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Solar Thermal Power Systems Project
Parabolic Dish Systems Development

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Hamid Habib-agahi
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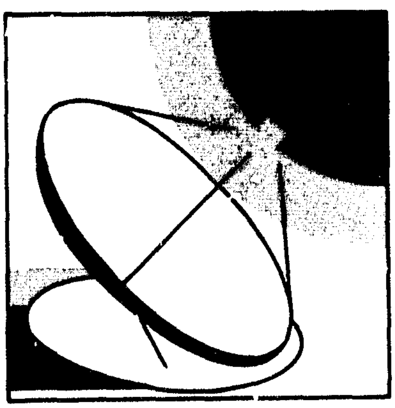

September 1, 1981

Prepared for
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ABSTRACT

The potential size of the onfarm-pumped irrigation market for solar thermal parabolic dish systems in seven high-insolation states is estimated. The study is restricted to the displacement of three specific fuels: gasoline, diesel and natural gas.

A model was developed to estimate the optimal number of parabolic dish modules per farm based on the minimum cost mix of conventional and solar thermal energy required to meet irrigation needs. Results indicate that the near-term market for such systems depends not only on the type of crop and method of irrigation, but also on the optimal utilization of each added module, which in turn depends on the price of conventional fuel, real discount rate, marginal cost of the solar thermal power system, local insolation level and parabolic dish system efficiency.

The study concludes that the potential market size for onfarm-pumped irrigation applications ranges from 101,000 modules when a 14% real discount rate is assumed to 220,000 modules when the real discount rate drops to 8%. Arizona, Kansas, Nebraska, New Mexico and Texas account for 98% of the total demand for this application, with the natural gas replacement market accounting for the largest segment (71%) of the total market.

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CONTENTS

Figures

Tables

SECTION I

INTRODUCTION

A. OBJECTIVE

Increasing fuel prices and short supplies of conventional fuels during the past few years suggest that there may be applications for which solar thermal power systems will find a near-term market. One such application is providing the power necessary to run onfarm-pumped irrigation systems, particularly in western and southwestern regions which have relatively high levels of solar insolation. Onfarm-pumped irrigation systems are isolated, and frequently a grid connection is not available. The objective of this paper is to estimate the potential size of the onfarm-pumped irrigation market for parabolic dish (PD) systems. For this purpose, the analysis was confined to seven states with both high levels of insolation and high acreage of irrigated land.

B. POTENTIAL

In 1974, the U.S. agricultural sector consumed over two quadrillion British thermal units (Btu). More than 10% of this amount was used for irrigation, which provided over 20% of total U.S. crop production. Thus, irrigation is now and will continue to be a major consumer of energy. Ground water is the main source of onfarm-pumped irrigation water. In 1977, total acreage irrigated with onfarm-pumped water was over 40 million acres. Seven states with relatively high levels of insolation (California, Arizona, Colorado, Texas, New Mexico, Kansas, and Nebraska) accounted for 67% of the total land irrigated with onfarm-pumped water. Table 1-1 summarizes the 1977 acreage irrigated with onfarm-pumped water in these states.

Electricity and natural gas supply 85% of the energy necessary to provide U.S. irrigation needs. Since 1974, the use of electricity, diesel, and natural gas to pump irrigation water has increased, while the use of gasoline has declined. Natural gas has been the least expensive fuel for pumping irrigation water, but it has been frequently unavailable. Electricity is generally the best alternative, but in some states utilities are operating at capacity and are not anxious to add to peak loads with more irrigation customers. Diesel fuel is the next best substitute, and its use for onfarm-pumped irrigation doubled between 1974 and 1977 (Ref. 6). Table 1-2 shows the prices of different fuel and energy used for pumping irrigation water in 1977.

C. RESTRICTIONS

The following analysis is restricted in two ways: (1) by fuel type, to the replacement market for gasoline, diesel, and natural gas used for onfarm-pumped irrigation water systems; and (2) by area, to seven states with characteristics which make the use of solar thermal parabolic dish systems attractive. The analysis is concentrated in this way for the following reasons:

(1) Market Size. In 1977, over 1.3×10^{14} Btu was generated to operate irrigation systems employing gasoline, diesel, and natural gas. In the near term, this is a reasonably-sized market to examine.

(2) Isolated Application. The modularity and "stand alone" features of PD modules make their use both feasible and attractive to isolated farms, especially where grid connections are unavailable and conventional fuels are both expensive and difficult to transport.

(3) Insolation. Many of the areas using irrigation systems in these states are also areas of relatively high insolation.

(4) Fuel Cost. A large percentage of onfarm-pumped irrigation system power is generated by gasoline, diesel, and natural gas. These are conventional fuels which solar will likely displace more rapidly than grid-connected power.

Table 1-1. Acreage Irrigated with Onfarm-Pumped Water in 1977, by Type of Energy Source and State (1000 acres)

State	Electricity	Diesel	Gasoline	Natural Gas
Kansas	503	534	--	1911
Nebraska	1885	2262	62	1319
Texas	2204	107	93	6476
Colorado	1138	100	20	332
New Mexico	223	76	23	473
California	4757	9	--	--
Arizona	648	--	--	291

Source: Reference 6, pp. 21-22.

Table 1-2. Price of Fuel by State in 1977
(1977 Dollars)

State	Electricity (per kWh)	Diesel (per Gallon)	Gasoline (per Gallon)	Natural Gas (per MCF)
Kansas	0.035	0.43	--	0.80
Nebraska	0.045	0.45	0.51	1.20
Texas	0.030	0.45	0.55	1.30
Colorado	0.035	0.45	0.52	1.15
New Mexico	0.035	0.45[a]	0.52[a]	1.80
California	0.042	0.50	--	--
Arizona	0.021	--	--	1.50

[a]This is an estimate based on values available from neighboring states.
Source: Reference 6, pp. 35-36.

SECTION II

MAXIMUM MARKET SIZE

In order to estimate the size of the 1990 irrigation market for parabolic dish systems, the energy demanded for irrigation must be determined. The total supply of solar thermal energy will depend on the energy output and number of solar thermal systems installed to meet these energy demands. The market analysis must make some rational assumptions about the degree to which the total energy demanded for irrigation will be covered by the output of the solar thermal system.

Reference 1 estimated the energy demanded by several hypothetical, but representative, farms in Arizona, California, Kansas, Nebraska, and New Mexico. It also provided solar energy supply schedules based on theoretical systems sized to cover all peak demands. The solar system utilization, here referred to as K, is defined as the ratio of the total annual demand satisfied to the total amount of solar energy supplied.

To illustrate, Figure 2-1 shows a composite energy demand and solar supply curve for a 260-acre Kansas farm. The energy demand is defined in megawatt hours per 15-day period. Demand includes residence, livestock operations and crop-drying requirements, as well as irrigation demands; since most of these additional demands occur at times when irrigation demands are lightest, they are included to increase the solar system utilization. The solar supply schedule is based on a system sized to cover all demand, taking into account regional insolation with variations throughout the year.

Appendix A provides further information about the supply and demand schedule of the representative farm for each state under study.

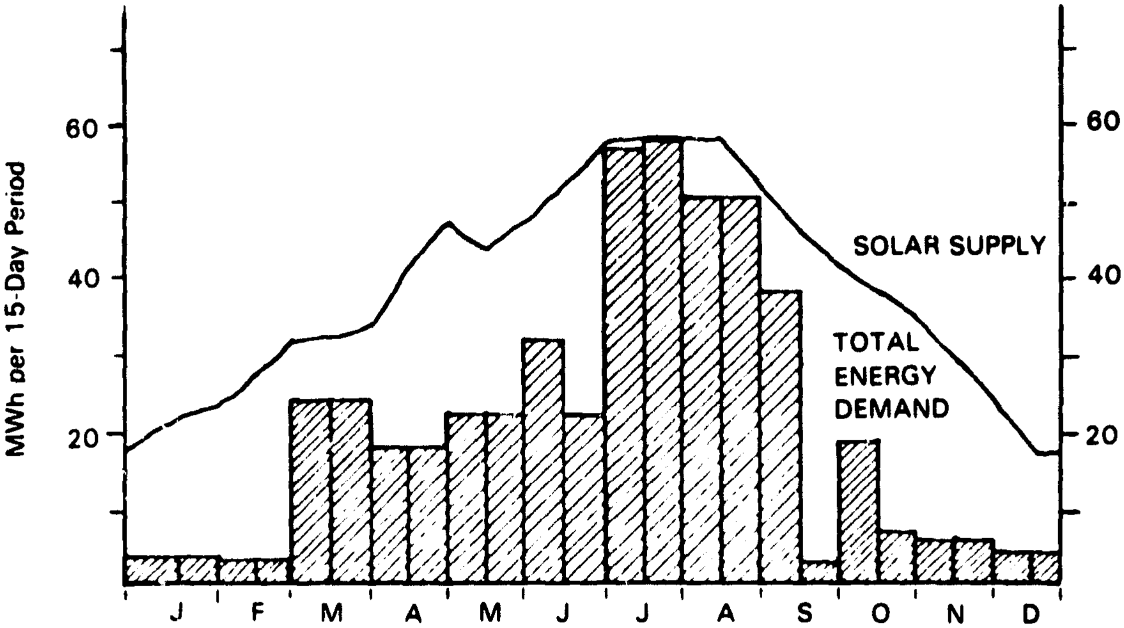

Figure 2-1. Composite Energy Demand and Solar Energy Supply for a Kansas Farm

The irrigation market for parabolic dish systems could be estimated using this supply and demand information, with the number of modules calculated by the formula:

$$X_{ij} = Z_{ij} / \left[A \bullet I_j \bullet \xi \right] \qquad (1)$$

where

i = fuel type = diesel, gasoline, or natural gas

j = seven states studied

X_{ij} = number of PD modules needed in the jth state to replace the ith fuel used for pumped irrigation

Z_{ij} = annual energy requirement for on-farm irrigation in state j using ith fuel, in kWh[1]

I_j = annual average insolation in state j in kWh/m^2-yr. (Table 3-1)

ξ = parabolic dish system efficiency = 20%

A = parabolic dish module size = 100 m^2/module

Using data provided by the United States Department of Agriculture (Ref. 6) on the energy required for irrigation needs by state and by type of fuel, the total number of solar thermal parabolic dish modules that could potentially cover the demand can be estimated. Assuming conservatively that there is no significant change in the amount of land irrigated or in the type of onfarm-pumped irrigation since the Agriculture Department's 1977 data, the estimated number of modules needed to cover demand would be over 240,000.

It should be noted that by using I_j, average annual insolation, and Z_{ij}, annual energy requirement, Equation (1) assumes that energy produced matches energy demanded. This would be a valid assumption if the solar thermal energy systems included a storage system that allowed energy produced in excess of demand, particularly during the off-seasons, to be used to meet peak demands for irrigation.

An alternative estimate can be made, based on the assumption that no auxiliary power or storage exists and that PD systems provide the total energy required. The utilization factor explained in Section III (Solar Plant Utilization) can be incorporated in Equation (1) to ensure an adequate number of parabolic dish modules to cover total demand, including peak periods. In this case, the number of solar thermal parabolic dish modules needed to cover the demand schedule in the seven states would be more than 500,000 modules. This implies the number of modules is sufficient to meet the peak requirements of the irrigation systems, but during the off-season when the demand for onfarm-pumped irrigation water is small, substantial energy would be wasted.

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[1] Source: The total energy in million kWh was estimated, using the quantity of energy used for onfarm-pumped irrigation water given by Reference 6, pp. 23-26, and conversion factors from Table 3-2.

SECTION III

OPTIMAL MARKET SIZE

A. ASSUMPTIONS

In the preliminary analysis, initial market-size estimates were based on two assumptions. The first premise is that a system would be sized to meet all demand, assuming perfect storage. Alternatively, a system could be sized to completely cover peaks, in which case the demand would all be met; however, a large amount of excess supply would lead to a low system utilization. The optimal number of dishes for any given farm may not be that required to cover total demand and will vary depending not only on the type of crop and method of irrigation, but also on the marginal cost and availability of conventional energy and the marginal cost of solar thermal energy. Rather than meeting all energy requirements with PD systems, any specific farm should attempt to arrive at a cost-effective combination of solar and conventional energy. Because the value of solar thermal energy is directly related to the irrigation demand satisfied by each module, the next step in estimating the optimal-sized solar thermal system for each farm is to determine the utilization of each individual solar thermal module.

B. MODEL DEVELOPMENT

The utilization factor (K) given in Figures A-1 through A-5 shows the percent utilization of a solar system sized to cover peak demand and will vary substantially from state to state. As a parabolic dish system is installed, the power output of the first module will be highly utilized in satisfying demand. With the installation of each additional module, the average utilization of the system drops as supply more frequently exceeds demand, especially during off-peak periods. Therefore, the value of each additional PD module drops so that at some point, generally short of covering total demand, the farmer becomes indifferent toward supplying his energy needs with solar energy and supplying them with conventional energy. Thereafter, it would be more economical to use conventional energy. Thus, for each farm, there is an optimal number of modules which gives the most cost-effective combination of solar and conventional power for onfarm-pumped irrigation systems.

To determine what this optimal number would be, a mathematical model representing the cost of the total energy supplied was developed. The objective in finding the optimal number of modules is to minimize the total cost of energy to the user, the total being a combination of solar and conventional costs.

The total cost of energy for any given farm currently using the ith fuel type would be:

$$C^i = C_s + C_c^i$$

where

C_s = cost of the solar thermal parabolic dish system

C_c^i = cost of the conventional energy supplied by the ith fuel (i = diesel, gasoline or natural gas)

$$C_s = N \bullet \left(CAP + \sum_{t=1}^{T} (OM_t)/(1+r)^t \right)$$

where

N = the number of parabolic dish modules

CAP = capital cost of each module

OM_t = operation and maintenance cost per module at time t

r = real discount rate

T = system lifetime, 30 years

$$C_c^i = \sum_{t=1}^{T} P_t^i \left(\overline{Q}_t - \sum_{n=1}^{N} (A \bullet I \bullet \xi \bullet K_n) \right) / (1+r)^t$$

which represents the demand for conventional energy as the difference between total energy demanded and that supplied by the solar system.

P_t^i = price in year t of the ith fuel type

$\overline{Q}_t$ = total energy demanded in year t

A = area per module, 100 m^2

I = local insolation rate

ξ = system efficiency

K_n = utilization of the nth module

The objective is to minimize the total cost with respect to N. Total cost can be written as:

$$C^i = N \bullet \left(CAP + \sum_{t=1}^{T} (OM_t)/(1+r)^t \right) + \sum_{t=1}^{T} P_t^i \left(\overline{Q}_t - \sum_{n=1}^{N} (A \bullet I \bullet \xi \bullet K_n) \right) / (1+r)^t$$

Optimality implies:

$$\Delta C^i = C^i (N+1) - C^i (N) \geq 0 \quad \text{and} \quad C^i (N) \leq C^i (N-1) \qquad (1)$$

or

$$\Delta C^{i} = (N+1) \bullet \left(CAP + \sum_{t=1}^{T} OM_t/(1+r)^t \right) + \sum_{t=1}^{T} P_t^i \left(\bar{Q}_t - \sum_{n=1}^{N+1} A \bullet I \bullet \xi \bullet K_n \right) \Big/ (1+r)^t$$

$$- N \bullet \left(CAP + \sum_{t=1}^{T} OM_t/(1+r)^t \right) - \sum_{t=1}^{T} P_t^i \left(\bar{Q}_t - \sum_{n=1}^{N} A \bullet I \bullet \xi \bullet K_n \right) \Big/ (1+r)^t$$

Monotonicity of K_n guarantees the existence of a solution, hence

$$\Delta C^{i} = CAP + \sum_{t=1}^{T} OM_t/(1+r)^t - \sum_{t=1}^{i} \left(P_t^i \bullet A \bullet I \bullet \xi \bullet K_{N+1}/(1+r)^t \right) \geq 0$$

Equation (1) can be solved for K_N and written,

$$K_N \geq K_{\hat{N}} = \left(CAP + \sum_{t=1}^{T} OM_t/(1+r)^t \right) \Big/ \left((A \bullet I \bullet \xi) \sum_{t=1}^{T} P_t^i/(1+r)^t \right) \geq K_{N+1} \qquad (2)$$

This solution, $K_{\hat{N}}$, gives the optimal utilization of the Nth module, where $\hat{N}$ represents the last module added.

This mathematical model, which will allow for the estimation of the optimal size of a farm's solar system, necessitates a rumerical definition of each term of the model.

C. DERIVATION OF TERMS

1. Insolation Evaluation

Average annual direct insolation data (I) for the seven states was obtained from Table 2 of Reference 3. The sites selected to represent the states were chosen based on the closest sites to SOLMET data stations in that region. It should be noted that in using average annual insolation data for the sites selected, it was assumed that at these locations, the data approximate the insolation and temperature characteristic of the state as a whole. Table 3-1 presents the insolation data used for each state.

2. Cost of Conventional Energy for Irrigation

Projected estimates for 1990 fuel costs for onfarm-pumped irrigation water to farmers (Table 3-2) were obtained from Reference 2. The following conversion factors were used to convert all fuel cost units for various types of resources into a common energy measure, \$/kWh.

Fuel prices were derived by simple multiplication from 1990 energy prices (in 1980 dollars). Table 3-3 gives the prices used as well as the projected growth rates and the energy conversion factors in Table 3-2.

Table 3-1. Average Annual Insolation by State

State	Observation Location	Insolation (kWh/m^2-yr.)[a]
Arizona	Phoenix	2526
California	Fresno	2237
Colorado	Great Falls, Montana[b]	1661
Kansas	Dodge City	2106
Nebraska	North Omaha	1632
New Mexico	Albuquerque	2602
Texas	Fort Worth	1705

[a]SOLMET long-term direct normal average (Ref. 3).
[b]This insolation data is used for the state of Colorado, since no SOLMET station is available in Colorado.

Table 3-2. Conversion Factors

Fuel	Conversion
Diesel	1 Gallon = 138,690 Btu
Gasoline	1 Gallon = 125,000 Btu
Natural Gas	1 Cubic Foot = 1000 Btu
Heat Rate[a]	
Gasoline Engine	1 kWh = 14,000 Btu
Diesel Engine	1 kWh = 15,000 Btu
Gas Turbine	1 kWh = 20,000 Btu
Coal Fired Steam	1 kWh = 10,000 Btu

[a]Based on experts' estimates for typical engines used for water pumping.
Source: Reference 5, p. 3-126.

Table 3-3. Energy Prices in 1990
($1980)

Fuel	$/Million Btu	$/kWh	Growth Rate, % (1990-2010)
Gasoline	$13.47	$0.188	2.8
Diesel	9.00	0.135	2.5
Natural Gas	6.02	0.120	3.2

3. Solar Thermal System Efficiency

In order to transform solar energy to electrical power, we used a solar thermal power system consisting of a series of point-focusing parabolic dishes with the following characteristics:

(1) concentrator efficiency = 90%

(2) receiver efficiency = 82%

(3) power conversion efficiency = 25-35%

(4) all other losses including transportation = 4%

(5) collector size = 100 m^2

(6) total system efficiency = 20%

(7) production at 5,000-25,000 units/yr.

Thus, throughout this paper, the solar thermal system efficiency (ξ) of 20% is assumed for all solar plants (Ref. 4).

4. Solar Plant Utilization

A solar thermal plant utilization factor (K) is defined as the ratio of the energy demand which is met by the solar thermal system to the total energy available from the solar system. Two identical solar systems can have vastly differing utilization factors depending both on the demand schedules and on differences in insolation levels, which create different power outputs. It should be kept in mind that a high utilization factor does not necessarily mean that all demand is being met but does indicate the percent of supply being utilized.

In this analysis, one farm for each state was selected as representative of that state's irrigation demand patterns and solar supply characteristics. Each farm's solar plant utilization factor closely resembles the average utilization factor obtained by Reference 1. The value of K varies from 64.6%

in Arizona to 36.9% in California. Crop-drying and livestock operations have relatively low summer energy requirements and can increase solar plant utilization factors by running their power requirements off the solar plant during times of under-utilization by the irrigation systems. Thus, in this study, the demand schedule includes energy required for irrigation, residence, and crop drying. The data obtained by Reference 1 indicates that in all the seven states except Nebraska, the energy requirement for farm residence and crop drying is very small relative to energy demanded for irrigation.

It should be noted that important factors such as farm size, type of irrigation, and cropping pattern have been considered in determining the energy demand schedule for irrigation. Further details are given in Appendix A, and Figures A-1 to A-5 show the energy supply and demand schedules. Table 3-4 provides the solar utilization factor (K) for a solar thermal system designed to satisfy peak power demand in Kansas, Nebraska, Texas, Colorado, New Mexico, California and Arizona.

a. Marginal Solar Plant Utilization. Table 3-4 gives an average utilization factor (K) for a system large enough to require no auxiliary power source. However, in practical terms, most consumers would attempt to achieve a cost-effective balance of solar and conventional energy sources by optimizing the utilization of the Nth module. The marginal utilization is the ratio of the additional demand covered by the nth module to the additional power supplied. As each module is added to a system, this ratio will drop. This is due to the variations of supply and demand over time, so that as a system gets larger and larger, the supply will more frequently exceed demand.

Table 3-4. Solar Plant Utilization Factor (K)

Location	K (%)
Kansas	55.1
Nebraska	43.9
Texas[a]	45.0
Colorado[a]	42.0
New Mexico	42.4
California	36.9
Arizona	64.6

[a]These are estimates based on values obtained from neighboring states.
Source: Reference 1.

For example, on the representative farm in the state of Kansas, the first three modules installed are utilized 100% of the time. The fourth module added to the system, however, is utilized only 97% of the time, while by the time the tenth module is added, the marginal utilization is 62%. This means that while the tenth module generates as much energy as each of the first nine, total demand met will only be increased by 62% of the amount generated. Thus, the marginal solar plant utilization (K_n) for Kansas is 0.62, when n = 10.

Appendix B details the derivation of each K_n for each farm in various regions, and contains complete tables of the results, Tables B-2 to B-6.

b. Optimal Solar Plant Utilization. The preceeding portions of Section 3 defined a mathematical model for determining the optimal utilization of the Nth module, expressed in Equation (2) as:

$$K_{\hat{N}} = \left(CAP + \sum_{t=1}^{T} OM_t/(1+r)^t\right) \Bigg/ \left((A \bullet I \bullet \xi) \sum_{t=1}^{T} P_t^i/(1+r)^t\right)$$

and the derivation of the variables needed to make the calculations. With the following assumptions, optimal solar plant utilization ($K_{\hat{N}}$) can be calculated for each state and fuel type.

(1) The first year of operation is 1990.

(2) All costs are in 1980 dollars.

(3) Capital cost per module is $27,000, the 1990 cost goal, established by the Cost Goal Committee (Ref. 4).

(4) Minimum production level of 5000/modules, necessary to meet cost goals.

(5) Annual operation and maintenance cost is 2% of capital cost.

(6) The real operation and maintenance (O&M) escalation rate is 1% annually.

(7) Real discount rate is 14%.

(8) Insolation is as presented in Section III.

(8) Dish size is 100 m^2.

(10) System efficiency is 20%, as presented in Section III.

(11) System lifetime is 30 years.

(12) The total energy supply and demand patterns per state are the same as that represented by the "typical" farms of Figures A-1 to A-5, increased multiplicatively.

(13) Average annual real price escalation rates for conventional fuels for the period 1990 to 2020 are derived from Reference 2 and continuation of past trend:

Gasoline	2.5%
Diesel	2.8%
Natural Gas	3.2%

Using Equation (2), the optimal marginal utilization of the last module added, $K_{\hat{N}}$, which would minimize the total cost of energy, was obtained for each state and fuel type. The results are given in Table 3-5.

5. Market Size

The marginal utilization of each module, K_n, was explained in Subsection a (Marginal Solar Plant Utilization), and is given in the tables in Appendix 2. Thus, when the optimal utilization of the last module, $K_{\hat{N}}$, is obtained from Subsection b (Optimal Solar Plant Utilization), the cost minimizing number of modules, $\hat{N}$, can be read from the tables. This gives the number

Table 3-5. Optimal Utilization of Last Module
(r = 14%)

State	Fuel Displaced	$K_{\hat{N}}$
New Mexico	Gasoline	0.37
New Mexico	Diesel	0.50
California	Diesel	0.59
Kansas	Diesel	0.62
Texas	Gasoline	0.57
Colorado	Gasoline	0.58
Texas	Diesel	0.77
Nebraska	Gasoline	0.59
Arizona	Natural Gas	0.63
New Mexico	Natural Gas	0.55
Colorado	Diesel	0.79
Nebraska	Diesel	0.80
Texas	Natural Gas	0.84
Kansas	Natural Gas	0.68
Colorado	Natural Gas	0.86
Nebraska	Natural Gas	0.87

of modules on the optimally-sized representative farm. Returning to the example of Kansas, $K_{\hat{N}}$ for diesel is 62%. Table B-4 shows that $\hat{N}$ associated with 0.62 is 10. Thus, on the representative farm in Kansas, if diesel fuel is used to run an onfarm-pumped irrigation system, an optimally sized PD system would be ten modules.

Using the data received from the Department of Agriculture (Ref. 6), giving the current energy usage in each of the seven states for irrigation by each fuel type, an equivalent number of farms irrigated by each fuel can be calculated. The potential solar market then becomes the product of the number of farms times the number of modules per farm. The results are given in Table 3-6, and a detailed explanation is given in Appendix B. For Kansas, the energy supplied by diesel fuel to power onfarm-pumped irrigation is 380×10^6 kWh. The annual energy used by the representative farm is 511,700 kWh. Therefore, there are 743 equivalent farms, each with a potential to install an optimally sized PD system of ten modules for a total potential market of 7430 modules.

The total potential market for parabolic dish systems to supply power for onfarm-pumped irrigation systems in these seven states is over 101,000 modules. As can be seen, five of the states provide most of the demand, with the other two accounting for less than 2% of the total. The natural gas replacement market accounts for the largest segment (71%) of the total market.

For a capital intensive technology such as parabolic dish systems, the results are sensitive to the real discount rate chosen. The analysis was performed with 14% as the real discount rate. If, however, we look at sizing a farm system for optimum cost effectiveness using a real discount rate of 8%, the total market size estimate will increase to over 220,000 modules from 101,000 with a 14% discount rate. Table 3-7 gives the re-estimated market size by state and fuel type.

Table 3-6. Total Market for Onfarm-Pumped Irrigation Systems (r = 14%)

	Number of Modules to Replace			
State	Gasoline	Diesel	Natural Gas	Total
New Mexico	1,044	2,568	13,520	17,132
California	--	189	--	189
Texas	1,365	344	9,695	11,404
Kansas	--	7,430	21,114	28,544
Colorado	56	70	692	818
Arizona	--	--	18,974	18,974
Nebraska	1,040	15,640	7,722	24,402
TOTAL	3,505	26,241	71,717	101,463

Table 3-7. Total Market for Onfarm-Pumped Irrigation Systems (r = 8%)

	Number of Modules to Replace			
State	Gasoline	Diesel	Natural Gas	Total
New Mexico	1,160	2,889	15,210	19,259
California	-	252	-	252
Texas	1,755	1,376	77,560	80,691
Kansas	-	8,916	28,152	37,068
Colorado	72	280	5,536	5,888
Arizona	-	-	21,112	21,112
Nebraska	2,080	39,100	15,444	56,624
TOTAL	5,067	52,813	163,014	220,894

SECTION IV

SUMMARY AND CONCLUSIONS

The characteristics of onfarm-pumped irrigation systems fit the profile of the near-term solar thermal parabolic dish market. While in some areas of the country, irrigation systems are grid connected, a portion of the market can be identified in which the irrigation systems are isolated, currently powered with increasingly expensive fuels and located in areas with available land for modules. In estimating the near-term potentials for PD markets, it is important to focus on specific applications in which success is most probable.

The foregoing analysis estimates the near-term market size as ranging between 101,000 and 220,000 modules. The market size estimates vary with the discount rate chosen, with the number of modules increasing as the rate drops. The 101,000-module and 220,000-module estimates are based on real discount rates of 14% and 8%, respectively. This market analysis is restricted to the seven states identified as having both high levels of insolation and high acreage of irrigation land. It is also restricted to displacement of three specific fuels, diesel, gasoline and natural gas, with relatively rapidly escalating prices. While this may lead to some underestimation due to the characteristics of the areas analyzed, the largest proportion of the market has been captured. One additional comment on the market in general is that a consideration of market estimates of parabolic dish modules is the availability of land. Since the number of modules per farm in this analysis averages 10 or fewer, the required land should not be a constraint to installation decisions on a farm.

The estimates take into account decisions about cost effective utilization of the solar thermal system to define the appropriate mix of solar and conventional power. Of course, the optimal mix of solar and conventional power on any farm will be influenced by the price of conventional fuels and anticipated relative escalation rates.

The model developed in this paper identifies the optimal utilization of the last module added to the system, and based on that calculation, defines the size of the optimal system. By finding the marginal utilization of each module added to a system, the effective utilization of the optimally sized system can be calculated. Relatively high effective utilization factors indicate high utilization of each module, with little wasted solar energy. The high effective utilization rates of the systems displacing natural gas, as shown in Table 4-1, indicate that this market will be relatively unaffected by minor fluctuations in insolation levels. This stability is significant to the analysis, as over 73% of the PD market is for displacement of natural gas.

In addition to limiting the scope of the analysis to seven states and three fuels, several assumptions were made. Data on the current size of the irrigation market was from 1977, and no significant changes were assumed for 1990. In cases in which no data existed, neighboring states were used as proxies. In all cases, attempts were made to keep estimates on the conservative side, if possible. Two major assumptions were: (1) that a single observation location adequately represented the insolation data for a state as a whole, and (2) that the representative farm adequately represented the supply and demand profiles of the state as a whole. Finally, there was no consideration of competition for the same market from any other renewable or alternative source.

The calculation of the optimal utilization rate of the last module added is highly sensitive to the real discount rate chosen. This suggests an area for future investigation.

Table 4-1. Effective Utilization of the Optimally Sized PD System (r = 14%)

State	Replaced Fuel	Effective Utilization
New Mexico	Gasoline	0.66
California	Diesel	0.68
New Mexico	Diesel	0.69
Texas	Gasoline	0.72
Colorado	Gasoline	0.72
New Mexico	Natural Gas	0.69
Nebraska	Gasoline	0.75
Texas	Diesel	0.80
Arizona	Natural Gas	0.84
Colorado	Diesel	0.80
Colorado	Natural Gas	0.88
Kansas	Diesel	0.86
Nebraska	Diesel	0.89
Texas	Natural Gas	0.88
Kansas	Natural Gas	0.88
Nebraska	Natural Gas	0.89

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APPENDIX A

STATE IRRIGATION ENERGY DEMAND AND SUPPLY

SOLAR ENERGY PROFILES

The following descriptive information concerning the irrigation energy demand and solar supply profiles for representative farms, as well as the graphs, was obtained from Reference 1.

In Kansas, cropping and livestock operations are common. Crop drying represents a substantial autumn energy requirement for the farms growing grain, while heating requirements for the residence and for swine operations are greater in the winter than in the summer. In the evaluation of energy demand schedules, the energy requirements for crop drying, residential use, animal operations and irrigation were considered. The solar utilization factor in this state is estimated to be 55.1%, with the peak demand occurring in the month of July (Figure A-1).

In California, farms are quite specialized in growing grapes, almonds, cotton, alfalfa and wheat. In this case, a solar utilization of 36.9% is expected. The residential demand is very small and peak demand for irrigation occurs during the summer season (Figure A-2).

In New Mexico, besides demand for irrigation, the energy requirements for residential use and crop drying were considered even though the demand is very small. The peak demand occurs in the month of May and the solar utilization factor is 42.4% (Figure A-3).

In Nebraska, farms growing corn, with crop drying, cattle feeding, residence, and swine operations were considered. The peak demand occurs in the month of August and the solar utilization factor is 43.9% (Figure A-4).

In Arizona, farms growing alfalfa and wheat were considered. The total energy demanded for irrigation in this case spreads over 9 months of the year with energy peak demand in the month of June. The solar utilization factor for this state is 64.6%, which is relatively high with respect to other states (Figure A-5).

For further information about the solar plant utilization factor, see Reference 1.

KANSAS FARM

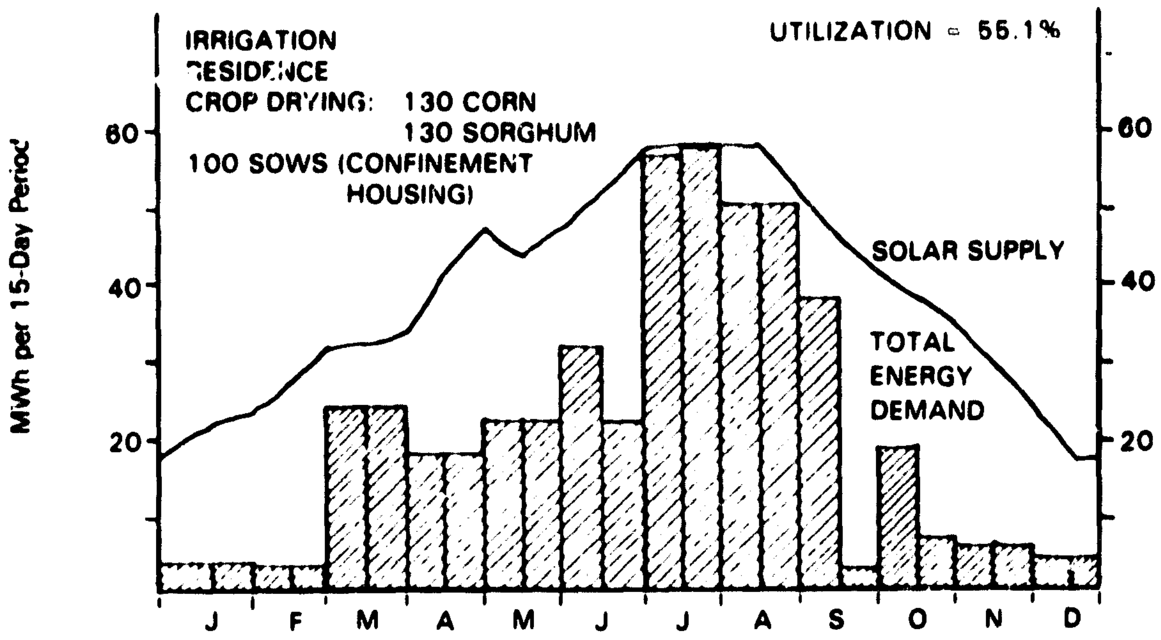

Figure A-1. Composite Energy Demand and Solar Energy Supply Curves for a 260-Acre Kansas Farm. Includes Irrigation, Residence, Crop Drying and Animal Production

CALIFORNIA - FARM

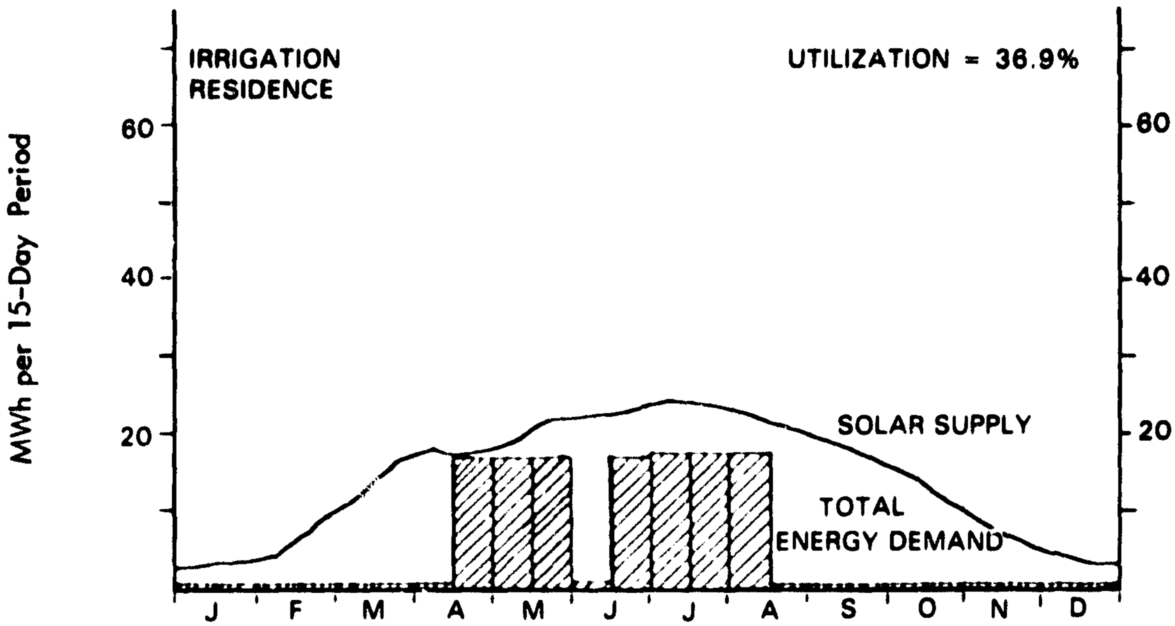

Figure A-2. Composite Energy Demand and Solar Energy Supply Curves for a 150-Acre Upper San Joaquin Valley, California, Farm, Includes Irrigation and Residence

NEW MEXICO - FARM

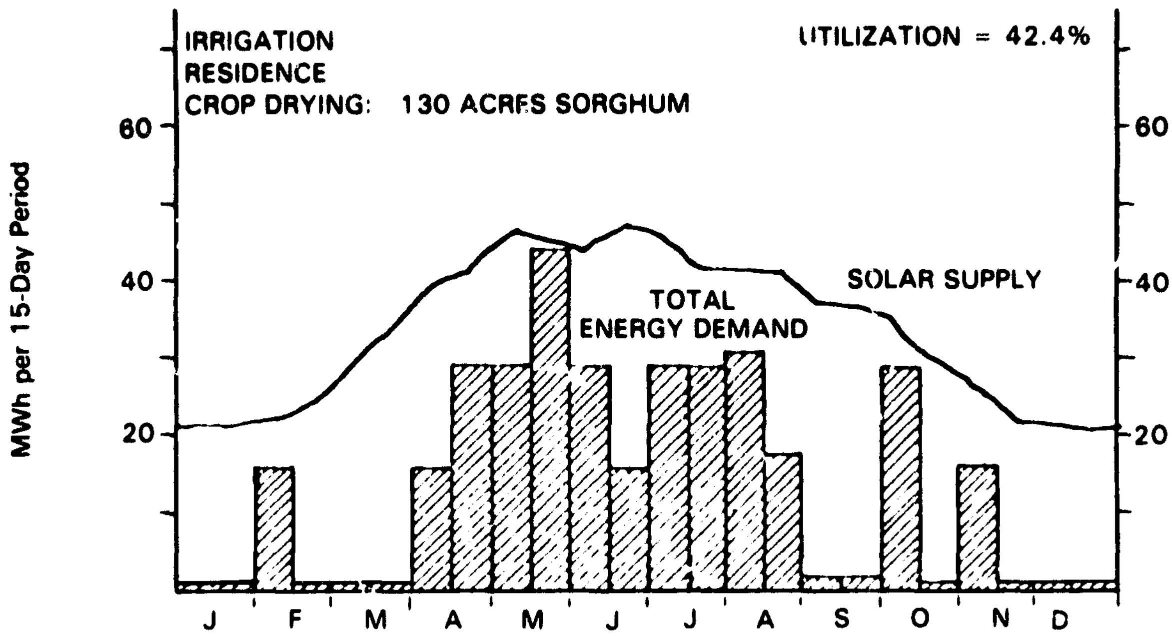

Figure A-3. Composite Energy Demand and Solar Energy Supply Curves for a 390-Acre Northern New Mexico Farm. Includes Irrigation, Residence, and Crop Drying

NEBRASKA - FARM

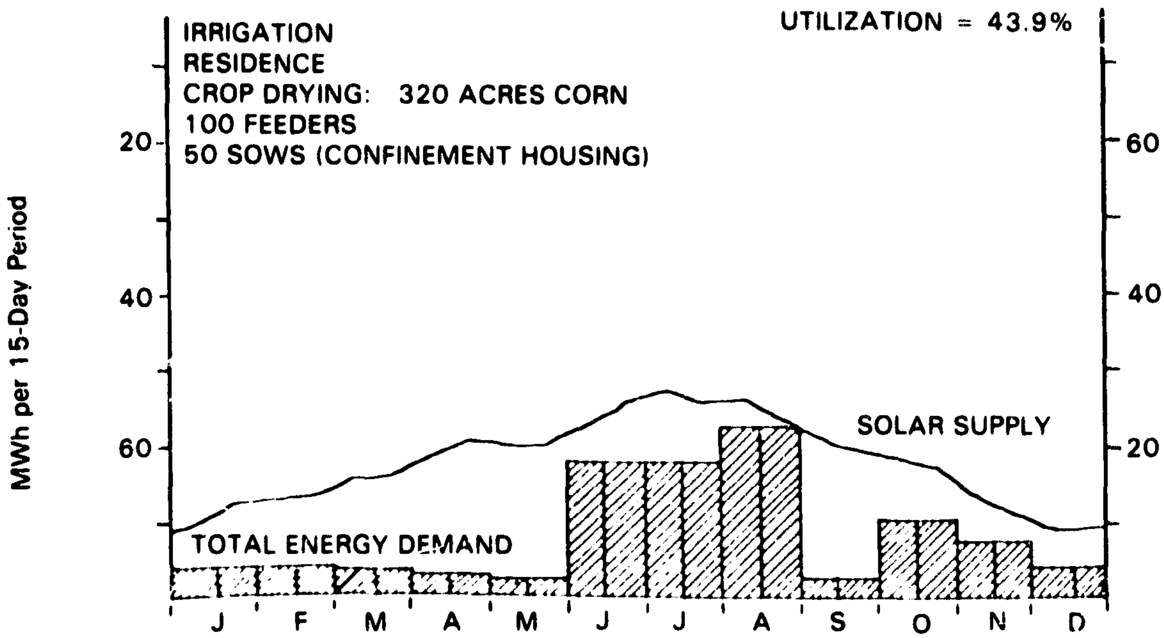

Figure A-4. Composite Energy Demand and Solar Energy Supply Curves for a 320-Acre Nebraska Farm. Includes Irrigation, Residence, Crop Drying and Animal Production

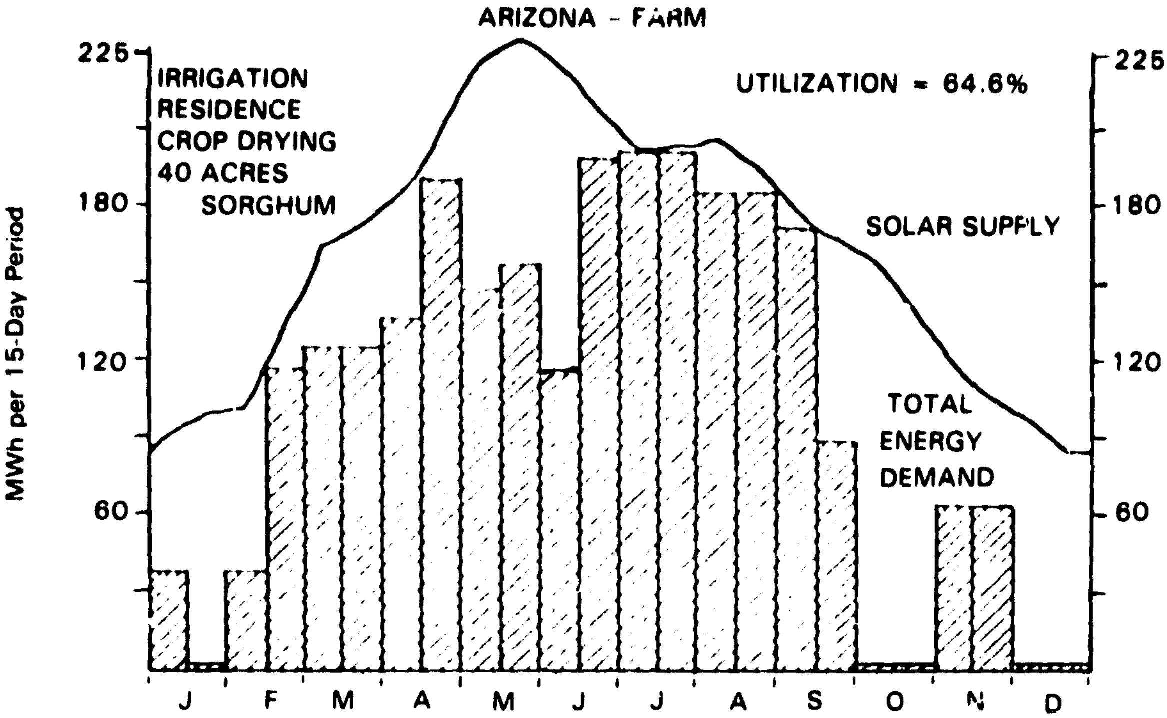

Figure A-5. Composite Energy Demand and Solar Energy Supply Curves for a 640-Acre Arizona Farm

APPENDIX B

DERIVATION OF K_n FOR VARIOUS REGIONS

Tables B-1 through B-6 were derived to aid in the calculations of the marginal utilization of each module added to a solar system. This allowed the calculation of the number of modules making up the optimally sized system, which led to the market size estimate.

(1) The annual power output of a module located on a farm in a given state was calculated as the product of the state's insolation level, the system efficiency, and the module size.

(2) The total solar energy supply for each state for a system designed to cover irrigation, crop, livestock operation and residential demands was taken from Reference 1. ("Supply" column of Tables B-1 to B-6.)

(3) Dividing the total annual solar thermal energy supply in kWh/yr. by the output of each module for a given state in kWh/module per year gives the equivalent number of PD modules required for a farm in that state. (Number of Modules per Farm, Table B-1.)

(4) The contribution of each module in a given month was obtained by dividing the monthly solar thermal energy supply by the total number of installed modules from (3) above. ($\bar{W}$ in the Tables.)

(5) Monthly demand was also obtained from Reference 6.

(6) For each month, for each state, the number of modules needed to cover the total demand was calculated, as well as the energy contribution of the last module utilized, assuming all previous modules were fully utilized. The total number used in any month is "J-max" in Tables B-2 - B-6. The columns headed "w_j" give the monthly power demanded which is supplied by the jth module added to the system.

(7) The annual power used of that supplied by the jth module is the sum of the monthly supplies, and is the total "w_j".

(8) The total utilization of the jth module added to the system is in the row labeled K_j and is the total power demand satisfied by the jth module divided by the total annual supply per module.

(9) The utilization factor close to $K_{\hat{N}}$, the optimal utilization of the nth module can now be read from the Tables for each state, for each type of fuel. The optimal number of modules per farm can be read from the table.

(10) The equivalent number of farms per state for each fuel type can be estimated by dividing the total energy demand for onfarm-pumped irrigation systems by fuel type and state (Ref. 6) by the total energy demand for the "typical" farm (Ref. 1).

(11) The PD system market by state and fuel type was then estimated as the product of modules per farm (Item 9) and number of farms (Item 10).

It should be noted that, due to lack of data for Texas and Colorado, the representative farm supply and demand profiles for New Mexico were used to derive the utilization factor.

Table B-1. Number of Modules per Farm per State

(Based on covering the peak demand)

No. Modules/Farm = (Solar Supply/Farm)/(100 m^2/module • 0.20 system efficiency • insolation level)

	Supply [a]	Insolation [b]	No. Mod. per Farm
New Mexico	808,300	2,602	15.53
California	344,784	2,237	7.71
Kansas	928,224	2,106	22.04
Texas	808,300[c]	1,705	23.70
Colorado	808,300[c]	1,661	24.30
Nebraska	394,989	1,632	12.10
Arizona	3,946,729	2,526	78.12

[a] Solar Supply for Total Demand (kWh), Ref. 1.

[b] Average Annual Insolation (kWh/m^2-yr.), Ref. 3.

[c] New Mexico's solar supply data was used.

DEFINITIONS FOR TABLES B-2 to B-6

Demand: Monthly totals are the totals of the two 15-day periods, total energy demanded, all farm uses. The representative farm of Reference 1 is used.

Supply: Total solar supply in kWh to cover all energy demands. Sum of two 15-day periods given in Reference 1 for the representative farm.

Number of Modules per Farm: from Table B-1.

$\overline{W}$: Total supply per month divided by the number of installed modules (kWh/modules).

J-Max.: Total number of modules needed by month to cover the monthly demand.

w_j: Marginal energy supplied by the jth module.

K_j: (Annual w_j)/(Annual $\overline{W}$).

TABLE B-2

ARIZONA

	DEMAND	SUPPLY	$\bar{W}$	J-Max.	W_1	W_{2-15}	W_{16}	W_{17-42}	W_{43}	W_{44-49}	W_{50}	W_{50-52}	W_{53}
JAN.	38,147	190,709	2,441	16	2,441	2,441	1,532	-	-	-	-	-	-
FEB.	156,328	231,981	2,969	53	2,969	2,969	2,969	2,969	2,969	2,969	2,969	2,969	1,940
MAR.	249,346	338,188	4,329	58	4,329	4,329	4,329	4,329	4,329	4,329	4,329	4,329	4,329
APR.	326,419	394,938	5,055	65	5,055	5,055	5,055	5,055	5,055	5,055	5,055	5,055	5,055
MAY	304,954	482,109	6,171	50	6,171	6,171	6,171	6,171	6,171	6,171	2,575	-	-
JUNE	315,506	448,307	5,739	55	5,739	5,739	5,739	5,739	5,739	5,739	5,739	5,739	5,739
JULY	398,536	400,295	5,124	78	5,124	5,124	5,124	5,124	5,124	5,124	5,124	5,124	5,124
AUG.	372,296	402,054	5,146	73	5,146	5,146	5,146	5,146	5,146	5,146	5,146	5,146	5,146
SEPT.	262,706	345,659	4,425	60	4,425	4,425	4,425	4,425	4,425	4,425	4,425	4,425	4,425
OCT.	1,734	299,583	3,835	1	1,734	-	-	-	-	-	-	-	-
NOV.	124,036	226,111	2,894	43	2,894	2,894	2,894	2,894	2,488	-	-	-	-
DEC.	1,036	186,795	2,391	1	1,036	-	-	-	-	-	-	-	-
TOTAL	2,551,044	3,946,729	50,519	-	47,063	44,293	43,384	41,852	41,446	38,958	35,362	32,787	31,758
K_J	-	-	-	-	0.93	0.88	0.86	0.83	0.82	0.77	0.70	0.65	0.63

No. Installed Modules = 78.12
Reference 1, p. 24.

TABLE B-2 (Cont'd)

	w_{54}	w_{55}	w_{56-57}	w_{58}	w_{59}	w_{60}	w_{61-64}	w_{65}	w_{66-72}	w_{73}	w_{74-77}	w_{78}
JAN.	-	-	-	-	-	-	-	-	-	-	-	-
FEB.	-	-	-	-	-	-	-	-	-	-	-	-
MAR.	4,329	4,329	4,329	2,593					-	-	-	-
APR.	5,055	5,055	5,055	5,055	5,055	5,055	5,055	2,899	-	-	-	-
MAY	-	-	-	-	-	-	-	-	-	-	-	-
JUNE	5,739	5,600	-	-	-	-	-	-	-	-	-	-
JULY	5,124	5,124	5,124	5,124	5,124	5,124	5,124	5,124	5,124	5,124	5,124	3,968
AUG.	5,146	5,146	5,146	5,146	5,146	5,146	5,146	5,146	5,146	1,784	-	-
SEPT.	4,425	4,425	4,425	4,425	4,425	1,631	-	-	-	-	-	-
OCT.	-	-	-	-	-	-	-	-	-	-	-	-
NOV.	-	-	-	-	-	-	-	-	-	-	-	-
DEC.	-	-	-	-	-	-	-	-	-	-	-	-
TOTAL	29,818	29,679	24,079	22,343	19,750	16,956	15,325	13,169	10,270	6,908	5,124	3,988
K_j	0.59	0.59	0.48	0.44	0.39	0.34	0.30	0.26	0.20	0.14	0.10	0.08

No. Installed Modules = 78.12.
Reference 1, p. 24.

TABLE B-3

CALIFORNIA

	DEMAND	SUPPLY	$\overline{W}$	J-Max.	w_1	w_2	w_3	w_4	w_5	w_6	w_7
JAN.	1,816	7,521	975	2	975	841	-	-	-	-	-
FEB.	1,600	13,132	1,703	1	1,600	-	-	-	-	-	-
MAR.	1,268	27,057	3,509	1	1,268	-	-	-	-	-	-
APR.	17,238	33,957	4,404	4	4,404	4,404	4,404	4,026	-	-	-
MAY	33,342	41,067	5,326	7	5,326	5,326	5.326	5,326	5,326	5,326	1,386
JUNE	17,134	45,799	5,940	3	5,940	5,940	5,254	-	-	-	-
JULY	33,488	47,489	6,159	6	6,159	6,159	6,159	6,159	6,159	2,693	-
AUG.	17,298	43,602	5,655	4	5,655	5,655	5,655	333	-	-	-
SEPT.	1,050	36,166	4,691	1	1,050	-	-	-	-	-	-
OCT.	808	26,838	3,481	1	808	-	-	-	-	-	-
NOV.	988	14,534	1,885	1	988	-	-	-	-	-	-
DEC.	1,344	7,622	989	2	989	355	-	-	-	-	-
TOTAL	127,374	344,784	44,717	-	35,162	28,680	26,798	15,844	11,485	8,019	1,386
K_j	-	-	-	-	0.79	0.64	0.60	0.35	0.26	0.18	0.03

No. Installed Modules = 7.71.
Reference 1, p. 28.

TABLE B-4

KANSAS

	DEMAND	SUPPLY	$\overline{W}$	J-Max.	W_{1-3}	W_4	W_5	W_6	W_7	W_8
JAN.	9,554	44,656	2,026	5	2,026	2,026	1,450	-	-	-
FEB.	8,848	56,474	2,562	4	2,562	1,162	-	-	-	-
MAR.	49,592	68,292	3,099	17	3,099	3,099	3,099	3,099	3,099	3,099
APR.	34,460	87,050	3,950	9	3,950	3,950	3,950	3,950	3,950	3,950
MAY	47,612	90,117	4,089	12	4,089	4,089	4,089	4,089	4,089	4,089
JUNE	54,596	107,618	4,883	12	4,883	4,883	4,883	4,883	4,883	4,883
JULY	116,670	117,173	5,316	22	5,316	5,316	5,316	5,316	5,316	5,316
AUG.	100,692	109,127	4,951	21	4,951	4,951	4,951	4,951	4,951	4,951
SEPT.	41,714	86,240	3,913	11	3,913	3,913	3,913	3,913	3,913	3,913
OCT.	26,836	74,327	3,372	8	3,372	3,372	3,372	3,372	3,372	3,232
NOV.	11,984	50,691	2,300	6	2,300	2,300	2,300	484	-	-
DEC.	9,142	36,459	1,654	6	1,654	1,654	1,654	872	-	-
TOTAL	511,700	928,224	42,115	-	42,115	40,715	38,977	34,929	33,573	33,433
K_j	-	-	-	-	1.0	0.97	0.93	0.83	0.80	0.79

No. Installed Modules = 22.04.
Reference 1, p. 35.

TABLE B-4 (Cont'd)

	w_9	w_{10}	w_{11}	w_{12}	w_{13-16}	w_{17}	w_{18-20}	w_{21}	w_{22}
JAN.	-	-	-	-	-	-	-	-	-
FEB.	-	-	-	-	-	-	-	-	-
MAR.	3,099	3,099	3,099	3,099	3,099	8	-	-	-
APR.	2,860	-	-	-	-	-	-	-	-
MAY	4,089	4,089	4,089	2,633	-	-	-	-	-
JUNE	4,883	4,883	4,883	833	-	-	-	-	-
JULY	5,316	5,316	5,316	5,316	5,316	5,316	5,316	5,316	5,034
AUG.	4,951	4,951	4,951	4,951	4,951	4,951	4,951	1,672	-
SEPT.	3,913	3,913	2,584	-	-	-	-	-	-
OCT.	-	-	-	-	-	-	-	-	-
NOV.	-	-	-	-	-	-	-	-	-
DEC.	-	-	-	-	-	-	-	-	-
TOTAL	29,111	26,251	24,922	16,982	13,366	10,275	10,267	6,988	5,034
K_J	0.69	0.62	0.59	0.40	0.32	0.24	0.24	0.17	0.12

No. Installed Modules = 22.04.
Reference 1, p. 35.

TABLE B-5

NEBRASKA

	DEMAND	SUPPLY	$\overline{W}$	J Max	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	w_{10-11}	w_{12}
JAN.	5,944	19,003	1,571	4	1,571	1,571	1,571	1,231	-	-	-	-	-	-	-
FEB.	5,462	24,032	1,986	3	1,986	1,986	1,490	-	-	-	-	-	-	-	-
MAR.	5,074	29,061	2,402	3	2,402	2,402	270	-	-	-	-	-	-	-	-
APR.	4,116	37,043	3,061	2	3,061	1,055	-	-	-	-	-	-	-	-	-
MAY	3,728	38,349	3,169	2	3,169	559	-	-	-	-	-	-	-	-	-
JUNE	33,390	45,796	3,785	9	3,785	3,785	3,785	3,785	3,785	3,785	3,785	3,785	3,110	-	-
JULY	33,470	50,132	4,143	9	4,143	4,143	4,143	4,143	4,143	4,143	4,143	4,143	326	-	-
AUG.	43,592	46,406	3,835	12	3,835	3,835	3,835	3,835	3,835	3,835	3,835	3,835	3,835	3,835	1,407
SEPT.	3,818	36,722	3,035	2	3,035	783	-	-	-	-	-	-	-	-	-
OCT.	18,236	31,629	2,614	7	2,614	2,614	2,614	2,614	2,614	2,614	2,552	-	-	-	-
NOV.	11,026	21,571	1,783	7	1,783	1,783	1,783	1,783	1,783	1,783	328	-	-	-	-
DEC.	5,666	15,515	1,282	5	1,282	1,282	1,282	1,282	532	-	-	-	-	-	-
TOTAL	173,516	394,989	32,666	-	32,666	25,798	20,773	18,673	16,692	16,160	14,643	11,763	7,271	3,835	1,407
K_J	-	-	-	-	1.00	0.79	0.64	0.57	0.51	0.49	0.45	0.36	0.22	0.12	0.04

No. Installed Modules = 12.10.
Reference 1, p. 42.

TABLE B-6

NEW MEXICO

	DEMAND	SUPPLY	$\overline{W}$	J Max	w_1	w_{2-5}	w_6	w_7	w_8	w_9	w_{10}	w_{11}	w_{12}	w_{13}
JAN.	1,600	41,853	2,695	1	1,600	-	-	-	-	-	-	-	-	-
FEB.	15,962	46,605	3,001	6	3,001	3,001	957	-	-	-	-	-	-	-
MAR.	1,270	53,642	4,098	1	1,270	-	-	-	-	-	-	-	-	-
APR.	44,810	80,256	5,168	9	5,168	5,168	5,168	5,168	5,168	3,466	-	-	-	-
MAY	73,948	91,135	5,868	13	5,868	5,868	5,868	5,868	5,868	5,868	5,868	5,868	5,868	3,532
JUNE	45,186	89,760	5,780	8	5,780	5,780	5,780	5,780	4,726	-	-	-	-	-
JULY	59,870	85,184	5,485	11	5,485	5,485	5,485	5,485	5,485	5,485	5,485	5,020	-	-
AUG.	48,884	80,960	5,213	10	5,213	5,213	5,213	5,213	5,213	5,213	1,967	-	-	-
SEPT.	3,724	72,512	4,669	1	3,724	-	-	-	-	-	-	-	-	-
OCT.	30,220	64,205	4,134	8	4,134	4,134	4,134	4,134	1,282	-	-	-	-	-
NOV.	15,850	48,259	3,107	6	3,107	3,107	315	-	-	-	-	-	-	-
DEC.	1,524	43,929	2,829	1	1,524	-	-	-	-	-	-	-	-	-
TOTAL	342,848	808,300	52,047	-	45,874	37,756	32,920	31,648	27,742	20,032	13,320	10,888	5,868	3,532
K_J	-	-	-	-	0.88	0.73	0.63	0.61	0.53	0.38	0.26	0.21	0.11	0.07

No. Installed Modules = 15.53.
Reference 1, p. 43.