The Analysis to Develop a Program for Energy Conservation in Irrigated Agriculture

September 1978

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**Pacific Northwest Laboratory
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THE ANALYSIS TO DEVELOP A PROGRAM
FOR ENERGY CONSERVATION IN IRRIGATED
AGRICULTURE

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I. PURPOSE OF THE RESEARCH

I. PURPOSE OF THE RESEARCH

The Division of Energy Conservation of the Department of Energy has chosen to allocate \$1.5 million to increase energy efficiency in irrigation. The research presented in this report was performed to aid in the development of a program for energy conservation which would result in the judicious use of these funds. This report was written to describe the rationale for developing the Energy Conservation Irrigation Program. In so doing, the intent is to stimulate discussion, encourage comment, and thereby create an informal forum which can synergistically result in the greatest possible impact of the federal funds on the use of energy in irrigation.

The point of departure for the program is an estimate by the Federal Energy Administration that 0.26 quad (quadrillion Btu) of energy is annually required to irrigate the nation's crops.⁽¹⁾

In designing the Energy Conservation Irrigation Program, the initial questions were: (1) how could energy consumption be reduced and (2) by how much. To seek answers to these questions, two workshops were held in Washington, DC. These workshops were attended by experts in academia and commercial sectors. The type of projects thought to reduce energy consumption in irrigation included: (1) development of deep well pumps exhibiting improved efficiency, (2) design and demonstration of irrigation power plants exhibiting improved mechanical efficiencies through the use of Rankine bottoming cycles or other techniques, (3) development and demonstration of systems for reducing pumping pressures required to distribute water to crops, (4) research and demonstration leading to reduction in water consumption by agricultural crops through optimum water scheduling, and (5) improved instrumentation for monitoring crop water needs.⁽²⁾

During the second workshop, it was concluded that a 30% to 50% reduction in irrigation energy requirements could result from the use of alternative hardware, improvements in scheduling and the education of irrigators. This could mean a 0.08 to 0.13 quad savings in energy. Part of the 30% to 50% reduction would result from a 40% to 50% reduction in the energy used to distribute water. Additional energy efficiency could result from the use of alternative power sources for prime movers. A 7% increase in efficiency was

thought technically possible through an improved design of the pump. A 20% reduction in pumping energy was thought possible through improved well design.⁽³⁾ Though a 50% reduction was thought possible by a plurality of workshop participants, a consensus was not in agreement with this estimate.

The workshop participants were experienced and knowledgeable in a wide cross section of irrigation technologies and practices. The lack of consensus regarding the energy that could be saved through adoption of existing technologies pointed to the need for a comprehensive understanding of: (1) specific elements of irrigation technology presented in the five categories above as they relate to the irrigation economy and (2) the potential for technological change to increase energy efficiency to meet this need.

This analysis is divided into three parts:

1. A technical description of the use of energy in irrigation
2. An abridged survey of energy-conserving research
3. A theoretical consideration of technological change.

The purpose of the data presented in Chapter 2 is to determine where and how the estimated 0.26 quad of energy is being used to irrigate the nation's crops. Chapter 3 describes who is presently doing research and developing energy-efficient irrigation techniques. Chapter 4 draws on theoretical constructs to determine some of the forces which induce the adoption of available technology.

The next questions in the design of the Energy Conservation Irrigation Program were (1) who could be funded to conduct research, development, and demonstration projects, and (2) how much would it cost. In order to answer these questions a program opportunity notice was issued through government procurement procedures.⁽⁴⁾ Proposals were submitted and contractors were chosen. The results of these procedures are presented in Chapter 5.

The Energy Conservation Irrigation Program presently consists of the ten projects described in the last chapters, and a project to design incentives to induce the results of these ten projects to be utilized in the irrigation economy. The design of incentives is predicated on the recommendations for further research that conclude this report.

REFERENCES - Chapter I

1. Federal Energy Administration, Office of Energy Conservation and Environment, Energy and U.S. Agriculture: 1974 Data Base, Volume 1, FEA/D-76/459, September 1976.
2. Washington Scientific Marketing, Inc., Department of Energy Programs and Objectives: Energy Conservation in Agricultural Production, prepared for the Department of Energy, Division of Industrial Energy Conservation, October 1977.
3. Department of Energy Programs and Objectives: Energy Conservation in Agricultural Production, Division of Industrial Energy Conservation, prepared by Washington Scientific Marketing, Inc., December 1977.
4. Program Opportunity Notice Number EC-77-N-01-5000, Issued as Part of the Commercial Demonstration Program, Energy Research and Development Administration, Office of Conservation, Division of Industrial Energy Conservation, October 1977.

II. THE USE OF ENERGY AND IRRIGATION

II. THE USE OF ENERGY AND IRRIGATION

In order to determine how Federal funds should be allocated to result in the greatest energy conservation, it is necessary to know where and how energy is currently consumed in irrigation systems. This chapter describes the geographic dispersion of irrigated agriculture in the United States and regional specialization by energy source. Use of energy for irrigation purposes is then discussed in three categories: (1) installation, (2) pumping, and (3) application.

AN OVERVIEW OF ENERGY USE

Energy is used for irrigation in each of the 50 states; acres irrigated range from about 2,000 in Vermont to almost 9,000,000 in Texas. Eleven states irrigate 79% of the total irrigated acreage and utilize 87% of the total energy used for irrigation purposes. In order of energy use, these states are: Texas, Nebraska, Kansas, Arizona, New Mexico, California, Washington, Oklahoma, Idaho, Colorado, and Oregon. Energy sources and volumes for these eleven states are shown in Table 1. Briefly, sources and volumes can be summarized as follows:

- Texas uses more than twice as much energy to irrigate its crops than any other state in the Union. Most of this energy is in the form of liquified petroleum gas (LPG) and natural gas.
- Nebraska, the second largest user of energy in irrigation, uses more LPG than any other state. It is also the leading user of diesel fuel to irrigate.
- Kansas, ranking third, uses mostly LPG and natural gas to irrigate.
- Arizona uses natural gas almost exclusively.
- Of the eleven high energy using states, New Mexico uses the most gasoline.
- The major source of irrigation power in California is electricity, with small amounts of natural gas and diesel.
- Washington uses electric power exclusively.

- Oklahoma has a distribution by type of energy comparable to that of Texas.
- Idaho and Oregon are primarily electricity users.
- The major energy source in Colorado is natural gas with electricity also being an important source.

TABLE 1. Types of Fuels Used in Irrigation for the
Eleven Leading Energy Consuming States - 1974

	Type of Fuel					TOTAL Bill. Btu
	Gasoline 1000 gal	Diesel 1000 gal	LP Gas 1000 gal	Nat. Gas ₃ Mill. ft	Electricity Mill. kWh	
Texas	7,006	448	36,818	63,973	1,407	73,141
Nebraska	4,415	84,136	101,131	6,167	937	31,064
Kansas	1,938	8,021	17,389	19,383	133	22,816
Arizona				14,425	2,081	21,527
New Mexico	7,824	9,381	17,115	15,163	404	20,439
California	--	69	--	1,164	4,514	16,850
Washington	--	--	--	--	3,758	12,826
Oklahoma	2,228	3,921	13,387	5,940	108	8,381
Idaho	3,678	1,385	2,165	406	1,581	6,667
Colorado	301	1,176	1,839	4,692	339	6,223
Oregon	--	1,320	--	--	1,588	5,605
TOTAL	27,390	109,857	189,844	131,313	16,850	225,269
Percentage of National	39%	62%	80%	99%	87%	87%

Federal Energy Administration, Office of Energy Conservation and Environment,
Energy and U.S. Agriculture: 1974 Data Base, Volume 1, FEA/D-76/459,
September 1976, pgs. 7, 30, 40, 46, 74, 94, 145, 164, 189, 194, 223 and 242.

Energy Source

Nine of these eleven states use natural gas as an energy source for irrigation and consume 99% of all natural gas used for irrigation nationally. All eleven states use electricity and consume 87% of the national irrigation total. Seven of the eleven states use LPG and consume 80% of the LPG used nationally for irrigation. Sixty-two percent of the diesel fuel used for irrigation in the nation is consumed in nine of these eleven states. Seven of the eleven states use gasoline as an energy source for irrigation. These seven states consume 39% of the total quantity of gasoline used for this purpose nationally.

Crop Specific Irrigation

Most of the energy consumed for irrigation is crop-specific. In the eleven high energy-consuming states, 62% of the energy consumed in irrigation is used in the production of: grain sorghum, cotton, winter wheat, corn for grain and silage, and alfalfa. Fifty-five percent of the energy used for irrigation nationally is consumed in the production of these crops. The energy consumed in irrigating these commodities is presented in Table 2. The energy used to irrigate these crops represents at least 30% of the total irrigation energy consumed by each of the eleven states in all cases except Idaho.

In Texas, 75% of the energy is used to irrigate these five commodities with over 30% of the energy being used to irrigate grain sorghum. Seventy-three percent of the energy used in Nebraska to irrigate crops is used on corn. In Kansas 64% of the energy is used to irrigate corn. Most of the irrigation energy in Arizona is consumed in the production of cotton. Alfalfa is a higher energy user in the states of Arizona, New Mexico, California, Colorado, and Oregon. No energy is used to produce grain sorghum or cotton in the Pacific Northwest. Over 50% of the energy used to irrigate wheat is consumed in Texas. Seventy-three percent of the energy used in corn production is consumed in Nebraska and Kansas.⁽¹⁾

TABLE 2. Billion Btu Consumed Through Irrigation
by Major Commodity for the Eleven Leading
Energy Consuming States - 1974

	Commodity						Percentage of all Crop Total
	Grain Sorghum	Cotton	Winter Wheat	Corn and Corn Silage	Alfalfa	TOTAL	
Texas	23,895	14,839	10,273	6,660	1,903	57,570	75%
Nebraska	--	--	--	23,000	2,291	25,291	80%
Kansas	3,212	--	1,661	15,343	1,673	21,889	92%
Arizona	2,659	7,764	2,951	125	4,533	18,032	81%
New Mexico	3,033	3,251	1,523	981	5,544	14,332	68%
California	349	3,055	197	667	2,982	7,250	44%
Washington	--	--	510	509	3,567	4,586	36%
Oklahoma	2,301	664	1,596	1,102	1,097	6,760	78%
Idaho	--	--	280	52	146	478	7%
Colorado	318	--	277	1,957	2,222	4,774	72%
Oregon	--	--	479	30	1,420	1,929	34%
TOTAL	35,767	29,573	19,747	50,426	27,378	162,891	62%
Percentage of National	98%	95%	97%	96%	92%		

Federal Energy Administration, Office of Energy Conservation and Environment,
Energy and U.S. Agriculture: 1974 Data Base, Volume 1, FEA/D-76/459,
September 1976, pgs. 12, 24, 32, 42, 48, 76, 96, 147, 166, 192, 196 and 225.

Irrigation Water Source

Technology to increase energy efficiency in irrigation will depend on whether the source of water is lakes and rivers (surface) or wells drawing on ground water. Most of the water utilized in Texas, Nebraska, Kansas, New Mexico and Oklahoma comes from ground water sources. Programs designed to increase the energy efficiency of wells and of turbine pumps would be most effective in these locations. Data describing the source of irrigation water are presented in Table 3.

TABLE 3. Source of Irrigation Water Reported by Farms as a Percent of Total Water Used for Irrigation - 1969

	<u>Surface</u>	<u>Ground</u>	<u>Private</u>	<u>Organized</u>
Texas	22.3	77.7	83.4	16.6
Nebraska	25.2	74.8	78.6	21.4
Kansas	6.3	93.7	96.0	4.0
Arizona	47.7	52.3	54.6	45.4
New Mexico	31.4	68.6	75.8	24.2
California	60.9	39.1	49.4	50.6
Washington	84.2	15.8	29.5	70.5
Oklahoma	14.1	85.9	94.5	5.5
Idaho	76.6	23.4	35.1	64.9
Colorado	72.4	27.6	53.2	46.8
Oregon	87.6	12.4	49.7	50.3

Source: Dvoskin, Dan and Heady, Earl O., Energy Requirements of Irrigated Crops in the Western United States, Center for Agricultural and Rural Development, Iowa State University, Ames, Iowa, November 1976, p. 4, Figure 2.

The adoption of energy-conserving technology may depend on whether the water is distributed through an organization that can establish energy conservation requirements, or through private individuals who would be most responsive to the price mechanism. Most of the water used to irrigate the crops of Texas, Nebraska, Kansas, New Mexico, and Oklahoma is controlled within the private sector. Only in Washington and Idaho is the major share of the water controlled through irrigation districts.⁽²⁾ Data describing this relationship can be found in Table 3.

Application Technology

Once reaching the farm gate, irrigation water is applied through gravity systems or through sprinklers. Although gravity systems are more energy efficient, the increase in irrigated acreage watered with gravity systems has not been as great as the increase in acreage irrigated with sprinklers. Only in Kansas has there been a major increase in actual acreage irrigated with gravity systems. Between 1961 and 1976, more than one million acres were brought

TABLE 4. Acreage Irrigated by Method of Application for
the Eleven Major Irrigation States for Four Years
Between 1961 and 1976

State	Method	1961	1966	1971	1976
Texas	Gravity	5,195,000	6,400,000	6,700,000	6,225,000
	Sprinkler	615,000	1,300,000	1,800,000	1,975,000
Nebraska	Gravity	2,838,000	3,246,000	3,567,970	3,978,414
	Sprinkler	250,000	395,000	913,180	2,323,026
Kansas	Gravity	906,813	1,224,054	1,598,163 ^(a)	2,247,000
	Sprinkler	100,000	155,000	370,796 ^(a)	785,160
Arizona	Gravity	1,087,500	1,104,400	1,114,000	1,096,650
	Sprinkler	5,500	20,600	31,000	53,350
New Mexico	Gravity ^(b)	841,000	850,000	900,000	910,000
	Sprinkler	19,000	25,000	115,500	159,600
California	Gravity	7,080,000	7,250,000	7,200,500	7,499,085
	Sprinkler	920,000	1,250,000	1,463,500	1,600,000
Washington	Gravity	711,000	885,000	850,000	787,000
	Sprinkler	360,000	455,000	650,000	827,500
Oklahoma	Gravity	208,000	341,000	435,000	492,725
	Sprinkler	112,000	157,000	215,000	448,495
Idaho	Gravity	2,465,621	3,000,000	2,959,400	2,641,670
	Sprinkler	302,831	569,600	859,000	1,439,400
Colorado	Gravity	2,640,000	2,910,000	3,140,000	2,540,000
	Sprinkler	60,000	140,000	360,000	560,000
Oregon	Gravity	1,100,878	1,320,000	1,190,500	1,105,200
	Sprinkler	303,406	420,000	650,025	853,000
TOTALS		28,121,549	33,147,654	36,973,534	40,547,275

(a) Average 1970 and 1972 figures

(b) Average 1960 and 1963 figures

Sources: Irrigation Journal, Volume 23, No. 6, Water Well Journal Publishing Company, Columbus, Ohio, November-December 1973, pp. 11-20.
Irrigation Journal, Volume 26, No. 6, Brantwood Publications, Inc., Elm Grove, WI, November-December 1976, pp. 23-29.

under irrigation with gravity systems in Kansas. During that 15-year period a million acres were also put under irrigation with gravity systems in Nebraska. But also in Nebraska, irrigation with sprinkler systems increased by over two million acres during the same period. In Arizona, New Mexico, California, Washington, and Oregon, less than 100,000 acres were added to gravity systems. In Colorado the acreage actually decreased. On the other hand, in all of the states except California those lands that were irrigated by sprinkler systems more than doubled.^(3,4) Data describing these relationships can be found in Table 4.

The major technical change in sprinkler irrigation has been the center-pivot system. In three years Nebraska, Kansas, Oklahoma and Idaho have more than doubled their center-pivot systems. The acreage irrigated with center pivots has increased five times in Arizona. In Washington and Oregon it has increased three times.

Acreage irrigated by hand-moved systems has decreased in five of the eleven states. Sideroll and towline systems have decreased in five states. This indicates a shift from hand-moved and towline systems to other less labor-intensive systems. Traveler and big-gun systems have been expanded primarily in Nebraska; although there have been significant percentage increases in other states, the total acreage remains small. Trickle irrigation systems have seen rapid growth only in California. While acreages have more than doubled in other states, the totals are still small.

Methods of irrigation are presented in Table 5. The major conclusion drawn from Table 5 is the dynamic nature of irrigation economy. Farmers have responded quickly and on a large scale to the technological developments in center pivot irrigation.

The trend toward more sophisticated irrigation systems, to improve irrigation efficiency and reduce labor costs during the past decade, occurred in an era of low energy costs. As a result, little attention has been paid to quantifying the total energy inputs involved. The remainder of this chapter provides a description of the energy use in irrigation by category of use.

TABLE 5. Method of Sprinkler Irrigation (in Thousand Acres) for Eleven Major Irrigation States for 1973 and 1976

State	Center Pivot	Trickle	Hand- Moved	Towline/ Sideroll	Solid Set	Traveler/ Gun	TOTAL (a)	Percentage Changes
Texas								
1973	230,000	---	630,000	920,000	<1,000	120,000	1,901,000	4%
1976	520,000	21,000	515,000	850,000	4,000	65,000	1,975,000	
Nebraska								
1973	833,846	40	78,780	388,520	2,600	3,000	1,306,786	77%
1976	1,762,856	40	35,830	475,000	3,300	45,000	2,322,026	
Kansas								
1973	319,000	36,600	---	40,000	640	---	396,240	93%
1976	727,000	---	5,000	32,600	1,000	---	775,600	
Arizona								
1973	5,000	2,000	10,000	13,000	7,000	300	37,300	59%
1976	25,000	5,200	13,000	9,100	7,000	---	59,300	
New Mexico								
1973	150,000	400	10,000	<1,000	---	<1,000	162,400	-2%
1976	150,000	1,000	7,000	1,000	100	500	159,600	
California								
1973	3,000	25,000	825,000	120,000	500,000	3,000	1,476,000	17%
1976	3,000	124,000	1,123,000	150,000	314,000	5,000	1,719,000	
Washington								
1973	80,000	1,000	154,500	485,500	28,000	1,000	750,000	10%
1976	240,000	2,000	130,000	414,000	35,000	6,500	827,500	
Oklahoma								
1973	68,000	---	90,000	71,000	1,000	20,000	250,000	79%
1976	141,275	40	90,150	187,020	5,380	24,670	448,535	
Idaho								
1973	100,000	---	557,000	196,500	55,000	500	909,000	58%
1976	209,670	300	800,140	353,720	74,570	1,000	1,439,400	
Colorado								
1973	300,000	---	20,000	50,000	10,000	1,000	381,000	47%
1976	500,000	---	12,000	30,000	16,000	2,000	560,000	
Oregon								
1973	37,000	150	500,000	160,000	18,500	8,000	723,650	18%
1976	135,000	1,000	500,000	182,000	22,000	13,200	853,200	
TOTAL 1973	2,125,957	65,190	2,875,280	2,445,520	623,740	157,800	6,582,476	
TOTAL 1976	4,413,801	154,580	3,231,120	2,684,440	482,350	157,870	9,346,661	
Percent Change	108%	137%	12%	10%	-23%	0	42%	

(a) Totals may not include small acreages reported as "miscellaneous" or "other."

Source: Irrigation Journal, Volume 23, No. 6, Water Well Journal Publishing Company, Columbus, OH, November-December 1973, pp. 11-20.
Irrigation Journal, Volume 26, No. 6, Brantwood Publications, Inc., Elm Grove, WI, November-December 1976, pp. 23-29.

MANUFACTURING AND INSTALLATION ENERGY

Manufacturing and installation energy is defined as the direct energy required to manufacture plastic, aluminum, steel or brass for piping and fittings, the direct energy required to manufacture and install pumping units, prime movers, and the energy needed for excavation and land leveling. The figures utilized here were adapted from previous research by Batty, et al., Energy Inputs to Irrigation.⁽⁵⁾ Indirect energy inputs such as transportation of pipe from place of manufacture to point of installation and movement of labor to the job site are not included.

Table 6 presents the installation energy inputs required for each of the seven system types. The figures presented have been computed on a per acre basis and prorated over a twenty-year life. The installation energy includes the replacement of system components with an expected life of less than twenty years and a salvage value of recyclable components lasting longer than twenty years. Annual installation energy required per acre ranges from 2,436.8 thousand Btu for a solid set system to 633.7 thousand Btu for the hand-moved system.

TABLE 6. Annual Installation Energy Per Acre Irrigated by Irrigation System, Based on 36-inch Net Irrigation Requirement and Zero Pumping Lift

Irrigation System	Installation Energy	
	(thousand Kcal per acre) ^(a)	(thousand Btu per acre)
Center-Pivot	388.5	1541.6
Trickle	530.5	2105.0
Hand-Moved	159.7	633.7
Towline/Sideroll	200.3	794.8
Solid Set	553.9 ^(b)	2436.8
Traveler/Gun	288.9	1146.4
Surface	201.9 ^(c)	801.2

(a) Reference 4 included 3% maintenance energy for all systems except for solid-set where 1% was used.

(b) Average of solid set and permanent as given in Reference 4.

(c) Average of surface w/o IRRS and surface with IRRS (return system).

By combining the acreage for gravity systems from Table 4 and the acreage for the various types of sprinkler systems from Table 5 with the appropriate installation energies from Table 6, it is possible to estimate the total energy consumed in the installation of irrigation systems by state and by type of system. These estimates are presented in Table 7.

While surface systems require relatively low installation energy, the large acreages devoted to these systems result in consumption of large amounts of installation energy. Surface irrigation systems require more installation energy than any of the other systems examined in all eleven of the high irrigation energy-consuming states. Center-pivot systems are the third largest installation-energy user on a per-acre basis and second only to surface systems in total installation energy consumption for the eleven states. Trickle and traveler/gun systems combined utilize only 1% of the total installation energy, mostly because they are used on only 1% of the irrigated land.

TABLE 7. Estimated Annual Installation Energy Required
by System, by State (Billion Btu)(a)

State	Center Pivot	Trickle	Hand Move	Towline/ Sideroll	Solid Set	Traveler Gun	Surface	TOTAL
Texas	801.6	44.2	326.4	676.6	9.8	74.5	4987.5	6920.6
Nebraska	2717.6	---	22.7	377.5	8.0	45.9	3187.5	6359.2
Kansas	1120.7	---	3.2	25.9	2.4	---	1800.0	2952.2
Arizona	38.5	11.0	8.2	7.2	17.1	---	878.6	960.6
New Mexico	231.0	2.1	4.4	0.8	0.2	0.6	729.1	968.2
California	4.6	261.0	711.7	119.2	765.2	5.7	6008.3	7875.7
Washington	370.0	4.2	82.4	329.1	85.3	7.5	630.5	1509.0
Oklahoma	217.8	---	57.1	148.6	13.1	28.3	394.8	859.7
Idaho	323.2	0.6	507.1	281.1	181.7	1.1	2116.5	3411.3
Colorado	770.8	---	7.6	23.8	39.0	2.3	2035.1	2878.6
Oregon	208.1	2.1	316.9	144.7	53.6	15.1	885.5	1626.0
TOTAL	6803.9	325.2	2047.7	2134.5	1175.4	181.0	23,653.4	36,321.0

(a) Based on 1976 acreage. Total installation energy prorated over 20-year life to obtain annual estimates.

Of the eleven states which consume the largest portions of irrigation energy, California uses the most energy for installation purposes. Texas and Nebraska are the second and third largest installation energy users, respectively.

Pumping Energy

Pumping energy is the energy consumed in getting the water to field level from the source; the source can be ground water (wells) and/or surface water (streams, lakes, reservoirs, or irrigation district canals). Pumping energy varies with the volume of water pumped, the average lift required, and the efficiency of pumps and power units. The volume of water pumped in each state is calculated by multiplying the weighted average of the acre-feet of water applied in each state by system type (Table 8), by the total acreage irrigated in 1976 (Table 4). The results of these computations are presented in Table 9.

California uses the most water, at 28.84 million acre-feet annually; this is more than twice as much as any other state. The four largest water using states (California, Texas, Nebraska and Idaho) account for 68% of the water use in the eleven states.

The average feet of lift, from ground water and surface water sources, required by each state are presented in Table 10. These figures were then weighted by the volumes of water pumped from each source to compute a weighted average lift required in each state. The average lift for each state is then used in the computation of the net pumping energy consumed.

Net pumping energy is computed in the following manner:

$$\text{Net Energy} = \frac{\left(\frac{\text{Volume Pumped}}{\text{Acre-ft}} \right) \left(\frac{\text{Average Lift}}{\text{ft}} \frac{2.718 \times 10^6}{\text{lb/acre-ft}} \right)}{(\text{Pump Efficiency})(777.9 \text{ ft-lb/Btu})}$$

The volumes of water pumped and the average lifts are taken from Tables 9 and 10 respectively. Pump efficiency was assumed to be 60%. The results of these computations are presented in Table 11.

Net pumping energy required per state ranges from 1,723 billion Btu in Oklahoma to 17,109 billion Btu in California. Total net pumping energy required in the eleven states is 88,234 billion Btu.

TABLE 8. Acre-Feet of Water Applied Per Acre

State	Weighted Average ^(a)	Surface ^(b)	Sprinkler ^(b)
Texas	1.5	1.57	1.26
Nebraska	1.83	1.96	1.57
Kansas	1.5	1.58	1.26
Arizona	5.5	5.55	4.44
New Mexico	2.5	2.58	2.06
California	3.17	3.29	2.63
Washington	3.8	4.23	3.38
Oklahoma	1.33	1.47	1.18
Idaho	2.5	2.69	2.15
Colorado	1.08	1.12	0.90
Oregon	2.83	3.10	2.48

(a) Sloggett, Gordon, Energy and U.S. Agriculture: Irrigation Pumping, 1974. Economic Research Service, U.S. Department of Agriculture, Agricultural Economic Report No. 376.

(b) Volumes of water applied by surface and sprinkler methods were disaggregated from the weighted average by the following equations described in Pumping Energy Requirements for Irrigation in California (6):

$$W_1 = \frac{A_1 + A_2}{A_1 + 0.8A_2} (W_A)$$

$$W_2 = \frac{0.65}{0.81} = 0.8W_1$$

where:

0.65 = average efficiency for surface method
 0.81 = average efficiency for sprinkler method
 W_A = average depth of water applied
 W_1 = depth of water applied by surface irrigation
 W_2 = depth of water applied by sprinkler irrigation
 A_1 = acres of surface irrigation
 A_2 = acres of sprinkler irrigation

TABLE 9. Total Acre-Feet of Water Applied by State

	<u>Total Acre</u> ^(a)	<u>Avg Acre-Ft</u> ^(b) <u>Per Acre</u>	<u>Total Acre-Ft</u> <u>(Millions)</u>
Texas	8,200,000	1.5	12.30
Nebraska	6,301,440	1.83	11.53
Kansas	3,032,160	1.5	4.55
Arizona	1,150,000	5.5	6.33
New Mexico	1,069,600	2.5	2.67
California	9,099,085	3.17	28.84
Washington	1,614,500	3.8	6.14
Oklahoma	941,220	1.33	1.25
Idaho	4,081,070	2.5	10.20
Colorado	3,100,000	1.08	3.35
Oregon	<u>1,958,200</u>	2.83	<u>5.54</u>
	40,547,275		92.70

(a) from Table 4

(b) from Table 8

The net pumping energy requirement is a measure of the energy input to the prime mover and the water output of the pump. There are two major energy losses which occur in the pumping process. One loss occurs as the result of pumps working at less than 100% efficiency. The other loss occurs in the prime mover during the conversion of thermal or electric energy to shaft energy.

In order of calculate the gross pumping energy requirement it is necessary to know the efficiencies of the various types of prime movers, the energy content of each of the five energy sources and the percent of total energy use represented by each resource type. These figures are presented in Table 12 and 13.

TABLE 10. Average Feet of Lift Required by State

	<u>Ground Water</u>	<u>Surface Water</u>	<u>Weighted^(a) Average</u>
Texas	200	40	173.4
Nebraska	100	20	91.5
Kansas	180	15	175.3
Arizona	350	0	350
New Mexico	350	5	332
California	110	10	102
Washington	250	250	250
Oklahoma	250	20	237
Idaho	275	0	203
Colorado	115	10	112
Oregon	200	150	162.3

(a) Average feet of life are weighted by volume of water pumped from each source.

Source: Sloggett, Gordon, Energy and U.S. Agriculture: Irrigation Pumping, 1974. Economic Research Service, U.S. Department of Agriculture, Agricultural Economic Report No. 376.

TABLE 11. Net Pumping Energy Required per State

	<u>Billion Btu</u>
Texas	12,420
Nebraska	6,144
Kansas	4,645
Arizona	12,902
New Mexico	5,162
California	17,130
Washington	8,939
Oklahoma	1,725
Idaho	12,058
Colorado	2,185
Oregon	5,236
TOTAL	88,546

TABLE 12. Energy Content of Fuels and Efficiencies of Power Units

Power Unit	Efficiency ^(a)	Energy Per Unit of Fuel	Net Energy Per Unit of Fuel
Diesel	0.24	140,000 Btu/gal ^(b)	33,600 Btu/gal
Gasoline	0.19	128,000 Btu/gal ^(c)	24,300 Btu/gal
LPG	0.21	92,500 Btu/gal ^(b)	19,400 Btu/gal
Natural Gas	0.19	1×10^6 Btu/1000 ft ^{3(b)}	190,000 Btu/1000 ft ³
Electricity	0.83	3,413 Btu/kWh ^(b)	2,833 Btu/kWh

(a) Fraction of thermal energy converted to shaft energy, Reference 5.

(b) J. H. Perry, Chemical Engineers' Handbook, McGraw-Hill Book Company, Fourth Edition.

(c) L. S. Marks, Mechanical Engineers' Handbook, McGraw-Hill Book Company, Fifth Edition.

TABLE 13. Type of Irrigation Power Units by Percent

	Diesel	Gasoline	LPG	Natural Gas	Electricity
Texas	6	---	4	60	30
Nebraska	37	1	14	23	25
Kansas	13	1	9	61	17
Arizona	---	---	---	28	72
New Mexico	10	5	15	40	30
California	---	---	---	2	98
Washington	---	---	---	---	100
Oklahoma	8	3.5	27	39.5	22
Idaho	1	---	0.5	1	97
Colorado	5	2	11	9	73
Oregon	---	---	---	---	100

Source: Irrigation Journal, Volume 26, No. 6, Brantwood Publications, Inc., Elm Grove, WI, November-December 1976, pp. 23-29.

Energy conversion efficiencies range from 19% for gasoline and natural gas to 83% for electricity. Electricity is the only energy source which is used in all eleven states. It is the major source in six of the eleven states and in Washington and Oregon it is the exclusive energy source used for pumping irrigation water.

The amounts of each of the five energy types used to pump water in each state were estimated in the following manner:

$$\text{Fuel Used} = \frac{\left(\frac{\text{Total Net Pumping Energy}}{\text{Net Energy Per Unit of Fuel}} \right) \left(\frac{\text{Percent of Fuel Type Used}}{\text{Type Used}} \right)}{\text{Net Energy Per Unit of Fuel}}$$

The results of these computations are summarized in Table 14. Nebraska uses the most diesel fuel and liquid petroleum gas (LPG); Texas uses the most natural gas, and the largest users of electricity and gasoline are California and New Mexico, respectively.

TABLE 14. Estimated Fuel Use for Pumping, by Type, by State

	<u>Diesel</u> <u>(1000 gal)</u>	<u>Gasoline</u> <u>(1000 gal)</u>	<u>LPG</u> <u>(1000 gal)</u>	<u>Natural Gas</u> <u>(million ft³)</u>	<u>Electricity</u> <u>(million kWh)</u>
Texas	22,179	---	25,608	39,221	1,315
Nebraska	67,657	2,528	44,338	7,437	542
Kansas	17,971	1,911	21,549	14,913	279
Arizona	---	---	---	19,013	3,279
New Mexico	15,363	10,621	39,912	10,867	547
California	---	---	---	1,803	5,926
Washington	---	---	---	---	3,155
Oklahoma	4,107	2,485	24,007	3,586	134
Idaho	3,589	---	3,108	635	4,129
Colorado	3,251	1,798	12,389	1,035	563
Oregon	---	---	---	---	<u>1,848</u>
TOTAL	134,117	19,343	170,911	98,510	21,717

The estimated volumes of each type of energy source used were then converted to a common energy measurement (Btu) by multiplying the units of fuel used by the energy content per unit for each fuel type. Gross pumping energy used in each state ranges from 4,788 billion Btu in Colorado to 49,183 billion Btu in Texas. By source type, natural gas accounts for the greatest pumping energy use followed by electricity, diesel, LPG and gasoline in that order. Total pumping energy used in the eleven states is estimated to be 209,698 billion Btu. These figures are presented in Table 15.

TABLE 15. Gross Pumping Energy, by Type, by State
(Billion Btu)

	<u>Diesel</u>	<u>Gasoline</u>	<u>LPG</u>	<u>Natural Gas</u>	<u>Electricity</u>	<u>TOTAL</u>
Texas	3,105	---	2,369	39,221	4,488	49,183
Nebraska	9,472	324	4,101	7,438	1,850	23,184
Kansas	2,516	245	1,993	14,913	950	20,619
Arizona	---	---	---	19,013	11,199	30,212
New Mexico	2,151	1,359	3,692	10,867	1,867	19,936
California	---	---	---	1,803	20,225	22,028
Washington	---	---	---	---	10,768	10,768
Oklahoma	575	318	2,221	3,586	457	7,157
Idaho	502	---	287	635	14,092	15,516
Colorado	455	230	1,146	1,035	1,922	4,788
Oregon	---	---	---	---	6,307	6,307
TOTAL	<u>18,776</u>	<u>2,476</u>	<u>15,809</u>	<u>98,510</u>	<u>74,127</u>	<u>209,698</u>

Application Energy

Once energy has been expended to manufacture and install the irrigation system and pump water to the field level, energy expenditure for water application is required to make the system useful. Water application energy depends on the pump and prime mover efficiencies, the volume of water applied and the type of application system.

The net application energy required to deliver one acre-foot of water by each of the six sprinkler application methods was computed using the following formula:

$$E = \frac{(\text{Head})(1 \text{ acre-ft of Water})(43,560 \text{ ft}^3/\text{acre-ft})(62.4 \text{ lb/ft}^3)}{(60\%)(777.9 \text{ ft-lb/Btu})}$$

Explicit in the formula is an assumed pump efficiency of 60%. The operating head and net application energies required are presented in Table 16. When comparing the application energy required by various sprinkler systems delivering the same volume of water, the only factor which varies among systems is the operating head. The difference in application energy required is then directly proportional to the difference in operating head. Referring to Table 16, the traveler/gun and center-pivot systems require the largest operating head and utilize the greatest amounts of energy to deliver one acre-foot of water. These systems require 2.21 and 1.34 million Btu per acre-foot respectively. Multiplying the energy requirement to deliver one acre-foot by the average number of acre-feet delivered per acre (Table 8) and by the total number of acres devoted to each system (Table 5) results in the total net energy required for each system in each of the eleven states. These figures are presented in Table 17.

TABLE 16. Operating Head and Net Energy Required to Apply One Acres-Foot of Water, by System Type

<u>System</u>	<u>Operating Head (ft)</u>	<u>Btu/Acre-ft (Millions)</u>
Center-Pivot	230 ^(a)	1.34
Trickle	115 ^(b)	0.67
Hand-Moved	160 ^(a)	0.93
Towline/Sideroll	160 ^(a)	0.93
Solid Set	160 ^(a)	0.93
Traveler/Gun	380 ^(a)	2.21

(a) Reference 7

(b) Reference 5

TABLE 17. Net Sprinkler Application Energy (Billion Btu)

	<u>Center- Pivot</u>	<u>Trickle</u>	<u>Hand-Moved</u>	<u>Towline/ sideroll</u>	<u>Solid Set</u>	<u>Traveler/ Gun</u>	<u>Total Net Application Energy</u>
Texas	878	18	603	996	5	181	2,681
Nebraska	3,732	---	53	698	5	140	4,628
Kansas	1,237	---	6	39	1	---	1,283
Arizona	149	15	54	38	29	---	285
New Mexico	414	1	13	2	---	2	432
California	11	219	2,747	367	768	29	4,141
Washington	1,090	5	410	1,305	110	49	2,969
Oklahoma	223	---	99	205	6	64	597
Idaho	604	---	1,600	707	149	5	3,065
Colorado	603	---	10	25	13	4	655
Oregon	<u>449</u>	<u>2</u>	<u>1,153</u>	<u>420</u>	<u>51</u>	<u>72</u>	<u>2,147</u>
TOTAL	9,390	260	6,748	4,802	1,137	546	22,883

The same method used to convert net energy to gross energy for pumping was used to compute the gross energy requirement for sprinkler application systems. These figures are presented in Table 18 by energy source for each of the eleven states.

Nebraska uses the largest amount of energy (17,462 billion Btu) for water application, an amount 26 times greater than that used in Arizona. Natural gas and electricity are the major application energy sources accounting for 72% of the total sprinkler application energy.

Surface application energy required by each state was computed in the same manner as described above for sprinkler systems. Net energy and total energy requirements are presented in Tables 19 and 20 respectively. Texas was found to be the largest energy user in surface systems followed closely by California and Nebraska. Natural gas and electricity are again the major energy sources, accounting for 80% of the total.

TABLE 18. Energy Used for Sprinkler Application
(Billion Btu)

	<u>Diesel</u>	<u>Gasoline</u>	<u>LPG</u>	<u>Natural Gas</u>	<u>Electricity</u>	<u>TOTAL</u>
Texas	670	---	511	8,466	969	10,616
Nebraska	7,135	244	3,085	5,602	1,396	17,462
Kansas	695	68	550	4,119	263	5,695
Arizona	---	---	---	420	249	669
New Mexico	180	114	308	909	154	1,665
California	---	---	---	436	4,891	5,327
Washington	---	---	---	---	3,577	3,577
Oklahoma	199	110	767	1,241	160	2,477
Idaho	128	---	73	162	3,580	3,943
Colorado	137	69	343	310	577	1,436
Oregon	---	---	---	---	2,587	2,587
TOTAL	9,144	605	5,637	21,665	18,403	55,454

TABLE 19. Net Energy Required for Surface Irrigation

	<u>Acres</u>	<u>(Acre/ft Acre)</u>	<u>Billion Btu</u>
Texas	6,225,000	1.57	682
Nebraska	3,978,414	1.96	544
Kansas	2,247,000	1.58	248
Arizona	1,096,650	5.55	425
New Mexico	910,000	2.58	164
California	7,499,085	3.29	1,722
Washington	787,000	4.23	232
Oklahoma	492,725	1.47	51
Idaho	2,641,670	2.69	496
Colorado	2,540,000	1.12	199
Oregon	1,105,200	3.10	239

$$E = \frac{(\text{Head})(\text{Acres Surface Irrigated})(\text{Acre-ft/Acre})(2.718 \times 10^6 \text{ lb/Acre-ft})}{(\text{Pump Efficiency})(777.9 \text{ ft/lb Btu})}$$

Head = 12 ft (Reference 2)

Pump Efficiency = 60%

TABLE 20. Energy Used for Surface Application
(Billion Btu)

	<u>Diesel</u>	<u>Gasoline</u>	<u>LPG</u>	<u>Natural Gas</u>	<u>Electricity</u>	<u>TOTAL</u>
Texas	170	---	130	2,154	246	2,700
Nebraska	839	29	363	659	164	2,054
Kansas	134	13	106	796	51	1,100
Arizona	---	---	---	626	369	995
New Mexico	68	43	117	345	58	631
California	---	---	---	181	2,034	2,215
Washington	---	---	---	---	280	280
Oklahoma	17	9	66	106	14	212
Idaho	21	---	12	26	580	639
Colorado	41	21	104	94	174	434
Oregon	<u>---</u>	<u>---</u>	<u>---</u>	<u>---</u>	<u>287</u>	<u>287</u>
Total	1,290	115	898	4,987	4,257	11,547

Total Energy Use

A summary of energy use by category, total energy use and total energy use per acre is presented, by state, in Table 21. Energy use for irrigation in the eleven states ranges from a low of 9,537 billion Btu in Colorado to 69,420 billion Btu in Texas. Total energy use in the eleven states was estimated to be 313,021 billion Btu. This amount is significantly greater than 0.26 quad which was the estimated use in 1974. The difference, however, is roughly proportional to the increase in irrigated acreage between 1974 and 1976.

TABLE 21. Summary of Energy Use in Irrigation, 1976
(Billion Btu)

	<u>Mfg. & Install.</u>	<u>Pumping</u>	<u>Sprinkler Appli.</u>	<u>Surface Appli.</u>	<u>Total</u>	<u>Energy Use/ Acre Btu</u>
Texas	6,921	49,183	10,616	2,700	69,420	8,456,854
Nebraska	6,359	23,184	17,462	2,054	49,059	7,785,363
Kansas	2,952	20,619	5,695	1,100	30,366	10,014,643
Arizona	961	30,212	669	995	32,837	28,553,913
New Mexico	968	19,936	1,665	631	23,200	21,690,351
California	7,876	22,028	5,327	2,215	37,446	4,115,359
Washington	1,509	10,768	3,577	280	16,134	9,993,137
Oklahoma	860	7,157	2,477	212	10,706	11,374,599
Idaho	3,411	15,516	3,943	639	23,509	5,760,499
Colorado	2,879	4,788	1,436	434	9,537	3,076,451
Oregon	1,626	6,307	2,587	287	10,807	5,518,844
TOTAL	36,322	209,698	55,454	11,547	313,021	

CONCLUSIONS

This chapter has shown that while some irrigation occurs in all fifty states, 79% of the irrigated acreage lies within the boundaries of eleven states. These eleven states use 87% of the total energy used for irrigation nationally. Further, it has been shown that energy consumption for irrigation purposes tends to be crop specific. Five crops which are produced in the eleven highest energy consuming states account for 55% of the total energy used for irrigation in the nation.

Three major areas of energy consumption in irrigation were identified as manufacturing, pumping, and application. Total manufacturing and installation energy for the eleven states was found to be 36,322 billion Btu. The utilization of energy by each state in this category is primarily related to the total number of irrigated acres. Those states with the greatest number of irrigated acres (California, Texas, and Nebraska) used the greatest amount of energy in system manufacture and installation.

More than two-thirds of the total energy used for irrigation is consumed in pumping water from the source to the field level. Pumping energy consumed depends on the volume of water pumped and the distance the water must be raised. The importance of the pumping lift may be shown by a comparison of two states, Nebraska and Arizona. Nebraska has five times the irrigated acreage of Arizona and pumps 82% more water. Arizona consumes 30% more energy because the average pumping lift is 3.8 times as great as the average lift in Nebraska.

On the basis of this analysis, it is concluded that projects should be selected which:

1. Are most applicable to cultural practices used in Texas, Nebraska, Kansas, Arizona, New Mexico, California, Washington, Oklahoma, Idaho, Colorado, and Oregon.
2. Applicable to the production of sorghum, cotton, wheat, corn, and alfalfa.
3. Reduce the energy required to pump ground water to the surface.

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III. AN ABRIDGED SURVEY OF ENERGY CONSERVATION RESEARCH .

III. AN ABRIDGED SURVEY OF ENERGY CONSERVATION RESEARCH

The purpose of this chapter is to describe that ongoing research which could be defined through a limited telephone survey. The source of technological invention is either the Colleges of Agriculture in those states which have large irrigated acreages, or private companies which use research, invention, and discovery to be more competitive. Current irrigation projects funded at the state universities of the eleven states which consume over 89% of the energy used in irrigation were identified. State water resource centers and agricultural extension offices were contacted when projects or project leaders overlapped. Manufacturers of irrigation equipment were also surveyed.

The universities of the eleven largest irrigation energy-consuming states were contacted by telephone and queried about ongoing or recently completed projects relating to technology transfer and economic studies of energy or water conserving techniques. The completed projects described were followed by an analysis of the published report when available. This chapter includes a list of these projects with a description of their main objective or result.

For the purposes of this analysis, the types of projects were classified by the applicable part of the irrigation process. These are:

- Well Design
- Pumps
- Prime Movers
- Application
- Scheduling
- Agronomics

Each type of project is discussed with respect to economics and technology.

Many projects are funded through the various state Water Resource Research Institutes that are often staffed by university professors. These institutes were established by the Office of Water Research and Technology, U.S. Department of Interior, under authorization of the Water Resource Research Act of 1964 (P.L. 88-379). State sources and contracts with local, state, and Federal agencies provided additional research support. Some projects overlap several

categories; these were classified according to the main thrust of the project. Table 22 summarizes by state the type and number of existing projects. By topic, the greatest number of projects currently funded are in the areas of application, scheduling and agronomics.

AGRICULTURAL ECONOMICS RESEARCH PROJECTS

No work is currently funded in the areas of well design or prime movers.

Pumps

Research concerning pumps is currently in progress in Colorado, Oklahoma, California and Texas.

Colorado State University is conducting work to (1) improve pumping efficiency, resulting in a 20 to 25% decrease in energy consumption, and (2) to develop better water management techniques which will result in a 20 to 35% decrease in consumption. Researchers at Colorado felt that no new pump technology is needed. Education of the farmers on the above items would result in a multiplicative effect of the items, resulting in a 50% savings in energy used for irrigation.⁽³⁾

Oklahoma State University has developed a computer program for estimating fixed and variable pumping cost for any deep water system (300 to 500 ft).⁽⁴⁾

The University of California (Davis) recently completed a study which calculated the pumping energy requirements for irrigation for various regions in California and for various crops.⁽⁵⁾

Texas Tech is currently looking at the cost trade-offs between fuel costs and increased maintenance costs which would be required to maintain pump efficiencies close to that of new pumps.⁽⁶⁾

Application

Oregon State University developed a linear program model for the Bureau of Reclamation to evaluate expected benefits from conservation methods (including pricing as a means of allocation) for three irrigation districts in Oregon.⁽⁷⁾ Another study at OSU involves irrigation development in the North Columbia Basin

TABLE 22. Existing Projects in Universities to Conserve Energy in Irrigation by State and Topic

	AZ	CA	CO	ID	KA	NB	NM	OK	OR	TX	WA	TOTAL
Well Design		x								x		2 x 0 *
Pumps		*	*	x			x	*		*		2 x 4 *
Prime Movers	x				xxx	x					x	6 x 0 *
Application	xxx	x ***		x *	xx		*		xxxx **	x **	xxx	15 x 9 *
Scheduling			x	*		x **			x	x	xx	6 x 3 *
Agronomics	**		x		x	x *	x	**	x	***	xx	7 x 8 *
TOTALS	6	6	3	4	6	6	3	3	8	9	8	62

x Agricultural Engineering
* Agricultural Economics

Region. The study includes resource substitution in both sideroll and center-pivot irrigation. The objective was to provide information to the farmers for deciding which irrigation system to use if water becomes scarce or expensive.⁽⁷⁾

New Mexico State University has several projects which analyze trickle irrigation economics. One involves a small pecan orchard; another one applies trickle irrigation to cotton.⁽⁸⁾

Texas Tech has completed an analysis of shifting from irrigation to limited irrigation on dryland farming, based on short-run rising natural gas prices. In another project, the long-range effects of rising natural gas prices on irrigation in Texas are being determined.⁽⁶⁾

University of California (Davis) expects that the state will fund a study to determine exactly where energy is saved when switching from surface to sprinkler or drip irrigation systems.⁽⁵⁾

University of California has a project titled Energy Considerations and Conservation in Coordinated Use of Surface Groundwater. Until recently, the design and operation of coordinated surface and groundwater storage and supply systems have been largely on technical and economic considerations without analysis of the consumption and conservation of energy. The main objectives of this project are to examine energy consumption in coordinated use of surface and groundwaters and to develop design criteria and operational procedures that will minimize energy consumption compatible with improved water conservation.⁽⁹⁾

University of California (Davis) has funds for a study designed to determine the total energy used in an irrigation system. It will include the energy inputs for digging wells, manufacturing the aluminum, and other inputs.⁽⁵⁾

The University of Idaho will define and identify various criteria affecting the level of water management in large irrigated areas. Techniques are to be developed for selecting optimal irrigation systems that meet specified water management criteria. The techniques developed will then be applied to a large (100,000 acre) tract in eastern Idaho.⁽¹⁰⁾

Scheduling

The University of Nebraska has developed a simplified irrigation scheduling model (IRRIGATE) as an educational tool for farmers. Irrigations are scheduled to produce maximum yields with a minimum of applied irrigation water.⁽¹¹⁾ Additional, a mathematical model, CORNGRO, has been developed to predict daily water crop use, plant growth and crop yield for corn. CORNGRO has the capability to predict corn yields as a result of different irrigation timing and amounts.⁽¹¹⁾

Utah State University has developed irrigation schedules as a method for conserving water,⁽¹²⁾ and the University of Idaho constructed a linear programming model to determine crop irrigation schedules.

Agronomics

University of Arizona has experimented with varieties of plants with the objective of: (1) providing the same yield with less water, and (2) increasing the yield by using different plant varieties.⁽¹⁴⁾

Oklahoma State University has developed budgets for various technologies of different production systems; the goal was to maximize return to irrigator. One of the main items considered was reduced tillage.⁽⁴⁾ In another project computer models for scheduling water application needed for the stage of growth are to be developed for corn, grain sorghum, and wheat. Models already exist for these crops at other universities, but Oklahoma State intends to improve them.⁽⁴⁾ Models now exist for:

- Grain sorghum at Texas A & M,
- Corn at Upper Midwest Universities, and
- Wheat at Oklahoma State

The University of Nebraska has studied the management of irrigated agriculture with a limited water and energy supply. Corn and grain sorghum are being analyzed in order to develop criteria for:⁽¹⁵⁾

- stress conditioning
- developing a corn growth/yield model
- determining a production function for water application.

Texas A & M University has recently completed an economic analysis of new crop production systems for cotton. This involved close coordination in the variety selection, fertilizer, irrigation water and pesticides as well as cultural practices. Texas A & M has documented that short season cotton can be produced using 45% to 56% less energy (in Kcal) per kg of lint produced.⁽¹⁶⁾ A linear programming model was developed for the High Plains area of Texas using multiple production activities of the various study crops; corn, cotton, grain sorghum, soybeans and wheat. The primary focus of the analysis was to evaluate the expected short run adjustments in agriculture that would be associated with changes in input prices, namely: diesel fuel, natural gas, nitrogen and water.⁽¹⁶⁾

AGRICULTURAL ENGINEERING DEPARTMENT RESEARCH PROJECTS

The majority of the research projects are being conducted in the area of application with emphasis on development and evaluation of low pressure nozzles for sprinkler irrigation systems. However, several studies concerned with application are aimed at improving the efficiency and reducing the labor requirements for irrigation.

A significant number of projects are concerned with measuring the energy and water efficiencies for irrigation systems and even for entire irrigation districts. Also, several projects have dealt with the development and dissemination of reference material on energy and water management methods.

Well Design

Texas A & M University has developed design procedures for drilling irrigation wells. Use of well screens, well sizing core samples, and other improvements which result in ease of pumping water and increased well life are included.

The University of California (Davis) has been involved in well drilling techniques which result in being able to pump water more efficiently.

Pumps

New Mexico State University is involved in a two-year program (1977-1978) to develop methods for testing pumping system efficiencies on the farm. The

main problem found has been a poor match between the pump and well, resulting from a problem found has been a poor match between the pump and well, resulting from a lowered water table. Some farmers have cut back on the pump's engine throttle in hopes of decreasing fuel consumption, but this has resulted in decreased efficiency and, because of the lower speed, has moved the pump off its maximum efficiency.

The extension services at the University of Idaho are working to promote energy conserving practices. Techniques for measurement of energy efficiency are being developed with emphasis on devices to measure water flow.

Prime Movers

Kansas State University has:

- A contract with FEA to gather data on fuel use to be used to develop educational material for farmers
- A paper study on alternate sources of energy (currently the state uses mostly natural gas)
- A study of off-peak operation of irrigation systems

The University of Nebraska has a program with MIT and DOE on the development of solar photo cells to generate electricity to operate pumps.

The University of Arizona has a project on development of variable speed induction motors which would result in a larger range of efficient operation.

Washington State University has conducted a study of more efficient use of electrical generating capacity by off peak operation.

Application

Kansas State University has two projects involving energy conservation in irrigation application:

- Development of automated gravity (or low pressure) pipe system for rill irrigation to replace center pivot and other high-energy sprinkler systems. The system would reduce the normally high labor requirements of rill irrigation. Keys to program are valve development, control system, and integration of the overall system.

- A study on reduction of pressure requirements for center pivots.

The University of Idaho is evaluating low pressure nozzles for both wheel line and center-pivot applications.

Oregon State University has had several projects involving energy conservation in irrigation distribution:

- Study of methods to remove silt and other materials from water to be used in drip irrigation systems. Drip irrigation can reduce both energy and water requirements, but problems with nozzle clogging has greatly limited its use.
- Determine overall effectiveness of continuous-move sprinkler systems (center pivots). Because of uniform application these systems can reduce water requirements by 20%, which reduces energy requirements, but they also require more energy for moving.
- Relation of low-pressure nozzles which have a high application rate and the ability of soils and crops to handle this higher rate.
- Study on total energy requirements for various types (pivot, wheel line, rill, etc.) of irrigation systems. Includes not only the operation requirements but also the energy used in the initial manufacture of each system.

The University of Arizona has been involved in:

- Promotion of water conservation techniques
 - (1) Use of laser plane for better control in field leveling.
 - (2) Use of basin irrigation which has no run-off.
 - (3) Sprinkler systems which use less water.
- Development of more efficient surface irrigation techniques (alternate row, length of runs, amount of depletion, field slope, etc.)
- Drip irrigation studies

Washington State University has projects involving:

- The study of the effectiveness of drop and trickle irrigation systems with respect to water use efficiency, and study of micro-irrigation systems for trees and other wide-spaced crops.
- The reduction of energy requirements in center-pivot operations which are consistent with soil and water requirements.
- Monitoring program for determining the efficiency of installed irrigation systems.

The University of California (Davis) has conducted an energy use study for the State of California for the surface, furrow, sprinkler and drip irrigation methods.

Scheduling

Oregon State University has promoted the use of moisture measurement devices (gypsum blocks, potentiometers, evaporation pans) for irrigation scheduling.

Washington State University is studying the control of center pivots by monitoring moisture conditions around the path of the pivot and studying the improvement of water use efficiency through management techniques such as irrigation scheduling and altered application rates.

The University of Nebraska has been involved in a promotion of water conservation management methods through irrigation scheduling. Between 10 and 12 Firms in Nebraska advise farmers on when to schedule irrigations.

Texas A & M University has studied the use of high-frequency irrigation with a frequency as high as once per day to 2 or 3 times per week. The method makes more efficient use of rain when it does come.

Agronomics

Kansas State University has an Evaporation-Transpiration Laboratory and field plots to study requirements in irrigation scheduling.

New Mexico State University is starting water application studies to determine the optimum time to apply water to various crops.

The University of Nebraska has conducted a study on crop water requirements.

Washington State University has made measurements of crop water consumption of various crops at different growth stages. Washington State University has also defined the hydraulics of surface water movement so that excessive water is not lost to ground water.

Colorado State University had made a characterization of water distribution patterns under surface irrigation. The results are to be used to decrease deep seepage of water. Field tests on furrow irrigation to determine characteristics of infiltration, soil moisture, inflow and outflow and advance and recession of water in the furrow emphasize the need for water management.

University Research

The survey of university research activities in the eleven highest irrigation energy consuming states resulted in the identification of sixty-two irrigation related projects. The majority of these projects (forty-eight) are in the categories of application, scheduling and agronomics. Irrigation research at the university level tends to be primarily concerned with the organization of existing material techniques rather than the generation of new techniques. That is, university research is geared to the more efficient use of productive resources; capital, labor, energy and water, given an existing material technology. While changes in systems of production or resource use constitute changes in technology, they may perhaps be aptly defined as changes in social technology. Some university-level research is directed toward changes in material technology (fourteen of the sixty-two projects identified). The majority of changes in material technology seem to emanate from the private sector.

EQUIPMENT MANUFACTURERS

Several manufacturers of irrigation systems and equipment were contacted in order to gain a better understanding of the research activities within the industry. The limited survey undertaken provided useful insights into industry activities. The research activities of the industry are not generally as well

defined as those for universities where research is done on a project basis. A general, non-discrete goal of each manufacturer was increased energy efficiency of the particular product or products manufactured. One problem facing manufacturers is that their products may face price competition from other less energy-efficient products. The drive toward energy efficiency is then constrained by price competition in the product market since substitutability is determined by each irrigator on the basis of factor prices.

Pump manufacturers are working to increase pump efficiency. One project was identified where a pump manufacturer was cooperating with a research organization in testing the efficiencies of vertical turbine pumps.⁽¹⁷⁾

One manufacturer of diesel engines is developing a direct injection engine for irrigation application. The direct injection engine is more fuel efficient but tends to have a higher rate of undesirable exhaust emissions. The use of heat exchangers in the pump discharge line for engine cooling is being considered as one method of reducing the engine power requirements for cooling purposes. Greater attention is being given to the sizing of the prime mover to the auxiliary equipment. It is also thought to be a method of reducing energy consumption, as needless overpowering of the system results in greater energy consumption than that which is actually required.⁽¹⁸⁾

A major effort is being made by manufacturers of application systems to reduce the power required for pumping water and moving the application system. For center-pivot systems these efforts include:

- Low-pressure center pivots with sprinkler head operating at 7 to 8 psi.^(19,21,22)
- Weight reduction through aluminum construction and decreased pipe size at the end farthest from center.⁽²⁰⁾
- Low-profile construction to get the pipe closer to the ground and low-angle sprinkler heads to reduce evaporative water loss.⁽¹⁹⁾
- Trail lines and drop tubes which apply water at ground level.^(19,20)

Continuous and non-continuous lateral move systems are also being developed.^(19,20)

CONCLUSIONS

This chapter has identified two types of technological change--social and material. Social technology is defined as that body of knowledge relating to the organization and efficient use of factor inputs in the production process. Material technology is defined as being machine- or hardware-oriented. A comprehensive Energy Conservation Program would integrate social and material technology.

The chapter identified 62 current research projects at universities in the eleven states using the most irrigation. Pumping energy was previously identified as using two-thirds of the energy required for irrigation. Only 14 of the 62 projects identified are addressed to this topic. The remaining 48 projects are addressed to topics which, in total, use 21% of the total energy use in irrigation. The most efficient allocation of Federal funds would be to instigate projects to increase energy efficiency in wells, pumps, and prime movers.

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IV. THEORETICAL CONSIDERATIONS OF TECHNOLOGICAL CHANGE

IV. THEORETICAL CONSIDERATIONS OF TECHNOLOGICAL CHANGE

Social and material technological change were identified in the preceding chapter. A comprehensive Energy Conservation Program would integrate social and material technology. That integrating process can begin with theoretical considerations of technological change. In so doing, recommendations can also be made for project selection.

When energy is defined as the capacity to do work it becomes apparent that the evolution of a productive and efficient agricultural economy in the United States has been the result of the movement to increasingly higher levels of energy utilization. U.S. agriculture has moved from a system which used human labor to one which used animal power to a system which uses machines and the energy from fossil fuels. The choice is now available to growers to become less dependent on direct rainfall for the production of crops. The discovery and invention of new irrigation technics, when innovated, have made available to producers a range of input substitutions which result in greater levels of energy utilization. The rate of technical innovation is constrained by the relationship between physical transformation possibilities, factor prices, and product prices.

If a grower can take a given quantity of water and land and combine it with more capital and less labor to get the same quantity of output, he has substituted capital for labor. If in the process less water evaporates, flows into drainage ditches, or is absorbed to a level below which the roots can use it, he has substituted capital for water. If he can now move less water to obtain the same yield, he has substituted capital for energy. He can substitute capital for labor by purchasing equipment that moves the water more easily. He can buy pipe and valves which are easier to handle than bordering tools and shovels. He can then purchase automatic valves that close after a preset amount of water has flowed through the pipes. With some investment in capital, he has not only made his life easier, he is also able to more precisely measure and control the water with which he works. The farmer, therefore, uses his water more efficiently. In so doing, he also uses energy more efficiently.

Consider the output of an irrigated farm enterprise as:

$$Y = f(K, N, E, V) \quad (1)$$

where:

Y = specifies the output of an irrigated enterprise,

K = specifies capital,

N = specifies labor,

E = specifies energy, and

V = specifies water.

Energy-conserving technological change in irrigation permits the same level of output to be produced with less energy or enables the former level of energy use to result in greater output. These situations are presented graphically in Figure 1 as a movement from point A to point B and from point A to point C, respectively. In both cases non-energy inputs have been substituted for energy inputs in the production process.

FIGURE 1. Production Isoquants

Energy-efficient technological change can use more capital, more labor, more water, or be neutral. This change occurs as the marginal rate of technical substitution of capital, labor, or water diminishes or remains unchanged at the original non-energy input/energy input ratio. If technological change increases the marginal product of one or more non-energy inputs more than the marginal product of energy (at a given non-energy input/energy input ratio), progress results from non-energy inputs. The technology creates an incentive to use more non-energy inputs relative to energy since the marginal product of non-energy inputs has increased relative to that of energy. The result is conservation of energy.

Constant and diminishing rates of technological change are presented in Figures 2 and 3. The level of output is I , and various isoquants (I , I' , I'') show the combination of inputs capable of producing this level of output in progressive time periods. OR is the ray whose slope gives a constant non-energy input/energy input ratio. The points A , B , and C show the points of production of the given non-energy input/energy input ratio as energy-conserving technological progress occurs over time.

Energy-conserving technological progress is shown by a shift of an isoquant in the direction of the origin. In Figure 2 the three isoquants, I , I' , and I'' represent the same level of output in different time periods. As technological progress takes place, I' shows that the given level of output can be produced by smaller quantities of all inputs than at I . Similarly, as technological progress continues, I'' shows that still smaller input combinations can produce the same level of output.

Figure 2 illustrates neutral technological progress. Recalling the definition, energy-conserving technological progress is neutral if at a constant non-energy input/energy input ratio the marginal rate of technical substitution of non-energy inputs for energy is unchanged (constant isoquant slope). Hence, Figure 2 represents a shifting production function characterized by neutral technological progress.

FIGURE 2. Neutral Technological Change

FIGURE 3. Energy Efficient Biased Technological Change

Figure 3 illustrates energy conserving technological progress. Energy-conserving technological progress occurs when, at a constant non-energy input/energy input ratio, the marginal product of one or more non-energy inputs increases relative to the marginal product of energy. Moving from A to B to C, the slope of the isoquant increases, representing an increase in the marginal rate of technical substitution of non-energy inputs for energy. Hence, Figure 3 depicts a shifting production function characterized by technical progress which is increasingly energy efficient.

The parameters necessary to determine the nature of the technological change are the change in output (Y), and the change in the inputs (I, N, E, and V). In progressing from a single farm to an entire industry, the same principles described above apply. The only difference is that more output is produced; but the same ratios among prices, marginal products and marginal rate of technical substitution exist.⁽¹⁾

While the same principles of technological change that apply to a farm also apply to U.S. agriculture, the rate of technological adoption is an issue at the industry level. Following the pioneering work of Zvi Griliches,⁽²⁾ Mansfield hypothesized that the rate of adoption of an innovation is a direct function of the profit from employing the innovation and a decreasing function of the size of investment required to use it.⁽³⁾ Historical data on substitution have been described as an elongated S-shaped curve. The slope of the curve before the first inflection point is relatively flat, reflecting the fact that during the first years a new product, process or service must overcome the lack of knowledge associated with development and use contract arrangements based on the old technology, limits to attaining economies of size, and adjusting to a new resource mix. During the later phases of the substitution, the rate of increase of market penetration increases as the constraint of these factors is released. The final phase is described by a relatively flat portion of the curve as market penetration becomes complete.⁽⁴⁾

Sahal points out that while the descriptive power of technological forecasting models predicated on the S-shaped curve is often good, their explanatory power is close to zero. These models do not provide information on the determinants of technological change nor the relative importance of various

determinants.⁽⁵⁾ These determinants, if economic, could have a major effect on the secondary impacts of the adoption of the technology.

Sahal concluded that technological substitution is best considered as an economic phenomenon. The assumption that the diffusion of innovation follows an S-shaped curve did not seem crucial. The production scale was identified as the most important determinant of technological substitution.⁽⁵⁾ Production scale has considerable value in determining the rate of technological change in industries that are perfectly competitive such as agriculture.

CONCLUSIONS

A review of the theoretical considerations applicable to technological change in irrigation identifies three criteria in choosing an efficient investment of federal funds to increase energy efficiency in irrigation. These are:

1. Projects which require small investments will be more quickly adopted than those which require large investments.
2. Given comparable levels of energy savings, projects which are more labor- or water-efficient should be given priority.
3. Projects should then be ranked on the basis of profit to the farmer.

Since sufficient information was not available at the time of project selection to implement the second and third criteria, these are deferred to recommendation for further research.

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V. AN ALLOCATION OF FEDERAL FUNDS FOR RESEARCH,
DEVELOPMENT, AND DEMONSTRATION

V. AN ALLOCATION OF FEDERAL FUNDS FOR RESEARCH, DEVELOPMENT, AND DEMONSTRATION

The primary purpose of the allocation of Federal funds during the life of the DOE Irrigation program is to support the design, development and commercial demonstration of new technologies for reducing energy consumption in irrigation systems. To that end, and to generate the greatest possible interest, a program opportunity notice was issued inviting the submission of research proposals. The areas to which the proposals could be directed were:

1. Programs directed toward design, development, and demonstration of irrigation pumps that are more efficient than conventional pumps (under conditions experienced in the field).
2. Programs directed toward design, development, and demonstration of irrigation wells that have minimum drawdown (difference between static water level and the dynamic pumping water level) head at rated pumping capacity.
3. Programs directed toward the design, development, and demonstration of sprinkler systems that operate effectively (good water distribution) at pressures significantly lower than conventional systems.
4. Programs directed toward the design, development, and demonstration of irrigation water distribution systems that reduce irrigation pumping energy requirements by improved water application efficiency (less water pumped as a result of more uniform application and/or reduced evaporation and percolation losses).
5. Programs directed toward the design, development, and demonstration of methods for significantly improving irrigation pump prime mover efficiency.
6. Programs directed toward the design, development, and demonstration of energy efficient irrigation systems using systems design and optimization techniques.⁽¹⁾

PROPOSALS SUBMITTED

Twenty-eight proposals were submitted for consideration. These 28 responses include a broad spectrum of innovative thought with respect to the reduction of energy use in irrigation. They are described briefly below. They are listed by the category which they address and not by the ranking assigned by the technical evaluation panel.

Wells

Two proposals were submitted that were specifically related to wells and ground water. In one, it was proposed to investigate the causes of ground water supply inefficiencies and to develop criteria for analyzing and improving overall well and pumping plant efficiency. Included in this proposal was the development of an optimization model which would be used to analyze water supply systems and diagnose inefficiencies and their causes.⁽²⁾

The second proposal was to design and construct production irrigation wells and to measure the hydraulic efficiency of each well. The project would culminate in a demonstration of the comparative draw down of each well to demonstrate the possible energy saving which would accrue to properly designed wells.⁽³⁾

Pumps

The objectives of one proposal in this category were to: (1) test irrigation pumps and to compare their performance with design standards, and (2) demonstrate to irrigators, well drillers, engine specialists, and consultants how to test a pumping plant and how to adjust and/or select the proper pump, gear head and prime mover to fit the well and the application system.⁽⁴⁾

A second proposal in this category would redesign and fabricate turbine pump impellers and diffusers to minimize the difference between field and design efficiencies.⁽⁵⁾

The third proposal submitted was to develop and demonstrate an energy-efficient variable-speed pump with a use efficiency better than 78 percent.⁽⁶⁾

Prime Movers

One proposal dealing with the prime mover for irrigation pumps was submitted in response to the program opportunity notice. This proposal suggested that a patented windmill driving a hydraulic motor be used to power irrigation pumps. The contractor would demonstrate technical feasibility and test the windmill on a farm pumping situation.⁽⁷⁾

Application

This category drew the largest response--eleven of the 28 proposals submitted. The first of these proposed to deliver a computer design program package for optimizing the irrigation system pipeline network based on life cycle costs. The programs would have the capability of sizing (1) the entire pipeline network of a permanent or solid set sprinkler system, (2) the main line and manifolds of a trickle system, and (3) the main line and submain system of a closed-conduit sprinkler or surface system.⁽⁸⁾

Another contractor proposed to design, develop, and demonstrate a low-pressure center-pivot system in combination with conservation tillage practices to determine the uniformity of water distribution, application rates, and water run off.⁽⁹⁾

A third contractor proposed to automate a gated-pipe system with the use of radio-controlled flow valves and to evaluate the potential energy savings of the system.⁽¹⁰⁾

A fourth proposal was for the design, development, and demonstration of a completely mobile, low-pressure trickle irrigation system adapted to large-scale row crop farming.⁽¹¹⁾

Another proposal suggested the measurement of water and energy use with various types of application systems in pecan orchards.⁽¹²⁾

One project was proposed to assess energy requirements and crop yield under a mechanical, continuous move system utilizing low water pressure, drop lines, and furrow checks. The project was specifically applicable to medium or low intake rate soils in a desert climate.⁽¹³⁾

The purpose of another project was to install and test a new type of drip irrigation emitter. These pressure container emitters are designed to operate with smaller delivery lines and unfiltered water.⁽¹⁴⁾

The synthesis of an optimal center-pivot system which would minimize water consumption and operating costs was the focus of one proposal. Of particular interest in the system design would be sprinkler operating pressures, pressure loss through the system and water distribution efficiency.⁽¹⁵⁾

Another type of application system suggested was the flooding of "dead level" field by either gravity or pump from on-farm storage ponds.⁽¹⁶⁾

The objective of one proposed study was to suggest and verify an analytical approach to selecting irrigation systems for conditions of widely differing characteristics.⁽¹⁷⁾

One proposal submitted suggested the development of a sensing and control device which would be used with center-pivot systems. The sensors would measure the intra-field variance in water requirements and control the center pivot to irrigate only those parts of a field which needed water.⁽¹⁸⁾

One project was proposed to develop and demonstrate the feasibility of irrigating orchard crops using a bubbler-type irrigation system. The system would operate with very low head and deliver one gallon per minute to each tree during the water delivery cycle.⁽¹⁹⁾

Scheduling

The work under one proposal in this category would involve the development of an instrumentation system composed of a field terminal, sensor,

actuator stations, and data processing center. A comprehensive computer program would be developed to predict and optimize irrigation practices.⁽²⁰⁾

A second submission in this category proposed to document the effects of irrigation scheduling on over 46,000 acres in California.⁽²¹⁾

A pulse irrigation system and instrumentation was proposed for use in determining the minimum water requirement for orchard crops.⁽²²⁾

One proposal was to be directed toward the design, development and demonstration of energy efficient irrigation systems using a systems approach. Factors to be analyzed included water requirements at various stages in the plant growth cycle, wind, soil moisture, temperature and day length, and cultural practices.⁽²³⁾

Another proposal in this category was to develop a control system for center pivots which would regulate sprinkler flows; sense lateral inlet flows, quantities and pressure; sense wind velocity and evaporation; analyze the data; and directly operate the system.⁽²⁴⁾

One proposal suggested the creation of an audio-visual presentation which could be used to educate irrigators in the proper use of various irrigation systems.⁽²⁵⁾

Agronomics

A proposal submitted in this category suggested that research be funded to determine the minimum root volume that must be wet in order to maintain yields at normal levels, and determine the relationship between water consumptive use and wetted root volume. The information generated would be used in conjunction with a drip irrigation system to reduce the volume of water applied to specific crops.⁽²⁶⁾

Semipermeable subsoil moisture barriers were proposed as a means of reducing the volume of water applied by reducing water lost to ground water.⁽²⁷⁾

Development of new methods of seed bed preparation were proposed for hard-to-work soil types. Methods would be developed which would substantially reduce draft horsepower requirements for land preparation under this proposed research.⁽²⁸⁾

TECHNICAL EVALUATION

The 28 proposals submitted were evaluated according to the criteria set forth in the program opportunity notice. These criteria were:

a. General

- (1) the overall technical feasibility of the proposed effort;
- (2) the potential contribution which the proposed effort is expected to have, if supported at this time, on DOE's responsibility to carry out programs so as to assist in solving energy extraction and storage, transportation, conversion, waste utilization, conservation, and the energy utilization efficiency problems of various areas and regions, under representative geological, geographic and environmental conditions;
- (3) the capabilities, related experience, facilities, instrumentation, or techniques which the proposer possesses and offers, and which are considered to be integral factors for achieving the objectives of the proposal;
- (4) the qualifications, capabilities and experience of the proposed key personnel; and
- (5) the ability of the proposer to furnish necessary financial support.

b. Specific

- (1) The anticipated objectives to be achieved by the activities or facilities proposed;

- (2) The economic, environmental, and societal costs and benefits which a successful demonstration program may have for the national fuels and energy systems;
- (3) The availability of non-Federal participant(s) to construct and operate the facilities or experiment or perform the activities associated with the proposal.
- (4) The total estimated cost including the Federal investment and the probable time schedule;
- (5) The proposed participants and the proposed financial contribution of the Federal government and of the non-Federal participants;
- (6) The proposed cooperative arrangement, agreements among the participants, and form of management of the activities;
- (7) The relationship of the proposal to the following priorities:
 - (i) The urgency of public need for the potential results of the proposed demonstration is high, and it is unlikely that similar results would be achieved in a timely manner in the absence of Federal assistance.
 - (ii) The potential opportunities for non-Federal interests to recapture the investment in the undertaking through the normal commercial utilization of proprietary knowledge appear inadequate to encourage timely results.
 - (iii) The extent of the problems treated and the objectives sought by the undertaking are national or widespread in their significance.
 - (iv) There are limited opportunities to induce non-Federal support of the undertaking through regulatory actions, end-use controls, tax and price incentives, public education, or other alternatives to direct Federal financial assistance.

- (v) The degree of risk of loss of investment inherent in the demonstration is high, and the availability of risk capital to the non-Federal entities which might otherwise engage in this effort is adequate for the timely development of the technology.
- (vi) The magnitude of the investment appears to exceed the financial capabilities of potential non-Federal participants.

SELECTED PROJECTS

The following section lists the contractors and projects which were selected:

The University of California (Davis)

The University of California will investigate causes of ground water supply inefficiencies in irrigation systems and evolve criteria for analyzing and improving overall well and pumping plant efficiency.

During 1978 the contractor will identify all factors affecting well and pump performance as a result of an extensive literature search and determine, by sensitivity analysis, which factors are most important to system efficiency. Existing pump testing procedures will be analyzed and a program for testing wells and pumps will be developed.

During 1978 the contractor will develop an optimization model. This will include a program to analyze water supply systems and diagnose inefficiencies and their causes. Methods to correct system inefficiencies and maintain optimal well and pump systems will be developed. Economic and other incentives for implementing operational and maintenance criteria will be investigated and related to improve water resource management. A format for disseminating this information to well owners and operators will be developed.

Irrigation Research Center
Area Vocational Institute
Staples, Minnesota

The contractor will design and construct production irrigation wells, in an unconsolidated aquifer, using commercially available well screen products, and test the wells for drawdown upon completion of three stages of well development, to determine the hydraulic efficiency of each well. He will then demonstrate the comparative drawdowns and energy savings and disseminate results to the well drilling industry and irrigators.

During 1978 the contractor will plan field operations and testing and order essential equipment. He will then drill 10 test holes for the purpose of selecting and designing the final demonstration layout. The water bearing formation samples collected in the test drilling stage will be submitted to the Johnson Division of Universal Oil Products for sieve analysis to determine the design of the production wells. Design recommendations will be reviewed by the University of Minnesota consultants and other industry personnel. Final well design specifications will be written. Construction of the wells in accordance with specifications described above will be completed under the supervision of a licensed well drilling contractor. Testing equipment will be installed to include pumps, discharge lines to disperse water pumping during testing, and electrical service to pumps. Instrumentation will include flow meters, pressure sensors to monitor drawdown, and data collection system for pressure sensors. First-stage data collection will focus on each production well by test pumping to determine the drawdown in the predevelopment stage. Partial development and second-stage data collection will coincide with common practices in the industry. Complete development and third-stage data collection will be designed to obtain minimum drawdown and highest efficiency of each well. After data collection has been completed and the results are available, the differences in drawdown that occurred will be demonstrated. During 1979 data analysis will be conducted to include projected savings and cost effectiveness of approved well construction.

Aerospace Research Corporation
Roanoke, Virginia

The contractor will analyze the differential between field pump efficiencies and laboratory pump efficiencies and provide means to reduce this differential. In addition he will analyze the current practice in which water is conducted to the surface through a pipe which fits inside the well casing and contains the line shaft that transmits power from the surface to the pump which requires the use of a packer which fits adjacent to the pump and seals the annulus between the pump and casing.

During 1978 the contractor will disassemble and examine turbine type irrigation pumps from at least two pump manufacturers. He will analyze the flow in the impeller and diffuser passage of at least one of the pump specimens. He will evaluate the sealing methods for the pumps and determine alternate sealing methods. He will then evaluate surface finishes on the pumps and contact both pump and other metal fabricators concerning achievement of smooth finishes and/or protective coatings. This will be followed by an evaluation of line shaft and piping systems which are supplied by the pump manufacturers and others conducting the water from the pump to the surface. Performance assessment will be conducted in consultation with agricultural extension agents and irrigators in Kansas, Nebraska, Texas, and California regarding current use of the pump. Specific consultation will be conducted with other project leaders in the DOE irrigation program. This will be followed by a comparative analysis of pump usage. Current practices with regard to pipe and line shaft sizes used in delivery of water from wells will be determined.

During 1979 the contractor will redesign and modify the irrigation pump in consultation with cooperating pump manufacturers. An evaluation plan and manufacturing procedure of the redesigned pump will be prepared. Special attention shall focus on pump repair, maintenance, and adjustment. The impeller and diffuser will be redesigned for optimal performance. A computer program will be prepared to be used by irrigation pump manufacturers for pump design. The contractor will cooperate with pump

manufacturers to achieve durable pump surface finishes and fabricate new pump components. He will then assist the pump manufacturer in adopting new proposed sealing methods and performance tests.

During 1980 the contractor shall determine the percentage of output loss caused by friction. He will then work with the hardware manufacturer in providing a system which uses the well casing as a delivery pipe. This will include providing information on interfacing a well packer and pump for well installations. He will then evaluate problems of removing and replacing pump, packer, and line shaft with tools on the farm. Installation, operation, and removal of improved pump, packer, and line shaft system will be demonstrated at a typical well situation.

Foster-Miller Associates, Inc.
Waltham, Massachusetts

The contractor will develop and demonstrate an energy efficient variable speed pump in an actual crop producing situation, utilizing a variable speed DC motor drive, directly coupled with a suitably selected downhole pump, to produce a system with a "wire to water" efficiency of better than 78%, with one moving part. The system will be constructed out of commercially available components.

During 1978 the contractor will define a detailed program plan and select appropriate equipment for the demonstration. Available equipment will be surveyed and a trade-off analysis will be conducted. A suitable site will be selected from sites already established in the Department of Energy Irrigation Program or from Maverick Agri-Services holdings near Barstow, California.

During 1979 delivery will be taken on the variable speed pump, motor, drive, and associated instrumentation. A bench test will be performed to verify performance over the full range of specified operating conditions. The equipment will be shipped to the test site, assembled over the well, debugged and testing. The instrumentation will be used to measure efficiency.

During 1980 the variable speed pump system will be demonstrated in full time operation with a working center pivot for the course of a growing season. Careful and complete data will be taken during the operation. This data will be compared with a theoretical model and data collected from a control operation.

Keller Engineering
Logan, Utah

The contractor will deliver a life-cycle-cost computer design program package for optimizing irrigation system pipeline network. The programs will have the capability of sizing (1) the entire pipeline network of a permanent or solid set sprinkler system, (2) the main line and manifolds of a trickle system, or (3) the main line and submain distribution system of a closed conduit sprinkler or surface system.

During 1978 the contractor will streamline an existing program and make it more efficient and generally applicable. This will require removal of any statements from the code that tie the use of the program to any specific computer, make the program capable of handling both metric and English units of measurement, and modifying the elevation control in the system to make the inputs more flexible and more involved. In addition, the concept of developing the hydraulic network to minimize errors and simplify input data will be reconstructed. The capability to incorporate portions of existing systems in the overall designs in retrofitting will be provided. Pumping plant characteristics and the selection of available heads for the different discharge requirements which may exist between operating stations within a given system will be incorporated. Means for maintaining pressure control throughout the entire block or region (controlled by single valve or pressure regulator) of a system rather than only in the laterals will be provided. In addition, input data requirements will be simplified so the program can be used with a modest knowledge of computer and data terminal. This will involve an examination of all the

input data parameters to remove ambiguities, minimize changes for error and minimize amounts of input data, and put internal checks and diagnostics in the program to recognize common input errors and take either appropriate corrective action or print diagnostic messages.

During 1979 the contractor will document the program and supply a user manual with sample irrigation system designs including detailed input instructions for the programs, remote data terminal use instructions, a listing of all the programs, and samples of typical PFC sprinkler and trickle irrigation system designs plus designs for main and submain distribution pipe network. These examples will include data setup and samples of the computer output. The adequacy of the user manual and simplicity of the program input will be tested by holding workshops with typical potential users. A preliminary test of the user manual and program operation will be conducted with a small group of local engineers and potential users. A three-day workshop in Salt Lake City, Utah, will be conducted to include approximately 50 participants. The participants will be required to apply the program to sample design problems with primary reference to the user manual and a minimum of direct supervision or instruction. The first workshop will be evaluated and revisions in the manual and program will be made as needed. Following these revisions a second three-day workshop will be conducted in Salt Lake City comparable to the first.

During 1980 a final revision of the manual will be made and submitted.

Kansas State University

Kansas State University will automate a gated pipe irrigation system using a radio control transmitter and receiver to direct flow of water through flow control valves, evaluate the performance of the system and valves, determine changes to increase water application and distribution efficiencies, and estimate potential savings in energy.

During 1978 the contractor will write the specifications for the irrigation system, purchase components through bids, install the gated pipe irrigation system, field test the system, modify the system as necessary and evaluate the system performance.

During 1979 the contractor will design experiments to test irrigation practices, monitor operation of the system, take field data to determine irrigation efficiency, and analyze those data.

During 1980 the contractor will redesign experiments to test the irrigation practices, monitor operation of the system, take field data to determine irrigation efficiencies, secure sediment samples in furrows, analyze field data, and estimate potential for saving energy.

Texas A & M Research Foundation

Texas A & M will design, develop, evaluate and demonstrate a completely mobile trickle irrigation system adapted to large scale row crop farming. Each component of the system will be evaluated individually for correct operation and modified as necessary during 1978. When mechanical operation meets the original design criteria, a minimum evaluation and demonstration period will begin during the 1979 crop year and extend through 1980.

During 1978, the contractor will evaluate mechanical operation of guidance and alignment system in the forward, backward, angular and pivotal modes of operation. Modifications will be made as necessary. The contractor will then evaluate mechanical operation of prime mover and drive system and estimate energy consumption and efficiency. He will then evaluate the conveyance system including operation of hose carts and the intermediate pressurization system. System hydraulic design including pressure losses within each segment of the system from the well discharge to the system emitters will be evaluated. Manifold distribution systems for both manual and automatic operation will be evaluated. Determination of distribution efficiency of the system will be performed.

During 1979 the contractor will instrument and prepare fields for evaluation of the system on cotton. Field data will be collected, analyzed, and reported.

During 1980 contractor will instrument and prepare fields for evaluation of the system on grain sorghum. Field data will be collected, analyzed, and reported.

The University of Nebraska

The University of Nebraska will design, develop, and demonstrate a reduced pressure center pivot sprinkler irrigation system used in combination with conservation tillage practices to determine the uniformity of water distribution, application rates, and water run-off.

During 1978 proper sprinkler spacing and sizes for each of the three application methods will be made. Equipment will be ordered and installed on an existing center-pivot system. Equipment necessary to measure run-off will be selected, ordered, and installed. A crop will be planted, cultivated, fertilized, and harvested. Data describing the operation of the crop production system will be collected and analyzed. The data collected will include (1) uniformity of water application, (2) water application rates, (3) surface run-off, (4) pressure distribution, (5) water use under each method of water application and tillage method, (6) energy conserved in tillage operations, (7) energy conserved with low pressure sprinklers, (8) plant response and crop production. A mathematical model will be developed with specified criteria to evaluate and select locations for low pressure systems. Field demonstrations of the system will be made.

During 1979 and 1980 data collection, mathematical model construction, and demonstration will continue as described above.

Prossen Industries Westminster, California

Prossen Industries will develop and demonstrate irrigated instrumentation system composed of a field terminal, sensor, and actuator stations; and data processing center will be expanded to accelerate the development of production sensors and a comprehensive computer program to predict and optimize irrigation practices.

During 1978 design, fabrication, installation and operation of two automated agricultural data collection and control systems will be accomplished. The first system shall be installed at a 7-acre avocado orchard located in Fallbrook, San Diego County, California. The second system shall be installed in a field crop situation under commitments received by Harza Agricultural Service in the San Joaquin Valley. The contractor will finalize the design of the tensiometer transducer to a level suitable to mass production. He will locate vendors to supply the hardware. The power subsystem consisting of a solar voltaic panel, a solar current integrator, and switch mode regulating power supply and battery system will be utilized. The panel will be assembled and tested at the avocado orchard. Commercial power will be utilized at the second site. The field terminal computer will be assembled into an available card cage to provide the basic computer. A time/data subsystem which has been designed and testing at the prototype state will be fabricated for production used to complete the field terminal. This subsystem will be in the form of a hand-assembled circuit card. The contractor will prepare the software problem statement and program for physical implementation of the method of transducer interrogation, local data storage, actuator management and data transmission to the host computer system. This will require generating the system programs. The software for the host computer system will be developed to perform the functions of monitoring each field terminal computer. The primary functions to be developed for this system are the methods of storage and display of data, various plotting subroutines to provide graphical presentation of the collected data, prediction algorithms for generating the irrigation forecasts and data communication protocol. Twenty-six tensiometer stations and 11 miscellaneous sensor or actuator stations will be installed for complete instrumentation coverage at each site. Commercial telephone type data communication channels will be used for the interconnection between the field terminal computers and the host system for both sites. This will require the installation of the data model to provide the analogue to digital interface between computer and telephone lines. Field terminal computers to both sites will be fully assembled and tested before installation. They

will then be physically installed and interfaced to the instrumentation arrays and data communication channels. The system software will be loaded. A fully integrated system functional check out included required troubleshooting and software debugging will be completed.

It is anticipated that most of 1978 will be required for system installation and checkout. During 1979 and 1980 the task emphasis will shift to actual use of the systems for data collection and analysis with hardware and software maintenance performed as required. Data will be accumulated by the field terminals and will be transmitted and processed at the host computer at least twice daily. Accumulated data pertaining to water consumption and related to weather and other parameters will be charted and compared to historical usage at the site. The contractor will conduct surveys of other fields and orchards to determine the actual water use in typical noninstrumented environments.

Harza Agricultural Services
Fresno, California

Harza Agricultural Services in conjunction with Pacific Gas and Electric Company will document the effect of an irrigation scheduling system on irrigation consumption on a representative sample of 46,500 acres in the Central San Joaquin Valley. The Central San Joaquin Valley will be divided into unique farming environments based on climatology, soil variation, water resources, and cropping patterns. The study parcels will be monitored under varying concepts of irrigation scheduling during two cropping seasons.

During 1978 project area selection will take place. Project standards will be set. Monitoring facilities will be established and data collection begun. Representative farming environments will be identified from a survey of climatology, soil variation, water sources and cropping patterns as a result of statistical evaluation. Project standards will be established with control data in each of the farming environments, following a survey

of historical data for climate, cropping patterns, water use, and yields for individual fields, individual farms, and groups of farms. Quality control criteria will be established. Equipment for monitoring facilities will be procured and installed. Data collection will include irrigation dates, irrigation depths, crop growth stage, soil characteristics, plant nutrition land/water ratios, climatic conditions, water use, and rooting depth. Additional data will include gross irrigation depths applied and measured, physical soil analysis, irrigation systems design and operational parameters, yield data, and time of day water demand. Data evaluation and analysis will commence in 1979. After reviewing the data for accuracy, it will be organized on computer files. Analysis will consist of a preliminary review for scope and accuracy, data compilation and organization, quality control checks, and statistical analysis. Energy value of irrigation water will be defined on the basis of water sources within farming environment and energy requirements for each water source.

During 1980 comparative analysis will take place on the basis of gross annual water use by crop, crop yield, and water yield ratios.

The projects selected represent a research effort in all phases of the irrigation system from well design through applications and scheduling. Because of such diversity, the projects selected were thought to represent that combination of possible projects most likely to have the greatest impact on energy conservation in irrigation.

RECOMMENDATIONS FOR FURTHER RESEARCH

The existing Energy Conservation Irrigation Program resulted from the drawing together of 10 projects which focus on changing elements in the hardware or method used to irrigate. The development of new techniques are not sufficient to reduce energy consumption. The technology must be adopted on the farms and ranches of America. To induce this adoption will require additional research. This report concludes with such recommendations.

Hayami and Ruttan state that the singlemost significant conclusion that emerged from their analysis of the agricultural development experience of Japan and the United States is the powerful role of economic forces in inducing technical change. Relative factor and product prices exert a pervasive impact on the direction of both innovation and production activity of farmers and of the firms that supply the industrial input in agricultural production.⁽¹⁾ Following their conclusions, it is recommended that a detailed analysis of the irrigation economy with respect to energy be undertaken. This analysis should begin with the collection and analysis of data describing the prices of alternative sources of energy in each of the major irrigation regions in the Western United States. In addition, projections of these prices should be made to 2020. Included in this analysis should be prices of labor, water, land and irrigation equipment. Analysis of these prices, together with an analysis of the input/output relationships of hardware and methods used to irrigate will result in an understanding of the irrigation economy with respect to energy use. Such an understanding is the prerequisite for developing a strategy of induced innovation of the 10 elements of hardware and methods that are being developed as a result of this program.

A limited survey was conducted to aid in project selection so that the Department of Energy would avoid the expenditure of funds on research already being accomplished in the public and private sectors. For the existing projects to have maximum impact on the irrigation economy, it is necessary to conduct a comprehensive survey of ongoing research to reduce energy consumption in irrigation. Such a survey is expected to result in:

1. data already generated which describe the irrigation economy,
2. the identification of engineers and scientists that are working on projects which complement the ten funded by the Department of Energy,

(1) Hayami, Y., V. W. Ruttan, Agricultural Development, the Johns Hopkins University Press, Baltimore, 1971, p. 305.

3. increased visibility among members of the research community of the 10 funded projects,
4. a clearer understanding of the irrigation economy in 1982, when the 10 projects are complete, and
5. the fitting of the 10 projects into a comprehensive frontier of technology change that can then be interpreted as reduced energy consumption or increased energy efficiency in irrigation.

If the 10 projects which make up the existing Energy Conservation Irrigation Program are to have maximum effect on the reduction of energy use in irrigation, they must be synchronized with a detailed knowledge of the irrigation economy and knowledge of impending technological changes resulting from other sources. Such a synchronization could form a basis for rational policy choices to induce a slight an economically viable energy efficient irrigated agricultural economy.

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August 5, 1977
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