation System Design
Central New Mexico ($5/Ft^2 Collector)

Parameter	Unit	Size	Cost(1978$)
Collector Area	Ft^2	33,102	205,200
Thermal Storage Capacity	Btu	57,416,723	143,500
Water Storage Capacity	Gal	8,421,501	40,400
Well Prime Mover	kW	30	18,600
Irrigation Prime Mover	kW	14	14,900
Well Pumping Rate	gpm	1,125	
System Capital Cost			422,700

TABLE XII

Solar Irrigation System Design
Central New Mexico ($10/Ft^2 Collector)

Parameter	Unit	Size	Cost(1978$)
Collector Area	Ft^2	24,422	273,500
Thermal Storage Capacity	Btu	68,749,134	171,900
Water Storage Capacity	Gal	20,121,684	87,200
Well Prime Mover	kW	26	17,700
Irrigation Prime Mover	kW	14	14,900
Well Pumping Rate	gpm	979	
System Capital Cost			565,200

TABLE XIII

Solar Irrigation System Design
Southeastern Oregon ($\$5/\text{Ft}^2$ Collector)

Parameter	Unit	Size	Cost (1978$)
Collector Area	Ft^2	34,728	215,300
Thermal Storage Capacity	Btu	38,685,491	96,700
Water Storage Capacity	Gal	20,107,465	87,200
Well Prime Mover	kW	39	20,600
Irrigation Prime Mover	kW	14	14,900
Well Pumping Rate	gpm	732	
System Capital Cost			434,700

TABLE XIV

Solar Irrigation System Design
Southeastern Oregon ($\$10/\text{Ft}^2$ Collector)

Parameter	Unit	Size	Cost (1978$)
Collector Area	Ft^2	35,500	397,600
Thermal Storage Capacity	Btu	33,316,424	83,300
Water Storage Capacity	Gal	27,901,121	118,400
Well Prime Mover	kW	36	19,900
Irrigation Prime Mover	kW	14	14,900
Well Pumping Rate	gpm	674	
System Capital Cost			634,000

TABLE XV

Solar Irrigation System Design
Southern High Plains, Texas ($\$5/\text{Ft}^2$ Collector)

Parameter	Unit	Size	Cost(1978$)
Collector Area	Ft^2	37,499	232,200
Thermal Storage Capacity	Btu	91,995,028	230,000
Water Storage Capacity	Gal	31,466,102	132,600
Well Prime Mover	kW	53	23,600
Irrigation Prime Mover	kW	14	14,900
Well Pumping Rate	gpm	982	
System Capital Cost			633,300

TABLE XVI

Solar Irrigation System Design
Southern High Plains, Texas ($\$10/\text{Ft}^2$ Collector)

Parameter	Unit	Size	Cost(1978$)
Collector Area	Ft^2	37,250	417,200
Thermal Storage Capacity	Btu	92,815,430	232,000
Water Storage Capacity	Gal	31,335,854	132,100
Well Prime Mover	kW	53	23,600
Irrigation Prime Mover	kW	14	14,900
Well Pumping Rate	gpm	984	
System Capital Cost			819,900

ECONOMIC ANALYSIS

An economic analysis methodology has been developed to analyze the economic feasibility of residential and commercial solar systems. For this study, this methodology was applied to commercially owned SIS. The methodology uses a technique known as life cycle costing. Life cycle costing provides a convenient method for comparing two systems with differing cost streams throughout their lifetimes. All costs incurred during a system's lifetime are reduced to a single amount at the beginning of system operation. This amount is known as the life cycle cost (LCC) or present value of the system. The LCC may be thought of as the amount of money necessary in the first year of operation, which, if invested at a certain rate, would pay for the system throughout its lifetime. This rate is known as the discount rate, and is one of the parameters necessary to carry out the economic analysis.

The methodology requires the parameters listed in Table XVII. The values of the parameters were chosen to model the situation faced by a farmer who might purchase a SIS. Most of the values were suggested by an accountant who deals with farmers in the Estancia Valley of New Mexico. The rest were chosen by surveying values used in other economic analyses.

TABLE XVII

Economic Parameters

Loan Rate	9%
Downpayment	20%
Market Discount Rate	10%
Effective Income Tax Rate	50%
System Lifetime	20 Years
General Inflation Rate	6%
Fuel Escalation Rate	10%
Investment Tax Credit	10%
Maintenance Expense (% of Capital Investment)	2%
Property Tax Rate	0%

Electricity and fossil fuel prices were obtained from irrigation price schedules provided by utility companies in the areas that were studied. These prices are not necessarily typical or average since they were obtained from one utility in each area. The prices used and where they were obtained are presented in Table XVIII.

TABLE XVIII

Energy Prices

State	(¢/kWh) Elec.	Utility	$/MCF N. Gas	Utility	¢/Gal Diesel	Utility
Arizona	4.3	Tucson G & E	1.29	Tucson G & E	--	
California	3.8	Turlock Irrig. District	--		--	
Nebraska	4.1	Nebraska Pub. Pwr. District	--		44	(a)
New Mexico	3.1	Central N.M. Elec. Co-op.	1.90	EMW Gas	--	
Oregon	2.1	Pacific Pwr. and Lights	--		--	
Texas	3.5	West Texas Utilities	1.55	(b)	--	

---

[a] Agricultural Prices, USDA A92:16.

[b] 1976 Pump Irrigation Energy Survey, Texas High Plains and Trans-Pecos Area, Texas Dept. of Agriculture.

Initial capital costs for the SIS were generated by the optimization procedure. Two systems were designed for each region, one using $\$5/ft^2$ and the other using $\$10/ft^2$ as initial collector costs in 1978 dollars. For systems beginning operation after 1978, all costs were inflated at 6% per year. Collector costs for 1980, 1985, and 1990 are shown in Table XIX.

TABLE XIX

Collector Costs ($\$/Ft^2$)

1978	$ 5.00	$10.00
1980	5.62	11.24
1985	7.52	15.04
1990	10.06	20.12

In order to assess the economic feasibility of each SIS, it was necessary to find the LCC of conventional methods of irrigating. Three conventional systems were studied--electrical, natural gas, and diesel.

For each conventional system, the cost of a conventional motor and the cost of purchasing energy for that motor were used in the LCC model. The costs and efficiencies of the motors appear in Table XX. The cost of conventional energy was determined for each region using the energy prices in Table XVIII and the demands generated by the optimization code. For each region, the LCC of the most popular conventional systems were determined.

TABLE XX

Conventional Systems

Type	Motor Cost (1978$)	Replacement	Efficiency
Electric	$13,891	None	0.9
Natural Gas	24,430	Every 10 Years	0.24
Diesel	17,777	Every 10 Years	0.28

Finally, given the initial capital costs and the above parameters, the LCC of each SIS was found. The economic feasibility of each SIS was determined by looking at the ratio of the LCC of the SIS to the LCC of each conventional system in each region. A ratio of one indicates a breakeven point. For larger ratios, a SIS is more expensive than its conventional counterpart. For ratios less than one, SIS are less expensive than conventional ones.

The results for each region are shown in graphic form, beginning with southern Arizona (Fig. 17). The horizontal axis represents SIS beginning operation in 1980, 1985, and 1990 with a lifetime of 20 years. The vertical axis shows the LCC ratios.

The bands were derived using $\$5/\text{ft}^2$ as a lower limit for initial collectors costs with $\$10/\text{ft}^2$ as an upper limit. In southern Arizona, the comparison is versus both electrically driven and natural gas driven conventional systems, since these are the two most frequently used. Since it is less expensive to irrigate using natural gas rather than using electricity in Arizona, solar compares more favorably with electricity. Tables XXI and XXII show the annual energy cost and/or life cycle cost for the two types of systems.

The results follow in Figures 18-22 and Tables XXIII-XXXII for the five other regions studied. In Figure 18 and Tables XXIII and XXIV the results for the San Joaquin Valley in California are shown. The comparison here is versus electricity only, since other irrigation methods are seldom used.

In northwestern Nebraska, solar must compete with both diesel and electric motors. As seen in Figure 19 and Tables XXV and XXVI, the two blocks nearly coincide, since the costs of the two conventional irrigation methods are almost identical.

The results for central New Mexico are shown in Figure 20 and Tables XXVII and XXVIII. Here the comparison is versus natural gas and electricity. Again, the blocks coincide because the costs of irrigating using these two conventional methods are nearly identical.

In southeastern Oregon (Figure 21, Tables XXIX, XXX), electricity is virtually the only conventional irrigation method. Solar's comparison to electricity looks particularly dismal here due to the availability of inexpensive hydroelectric power.

The last region studied is the southern High Plains of Texas (Figure 22, Tables XXXI, XXXII). In Texas, the comparison is versus both natural gas and electricity.

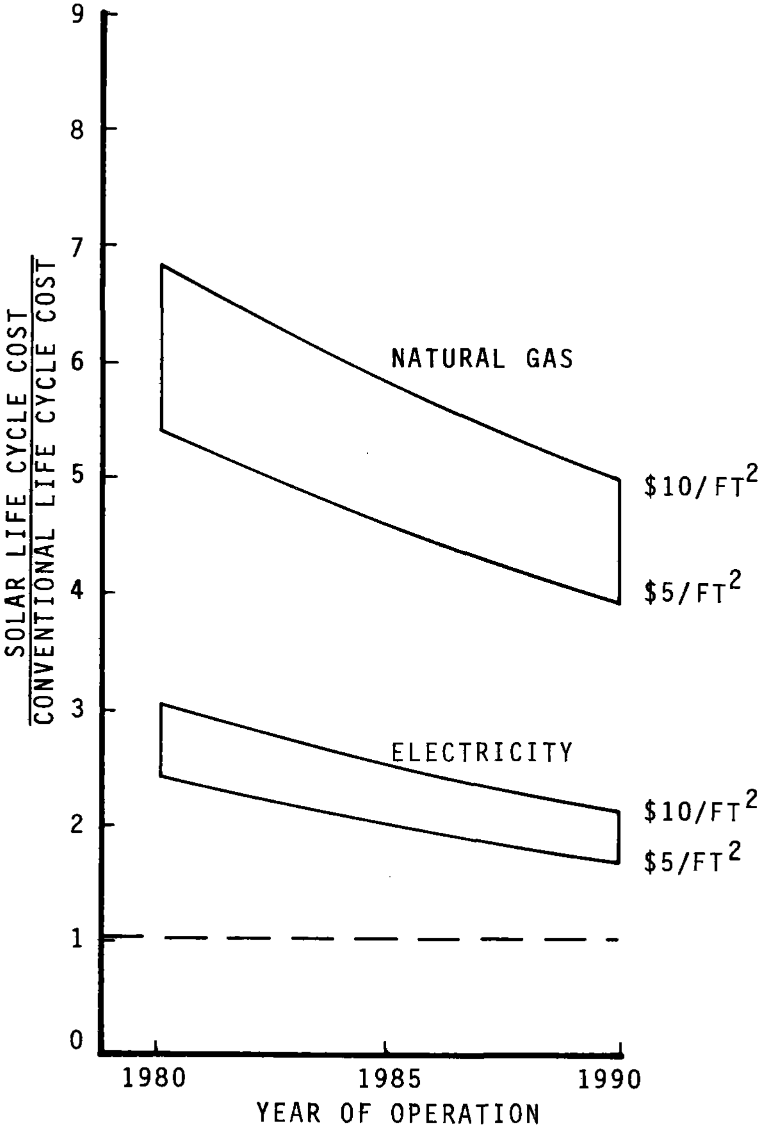

Figure 17. Life Cycle Cost Ratios for SIS Starting Operation in 1980, 1985, or 1990 in Southern Arizona (Open-Ditch Gravity-Flow Irrigation of Cotton, 350' Lift)

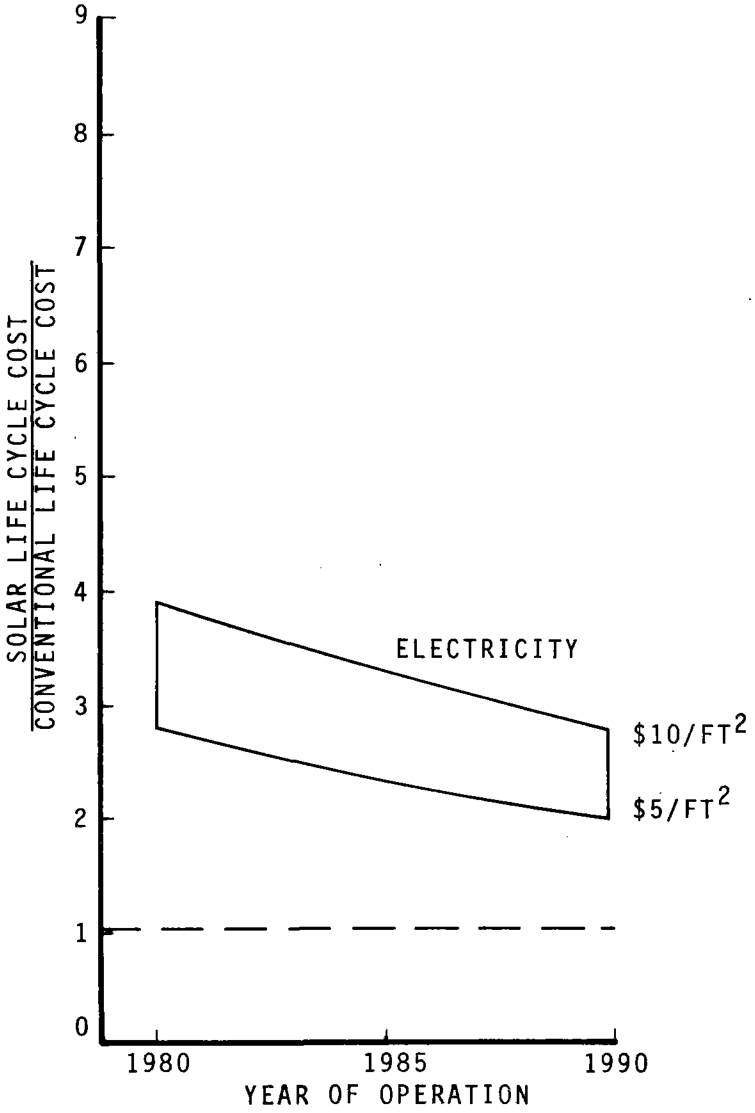

Figure 18. Life Cycle Cost Ratios for SIS Starting Operation in 1980, 1985, or 1990 in San Joaquin Valley, CA (Open-Ditch Gravity-Flow Irrigation of Orchard, 110' Lift)

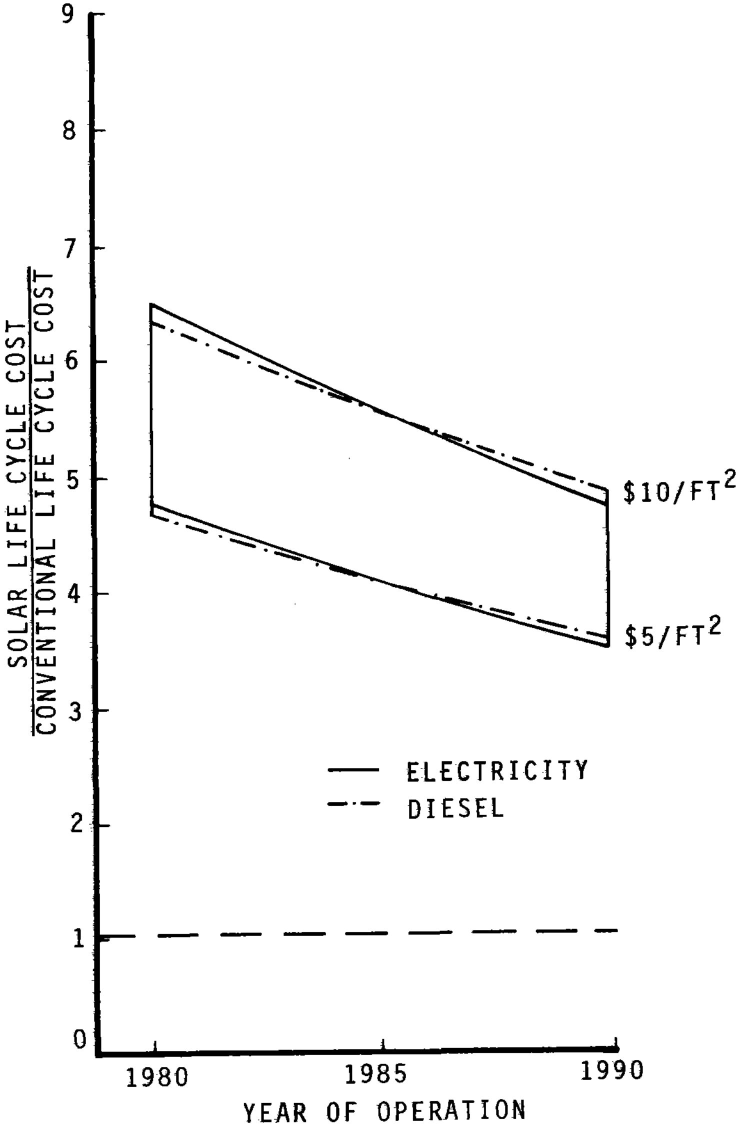

Figure 19. Life Cycle Cost Ratios for SIS Starting Operation in 1980, 1985, or 1990 in Northwestern Nebraska (Open-Ditch Gravity-Flow Irrigation of Corn, 100' Lift)

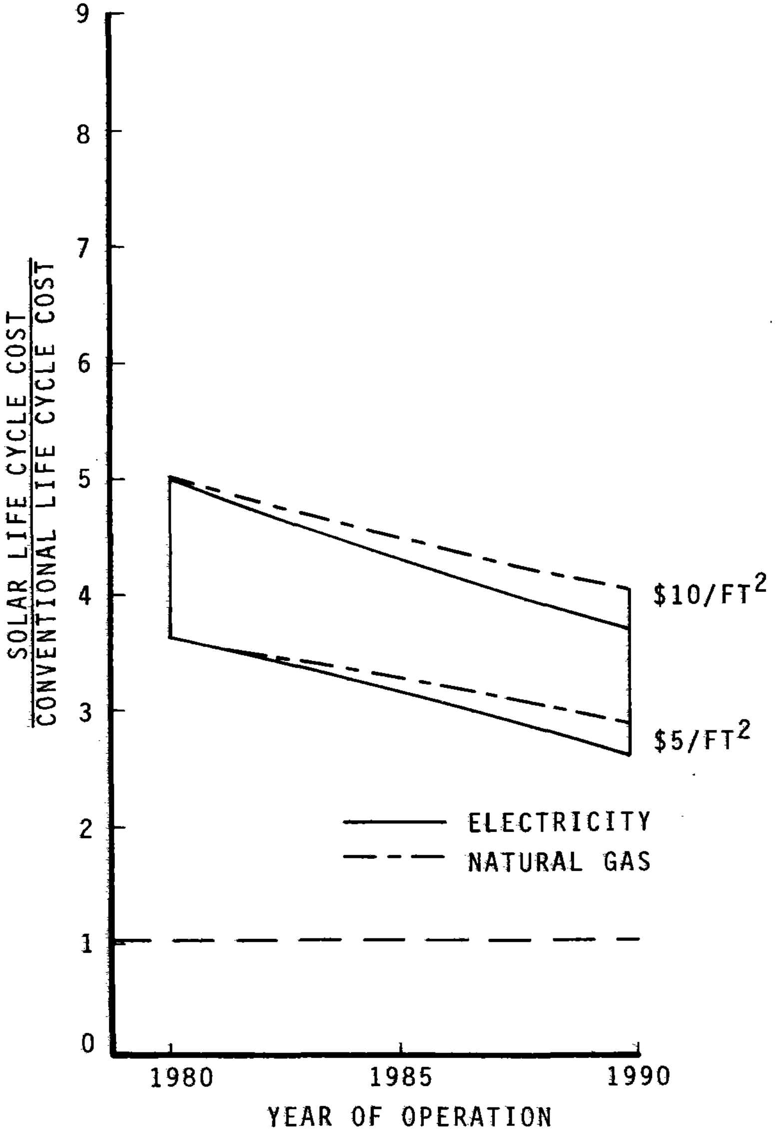

Figure 20. Life Cycle Cost Ratios for SIS Starting Operation in 1980, 1985, or 1990 in Central New Mexico (Open-Ditch Gravity-Flow Irrigation of Alfalfa, 100' Lift)

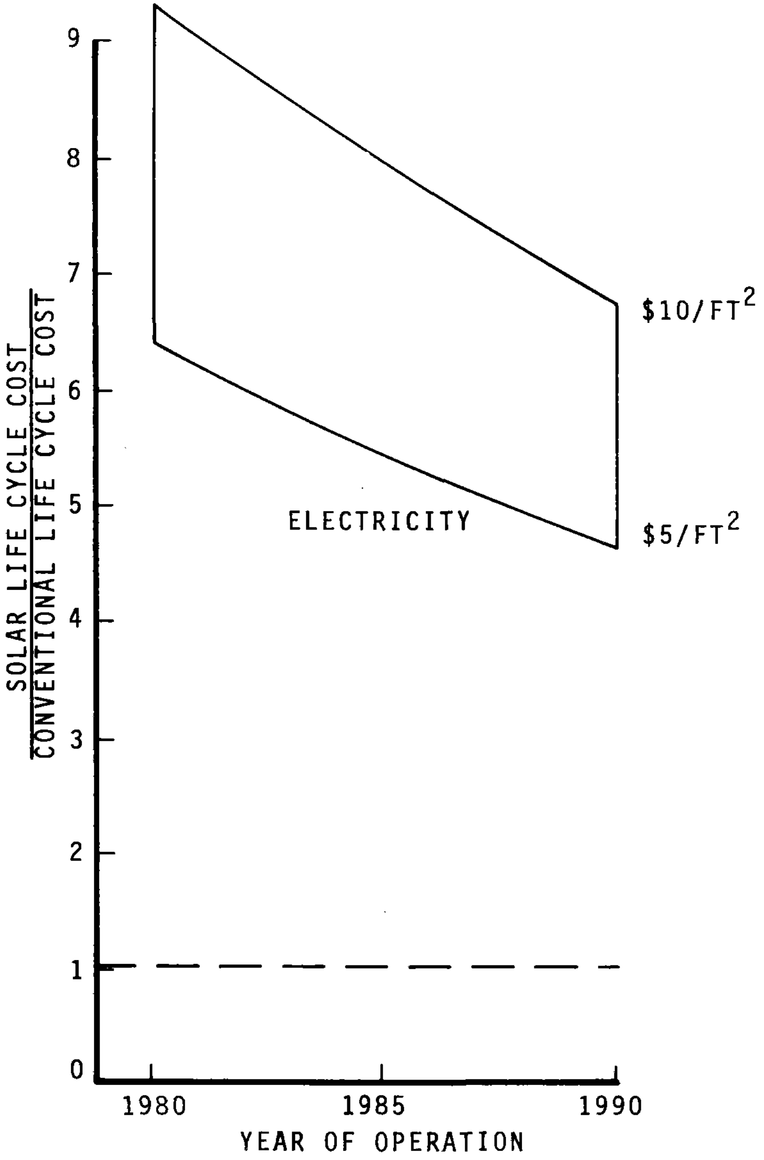

Figure 21. Life Cycle Cost Ratios for SIS Starting Operation in 1980, 1985, or 1990 in Southeastern Oregon (Open-Ditch, Gravity-Flow Irrigation of Alfalfa, 200' Lift)

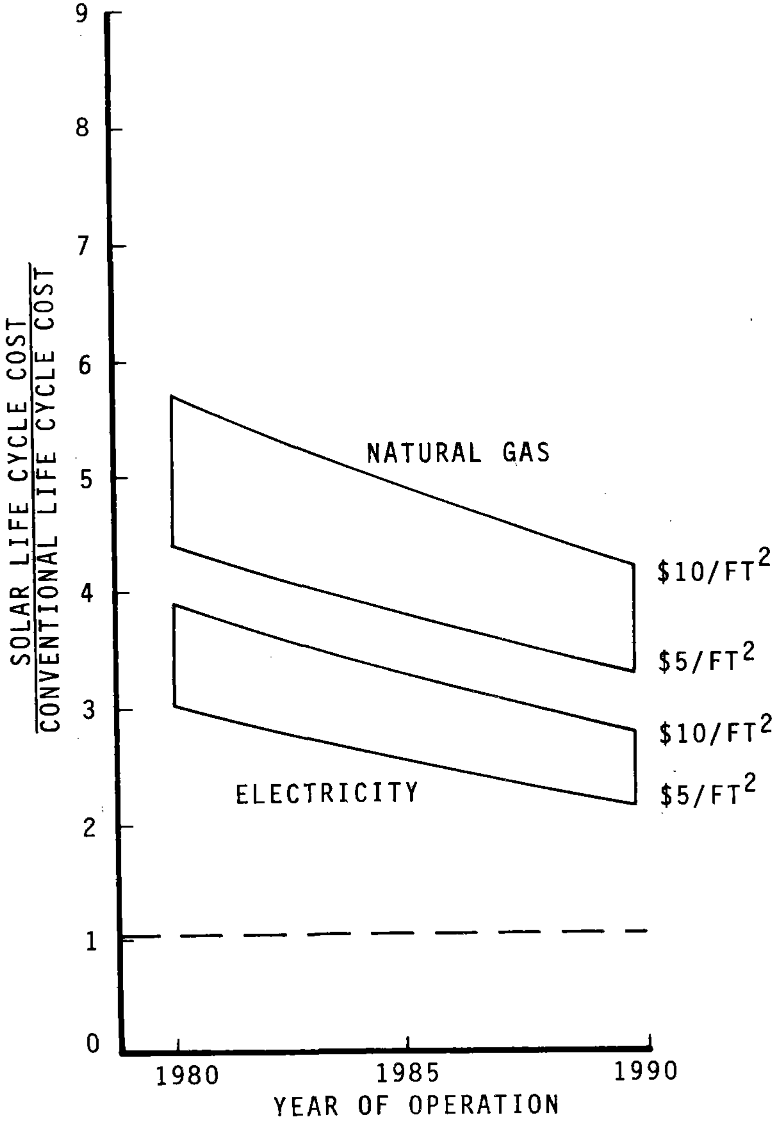

Figure 22. Life Cycle Cost Ratios for SIS Starting Operation in 1980, 1985, or 1990 in the Southern High Plains of Texas (Open-Ditch, Gravity-Flow Irrigation of Sorghum Double Crop, 200' Lift)

TABLE XXI

Life Cycle Cost for SIS Starting Operation In 1980, 1985, or 1990 in Southern Arizona*

	Life Cycle Cost ($)		
Collector Cost	1980	1985	1990
$ 5	575,472	770,109	1,030,579
10	728,582	975,004	1,304,775

TABLE XXII

Life Cycle Cost for a Conventional System Starting Operation in 1980, 1985, Or 1990 in Southern Arizona*

		Life Cycle Cost ($)		
Energy Source	Annual Energy Cost (1978$)	1980	1985	1990
Electricity	21,413	240,837	386,429	620,418
Natural Gas	8,202	105,961	166,365	262,198

---

*An open-ditch gravity-flow irrigation system for cotton, with a 350-foot well lift.

TABLE XXIII

Life Cycle Cost for SIS Starting Operation In 1980, 1985, or 1990 In San Joaquin Valley, California*

	Life Cycle Cost ($)		
Collector Cost	1980	1985	1990
$ 5	195,792	262,014	350,633
10	274,613	367,493	491,789

TABLE XXIV

Life Cycle Cost for a Conventional System Starting Operation in 1980, 1985, or 1990 In the San Joaquin Valley, California*

		Life Cycle Cost ($)		
Energy Source	Annual Energy Cost (1978$)	1980	1985	1990
Electricity	5,962	70,876	112,705	179,583
Natural Gas	--	--	--	--
Diesel	--	--	--	--

---

[*] An open-ditch gravity-flow irrigation system for an orchard, with a 110-foot well lift.

TABLE XXV

Life Cycle Cost for SIS Starting Operation in 1980, 1985, or 1990 In Northwestern Nebraska*

Collector Cost	Life Cycle Cost ($)		
	1980	1985	1990
$ 5	180,223	241,178	322,750
10	246,517	329,894	441,473

TABLE XXVI

Life Cycle Cost for a Conventional System Starting Operation in 1980, 1985, Or 1990 in Northwestern Nebraska*

Energy Source	Annual Energy Cost (1978$)	Life Cycle Cost ($)		
		1980	1985	1990
Electricity	2,940	37,634	59,168	93,362
Natural Gas	--	--	--	--
Diesel	2,466	38,579	59,013	90,868

---

*An open-ditch gravity-flow irrigation system for corn, with a 100-foot well lift.

TABLE XXVII

Life Cycle Cost for SIS Starting Operation in 1980, 1985, or 1990 In Central New Mexico*

	Life Cycle Cost ($)		
Collector Cost	1980	1985	1990
$ 5	198,392	273,180	373,262
10	275,753	376,706	511,805

TABLE XXVIII

Life Cycle Cost for a Conventional System Starting Operation in 1980, 1985, Or 1990 in Central New Mexico*

		Life Cycle Cost ($)		
Energy Source	Annual Energy Cost (1978$)	1980	1985	1990
Electricity	4,529	55,113	87,318	138,698
Natural Gas	3,525	54,514	83,509	128,758
Diesel	--	--	--	--

---

*An open-ditch gravity-flow irrigation system for alfalfa, with a 100-foot well lift.

TABLE XXIX

Life Cycle Cost for SIS Starting Operation In 1980, 1985, or 1990 in Southeastern Oregon*

	Life Cycle Cost ($)		
Collector Cost	1980	1985	1990
$ 5	229,565	307,208	411,114
10	334,837	448,086	599,640

TABLE XXX

Life Cycle Cost for a Conventional System Starting Operation in 1980, 1985, Or 1990 in Southeastern Oregon*

		Life Cycle Cost ($)		
Energy Source	Annual Energy Cost (1978$)	1980	1985	1990
Electricity	2,763	35,687	56,033	88,312
Natural Gas	--	--	--	--
Diesel	--	--	--	--

---

[*] An open-ditch gravity-flow irrigation system for alfalfa, with a 200-foot well lift.

TABLE XXXI

Life Cycle Cost for SIS Starting Operation in 1980, 1985, or 1990 In Southern High Plains, Texas*

Collector Cost	Life Cycle Cost ($) 1980	1985	1990
$ 5	334,442	447,557	598,933
10	432,964	579,402	775,370

TABLE XXXII

Life Cycle Cost for a Conventional System Starting Operation in 1980, 1985, Or 1990 in the Southern High Plains, Texas*

Energy Source	Annual Energy Cost (1978$)	Life Cycle Cost ($) 1980	1985	1990
Electricity	9,583	110,707	176,853	282,895
Natural Gas	5,460	75,799	117,789	183,966
Diesel	--	--	--	--

---

[*] An open-ditch gravity-flow irrigation system for sorghum (double-crop), with a 200-foot well lift.

In all of these cases the cost of irrigating by use of solar energy is somewhat greater than any of the conventional methods. However, there are several ways of improving the feasibility of solar irrigation.

One important way of improving the solar irrigation picture is finding alternative uses for the energy which the SIS is capable of producing--energy that is not needed for irrigation purposes. In other words, it would be beneficial to utilize 100% of the energy that the system can produce, diverting to other farm uses the amount not needed for irrigation, and displacing that amount of fossil fuel. Figure 23 and Table XXXIII show the impact of 100% utilization for one case.

In the southern Arizona region, only 56% of the energy that the system was capable of producing was utilized for irrigation. This was determined by using the optimization code, summing the total available energy throughout the year and finding what percentage was used for irrigation. The code designed slightly different systems for the two initial collector costs, so that the total energy displaced by the two systems varies somewhat. Therefore, Table XXXIII reflects this difference in the cost of conventional energy displaced. As shown in Figure 23, use of 100% of the energy would considerably improve the solar irrigation picture. Solar systems are brought within a factor of two of electrically driven systems and break even soon after 1985. This indicates that it would be beneficial to identify alternative uses for the energy provided by the SIS.

Government incentives can have an enormous effect on the economic feasibility of SIS. One possible incentive is a tax deduction of the cost of energy saved. This incentive would allow the farmer to deduct from his income the cost of the energy that he would have had to purchase had he not installed a SIS. For example, the farmer would purchase no energy, but would still take the previous year's energy expense as a tax deduction.

The effect of this incentive is shown in Figure 24, for the region in southern Arizona. The $5/ft^2 SIS breaks even in 1985, with the $10/ft^2 nearing breakeven in 1990. Table XXXIV shows the life cycle cost of the system after the deduction is taken.

The combined impact of deducting the energy saved by 100% utilization of the SIS is shown in Figure 25. Here the farmer would retain

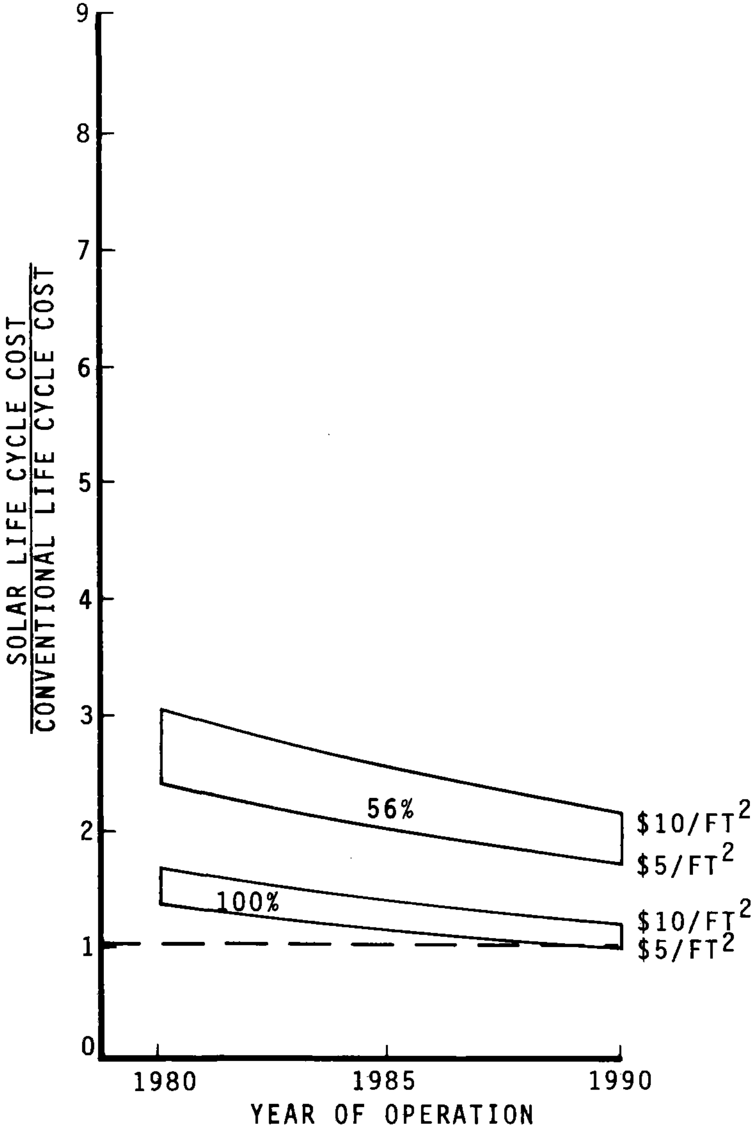

Figure 23. Impact of Utilizing 100% of System Capacity to Displace Electricity in Southern Arizona

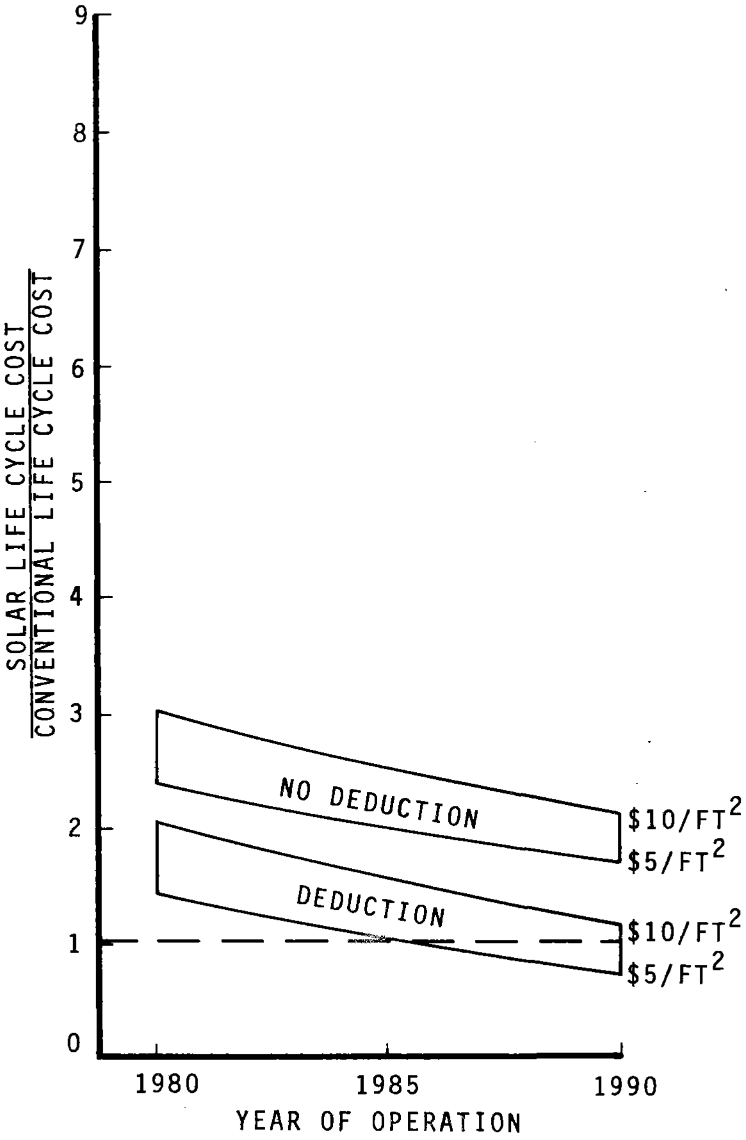

Figure 24. Impact of Allowing Tax Deduction of Electricity Saved in Southern Arizona

TABLE XXXIII

Life Cycle Cost of Energy Displaced by 100% Utilization of SIS Starting Operation In 1980, 1985, or 1990 in Southern Arizona*

Collector Cost	Annual Electricity Cost (1978$)	Life Cycle Cost ($)		
		1980	1985	1990
$5/Ft^2	39,003	429,033	690,962	1,112,801
$10/Ft^2	40,481	445,291	717,146	1,154,970

TABLE XXXIV

Life Cycle Cost after Deducting the "Expense" Of Electricity, of a SIS Starting Operation In 1980, 1985, or 1990 in Southern Arizona*

Collector Cost	Life Cycle Cost ($)		
	1980	1985	1990
$ 5	339,929	390,764	419,641
10	493,039	595,659	693,837

---

[*] An open-ditch gravity-flow irrigation system for cotton, with a 350-foot well lift.

the tax deduction for all the energy he is not purchasing by using 100% of the SIS energy. This combination effect makes SIS more than break even at all points. Table XXXV shows the life cycle cost of the system after this deduction is taken. This demonstrates the impact of one possible government incentive on SIS economic feasibility.

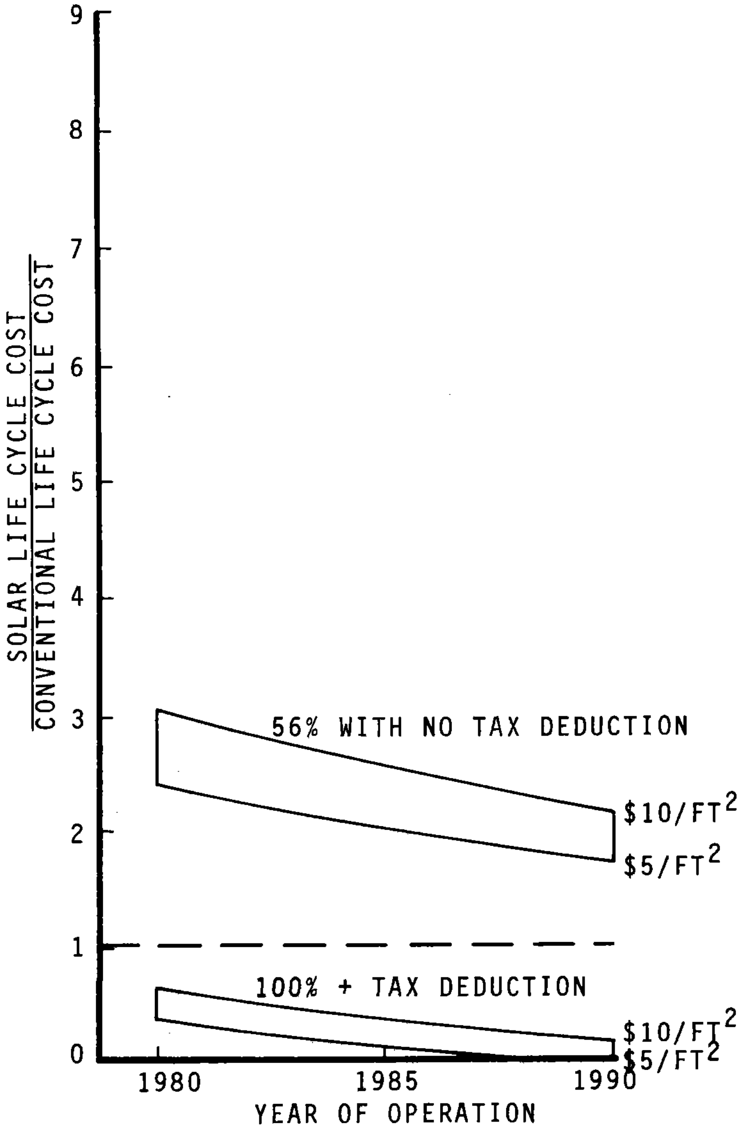

Figure 25. Combined Impact of Deducting Electricity Saved By 100% Utilization in Southern Arizona

TABLE XXXV

Life Cycle Cost after Deducting the "Expense" Of Electricity Displaced by 100% Utilization of SIS Starting Operation in 1980, 1985, or 1990 in Southern Arizona*

	Life Cycle Cost ($)		
Collector Cost	1980	1985	1990
$ 5	146,439	79,147	-82,222**
10	283,291	257,858	149,805

---

*An open-ditch gravity-flow irrigation system for cotton, with a 350-foot well lift.

**The minus sign indicates that the tax deduction exceeds the LCC of the SIS (see Table XXII); it in effect reduces the farmer's tax liability by $82,222.

HYBRID SYSTEM ANALYSIS

A hybrid SIS is a dual-powered irrigation system. In this case the two systems making up the hybrid system are a SIS identical to the stand-alone system studied earlier combined with a conventional electrically powered system. The solar system would be used to satisfy irrigation demand when solar energy is sufficient and the conventional system would be used to satisfy system demand when solar energy is insufficient to meet the demand. In other words, a percentage of the energy required for irrigation is provided by the solar system with the remainder purchased from the local utility.

The optimization procedure used in the design of a hybrid SIS was the same as that for a stand-alone with one major exception. The optimization criteria was changed from minimizing the capital costs of a SIS which will meet the irrigation demand to minimizing the life cycle cost of irrigation using a solar/conventional hybrid system. The optimization procedure uses the price of energy and the SIS cost to determine the amount of energy to be purchased. It was assumed that the utility would charge the owner of a hybrid SIS the same amount for his energy as it would any similarly sized customer. This will not necessarily be the case. The problem of interfacing SIS with local utilities needs to be explored; it can be avoided by combining a diesel back-up system instead of an electrical one. Table XXXVI shows the design results for an optimized hybrid SIS.

TABLE XXXVI

Hybrid Solar Irrigation System Design
Southern Arizona ($5/Ft^2 Collector)

Parameter	Unit	Size	Cost (1978$)
Collector Area	Ft^2	38,872	241,000
Thermal Storage Capacity	Btu	8,606,789	21,500
Water Storage Capacity	Gal	14,851,369	66,200
Well Prime Mover	kW	163	48,200
Irrigation Prime Mover	kW	14	14,900
Percent Solar	%	71	
Well Pumping Rate	gpm	1,725	
System Capital Cost			391,800

For a SIS operating in 1990 with $5/ft^2 as initial collector cost, the optimization procedure designed a 71% hybrid system--71% of the energy is provided by the SIS and 29% (electricity) is purchased from the utility. This hybrid system can be compared both to a completely electrically driven system and to the stand-alone system previously designed for this case. Table XXXVII shows these results. The hybrid system is approximately 10% cheaper than an electrically driven conventional system. In a comparison with the stand-alone system, the table indicates that component sizes have been substantially reduced, with the LCC dropping by 53%.

TABLE XXXVII

Hybrid SIS Comparisons with Conventional
Powered Irrigation and Stand-Alone SIS
For Southern Arizona Case

Comparison to Electrically Driven System

$$\frac{\text{LCC Hybrid}^*}{\text{LCC Electric}^*} = 0.9$$

Comparison to Stand-Alone System

Component	Size (%) Reduction
Collector Area	26
Thermal Storage Capacity	94
Water Storage Volume	84
Life Cycle Cost*	53

---

*The hybrid LCC = $ 549,567
The conventional LCC = $ 610,938
The stand-alone LCC = $1,030,579

ADDITIONAL ANALYSIS REQUIREMENTS

Much of the analysis presented here has indicated the need for future work. Many of the results have been based on preliminary assumptions, and more work will be necessary to determine the true economic picture for SIS. To this end, several facets of the present work will be expanded.

A broad-scale parameter sensitivity analysis will be undertaken to determine which parameters most affect a SIS economic feasibility. Different field descriptions, crops, and irrigation techniques will be explored. A range of well lifts will be examined. Initial energy costs will be parameterized to correspond to the range of prices found in each region. Economic parameters will be examined, particularly the difference between the general inflation rate and the fuel escalation rate. Finally, the effects of cost and performance of system components on system design will be studied. Although the results presented in this study have been based on efficiencies representative of today's components, technological improvements could lead to better component efficiencies, better performance, and thereby lower system cost.

Hybrid SIS will be examined on a much broader level. The possibility of fixing the percentage of power produced by the solar system and designing a system on that basis will be explored. The impact of interfacing with local utilities will need to be taken into account.

Alternative uses of the excess energy not needed for irrigation will be sought out which can improve the solar irrigation picture. Possibilities for this include the ginning of cotton, crop drying, heating of barns and other farm buildings, etc.

Finally, the effect of government incentives necessary to close the remaining gap between SIS and conventional systems will be studied. In addition to the tax deduction of energy saved, investment tax credits, low interest loans, and property tax exemptions are a few of the possibilities in this area.

In this paper, we have looked at the economic feasibility of several SIS under specific conditions. Through future work, the overall picture of the economics of SIS should emerge.

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