TR- 119
1982

Economic Effect of Energy Price and Economic Feasibility and Potential New Technology and Improved Management for Irrigation in Texas

R.D. Lacewell
D.C. Petty
J.A. Petty
R.E. Whitson

Texas Water Resources Institute

Texas A&M University

RESEARCH PROJECT COMPLETION REPORT

Project Number A-045-TEX
October 1, 1978 - December 31, 1981

Agreement Numbers

14-34-0001-9046
14-34-0001-0146
14-34-0001-1146

ECONOMIC EFFECT OF ENERGY PRICE AND ECONOMIC FEASIBILITY AND POTENTIAL OF NEW TECHNOLOGY AND IMPROVED MANAGEMENT FOR IRRIGATION IN TEXAS

Principal Investigators

Ronald D. Lacewell
Daniel C. Hardin
James A. Petty
Robert E. Whitson

The work on which this publication is based was supported in part by funds provided by the Office of Water Research and Technology, U.S. Department of the Interior, Washington, D.C., (Project A-045-TEX) as authorized by the Water Research and Development Act of 1978, Texas Agricultural Experiment Station, Texas Water Resources Institute, and Center for Energy and Mineral Resources.

TECHNICAL REPORT NO. 119
Texas Water Resources Institute
Texas A&M University

May 1982

ABSTRACT

Irrigation is a major contributing factor in crop production on the Texas High Plains. It is responsible for greatly increasing crop production and farm income for the region. Two factors, a declining groundwater supply and increasing production costs, are of primary concern because they impact on farm operations and producer economic viability.

Recursive linear programming models for a typical Texas High Plains irrigated farm were developed to evaluate expected impact of energy and crop price changes, tenure and new technology. The model includes a Fortran sub-routine that adjusts irrigation factors each year based on the linear programming solution of the previous year. After calculating new pumping energy requirements, well yield, and pumping lift, the Fortran component updates the linear programming model. This procedure continues automatically to the end of a specified planning period or to economic exhaustion of the groundwater, whichever occurs first.

Static applications of the model, in a deep water situation, showed that a natural gas price increase from $1.50 to $2.20 per thousand cubic feet (mcf) would result in reductions in irrigation levels. Irrigation was terminated when the price of natural gas reached about $7.00 per mcf. In a shallow water situation, much higher natural gas prices were reached ($3.60 per mcf) before short-run adjustments in farm organization began to occur. Under furrow irrigation, irrigation was terminated when the natural gas price reached $7.00 per mcf.

Increased natural gas prices impact heavily on returns above variable costs (up to 15 percent reductions) for a 60 percent natural gas price increase. The effects of rising natural gas prices over a longer period of

time were more significant. Annual returns (above variable and fixed costs) were reduced by as much as 30 percent, and the present value of returns to water was reduced by as much as 80 percent as the natural gas price was increased annually by $0.25 per mcf (from $1.50 per mcf). The economic life of deep groundwater was shortened by as much as 18 years.

Renter-operators are even more vulnerable to rising natural gas prices than are owner-operators. With rising natural gas prices, profitability over time for the renter is low. As natural gas prices continue to increase, the greater will be the incentives for renter-operators to seek more favorable rental terms such as a sharing of irrigation costs.

With the problem of a declining groundwater supply and rising natural gas prices, an economic incentive exists for producers to find new technologies that will enable them to make more efficient use of remaining groundwater and of natural gas. Substantial economic gains appear feasible through improved pump efficiency. Increasing pump efficiency from 50 to 75 percent will not incresae the economic life of the water supply, but can improve farm profits over time; e.g., the present value of groundwater was increased 33 percent for a typical farm with an aquifer containing 250 feet of saturated thickness and 15 percent for 75 feet of saturated thickness.

Improved irrigation distribution systems can help conserve water and reduce irrigation costs. Results indicate that irrigation can be extended by 11 or more years with 50 percent improved distribution efficiency. In addition, the increase in present value of groundwater on the 1.69 million irrigated acres of the Texas High Plains was estimated to be $995 million with 50 percent improved efficiency.

New technology opportunities were expanded to include analysis of the economic feasibility of wind assisted irrigation pumping. Two wind machines were analyzed, with rate outputs of 40 to 60 kilowatts (KW). Each was applied to the Northern and Southern Texas High Plains over a range of land and water resource situations. Breakeven investment was estimated at discount rates of three, five and ten percent.

Cropping patterns on the Southern High Plains were dominated by irrigated cotton and were insensitive to changes in crop or electricity prices. On the Northern High Plains, irrigated corn and grain sorghum were the major crops, with acreage reverting to dryland wheat at the higher electricity prices. The cropping patterns in this area were impacted heavily by labor restrictions. Considerations of wind power had little effect in determining optimal cropping patterns.

When wind power was applied to an irrigated farm on a static basis, the set of crop prices applied had little effect on the annual value of a wind system. Value of wind power was increased, but by smaller proportions, in response to increases in the price of electricity. Each machine size had a greater value when operated on the larger of the two applicable land units (100 acres for the 40 KW machine and 144 acres for the 60 KW system). The 60 KW system was also tested on the 100 acre unit but returned less per KW than the 40 KW system.

Available wind power in the temporal analysis was less than in the static analysis, thus temporal estimates of wind system value should be regarded as conservative. On the Southern High Plains, breakeven investment was decreased slightly from the static analysis. However, in some situations on the Northern High Plains, breakeven investment increased. This indicates that the value of wind power could increase as the aquifer declines in some situations. Breakeven investment increased by up to 80 percent when the price of electricity was increased by $.005 per KWH per year. The most significant effect of wind power was that it allowed the maintenance of irrigation levels which, without wind power, had been made uneconomical.

These results indicate that, at least in the future when wind system costs decrease and stabilize, wind-assisted irrigation could be an economically viable alternative for Texas High Plains producers. The results are limited by the need for future research regarding the effect of irrigation timing on crop yield as well as some of the long-term characteristics of wind system operation, such as durability and the requirements and costs for system repairs and maintenance.

ACKNOWLEDGEMENTS

A special appreciation is felt for Dr. John Shipley. He rendered invaluable technical assistance in the development of input-output data used in the linear programming model. We regret to add that Dr. Shipley died, after a brief illness, in January 1979.

Many other scientists made major contributions to this work. Allan Weise provided weed control suggestions, Charles Wendt, Bill Lyle and Lavon Ray assisted in developing cotton enterprise budgets and specifying the irrigation systems.

Nolan Clark, Bob Lansford and Ray Supalla contributed information about wind machines. Unpublished data from irrigation experiments were provided by Jack Musick and Dan Undersander. Don Reddel and Wayne LePori aided in the technical equations. Wyatt Harman was extremely helpful in model development and providing much of the input data to models. Technical guidance and suggestions that improved the research effort were provided by J. R. Runkles, Bill Ott, Wayne Wyatt, Bruce Beattie and Bob Taylor. Also, we are most grateful to Evelyn Teaff and Pat Feagan for their dedication to timely reporting of progress and budget considerations. Lastly and especially, we want to thank Dianne Miller for her excellence in typing this manuscript.

To these and the many others that unselfishly provided their skills and time we are most grateful. Of course, the results and interpretations are the responsibility of the authors.

TABLE OF CONTENTS

Introduction

The Texas High Plains is a fairly level, semi-arid region located on the Southern Great Plains, encompassing about 35,000 square miles. The region's climate and land resource capability support dryland production of cotton, grain sorghum and wheat. With irrigation, yields of these crops can be increased substantially and other crops such as corn and soybeans can be produced. In addition, irrigation can greatly reduce the risk of drought (Black).

Irrigation water on the High Plains is pumped from the underlying Ogallala aquifer. This aquifer receives a negligible amount of recharge (one-half to one inch per year) compared to the amount of water withdrawn annually. Average annual rates of decline in the static water level have been projected to be from .35 to 4.08 feet, depending on the original saturated thickness (Wyatt, et al.). For the farmer, this results in (1) declining well yields, where less water can be pumped in a given period of time, (2) increased energy requirements as pumping lift increases and (3) eventual economic exhaustion of the water supply for irrigation.

Energy is one of the most important input factors in irrigated crop production. In 1973, it was estimated that 39 percent of the total agricultural energy demand in Texas was for pumping groundwater (Coble and LePori). This figure is likely understated for the High Plains, due to the relatively higher intensity of irrigation in the area. An estimate of this region in 1975 showed that 53.4 percent of the total variable costs of producing irrigated corn was energy related (Skold).

The combination of declining groundwater, increasing fuel requirements, and escalating prices of irrigation fuel leads to a rapid rise in production costs. Dramatic increases in the costs of production can result in a shortening of the "economic life of the water supply." The economic life of the water supply is the period of time over which returns attributable to water are positive. Conversely, economic exhaustion of the water supply is defined as that point when returns to water have declined to zero. With economic exhaustion of the water supply, irrigated production can be expected to revert to dryland crop production, pasture or to remain as idle acres.

The dramatic increase in energy prices since 1973, in conjunction with higher variability of crop prices, have accelerated research directed to reducing costs of production. For example, emphasis has been placed on modified crop production systems which seek to improve the energy efficiency of irrigated production by reducing the usage of energy inputs (Condra, et al.; Sprott, et al.). Other studies have focused on the benefits of reducing the amount of water pumped, improving irrigation and pumping plant efficiencies, and lowering the distribution system pressure requirements (Hardin, et al.; Hardin and Lacewell, 1979).

The sensitivity of irrigated agriculture to increased fuel costs has placed considerable emphasis on the development of new and competitive alternative energy supplies. Much of the research emphasis in agriculture has been placed on biomass; i.e., the conversion of crop residue into usable energy (LePori and Lacewell). In addition, the utilization of grain for the production of alcohol has gained substantial interest (Hiler). Solar energy has been proposed as an alternative to the use of natural gas in grain drying applications (Knutson, et al.) and for irrigation

(Katzman and Matlin).

This report describes research results relative to two major efforts. First is a study of the effect on irrigated crop production attributable to increased energy costs, tenure arrangements and irrigation technologies (Petty, et al.). The second study focused on the economic implications of wind powered irrigation wells for the same region, the Texas High Plains (Hardin and Lacewell, 1981). For a detailed discussion of these studies the reader is referred to the two publications.

The central problem faced by managers of irrigated farms is that rising natural gas prices and a declining irrigation water supply cause pumping costs to increase and thus impacts negatively on the farm's profitability. The farmer who irrigates needs to consider possible adjustments in farm plans that would potentially reduce requirements for both natural gas and irrigation water. Such adjustments could contribute to profitability of the irrigated farm and extend the economic life of the water supply. Adjustments might take the form of new technology which require less inputs (particularly less water and natural gas) or improved efficiencies from the pumping and distribution of irrigation water. Improved farm planning is needed to make more effective use of the limited irrigation water supply, irrigation fuel, and other scarce resources available to the farmer.

The wind-assist concept appears to be a particularly attractive alternative on the High Plains. A study by Elliot shows that the mean annual wind power available is as high as in any other area in the nation, with monthly average wind speeds ranging from 15.6 miles per hour (mph) in March to 12.1 mph in August. In addition, about 50 percent of the energy used on irrigated farms in the area is accounted for by irrigation pumping (Clark and Schneider), thus providing a large potential for energy substitution.

Previous studies (Clark and Schneider; Buzenberg, et al.) considering wind power application to irrigation have shown potential savings but have assumed no load management; i.e., rescheduling energy use to periods of expected high winds. This leaves open the possibility of further savings. For example, on the High Plains, traditional cropping patterns (involving corn, grain sorghum and cotton) make the summer months (when post-plant irrigations are applied) the peak water use period. However, peak winds occur in the spring months when wheat, which in the past has not been one of the area's major irrigated crops, uses the bulk of its irrigation water. Further load management strategies might include the consideration of non-optimal irrigation timing, that is, shifting one or more post-plant irrigations to different time periods. The negative effect on yield might be compensated for not only in energy savings from wind, but also through the possible extension of a seasonally limited water supply. High Plains producers, faced with declining well yields and increasing energy requirements due to the continuing depletion of the Ogallala aquifer, are in a position to benefit considerably from the use of wind energy. However, these benefits must be quantified.

Study Area

The High Plains of Texas includes 42 counties and is roughly rectangular, averaging about 300 miles north to south and 120 miles east to west. The Canadian River flows from west to east, dividing the region. The main soils in the region include Pullman, Mansker and Richfield in the "Hardlands", Amarillo and Portales in the "Mixed Lands", and Brownfield and Tivoli in the "Sandy Lands". Average annual rainfall averages from 14 to 21 inches, with the growing season ranging from 180 to 220 days (Godfrey, et al.).

The High Plains region has 34 percent of the total cropland, and approximately 70 percent of the irrigated cropland in Texas. Over the period from 1970 to 1977, crop production from the region (as a percentage of total state production) was 61 percent of cotton, 50 percent of grain sorghum and 61 percent of wheat. The area also produces 78 percent of the fed cattle in Texas, enough to feed 13.2 million people (Texas Department of Water Resources).

Pumpage from the Ogallala for irrigation purposes began to rise to a significant level in the late 1930's and accelerated in the 1950's, spurred by the availability of low-cost natural gas. This rapid development has resulted in the mining of Ogallala water. In 1974, there were nearly 5.9 million irrigated acres on the High Plains. However, based on projected pumpage rates, the aquifer will be able to supply enough water to irrigate only 53 percent of these acres by the year 2000 and only 35 percent in 2030 (Texas Water Development Board).

The study area lies within a 21-county sub-region of the High Plains, Figure 1. In 1974, 4.16 million acres in the region were irrigated, which was 66 percent of the total crop acreage (New, 1977). In 1979, irrigated acreage had decreased to 3.27 million acres (57 percent of total cropland), while total crop acreage had declined by over 572 thousand acres (Texas Crop and Livestock Reporting Service, 1979).

There were 37,010 irrigation wells in the area in 1977, 9,029 of which were powered by electricity. Natural gas was the predominant fuel

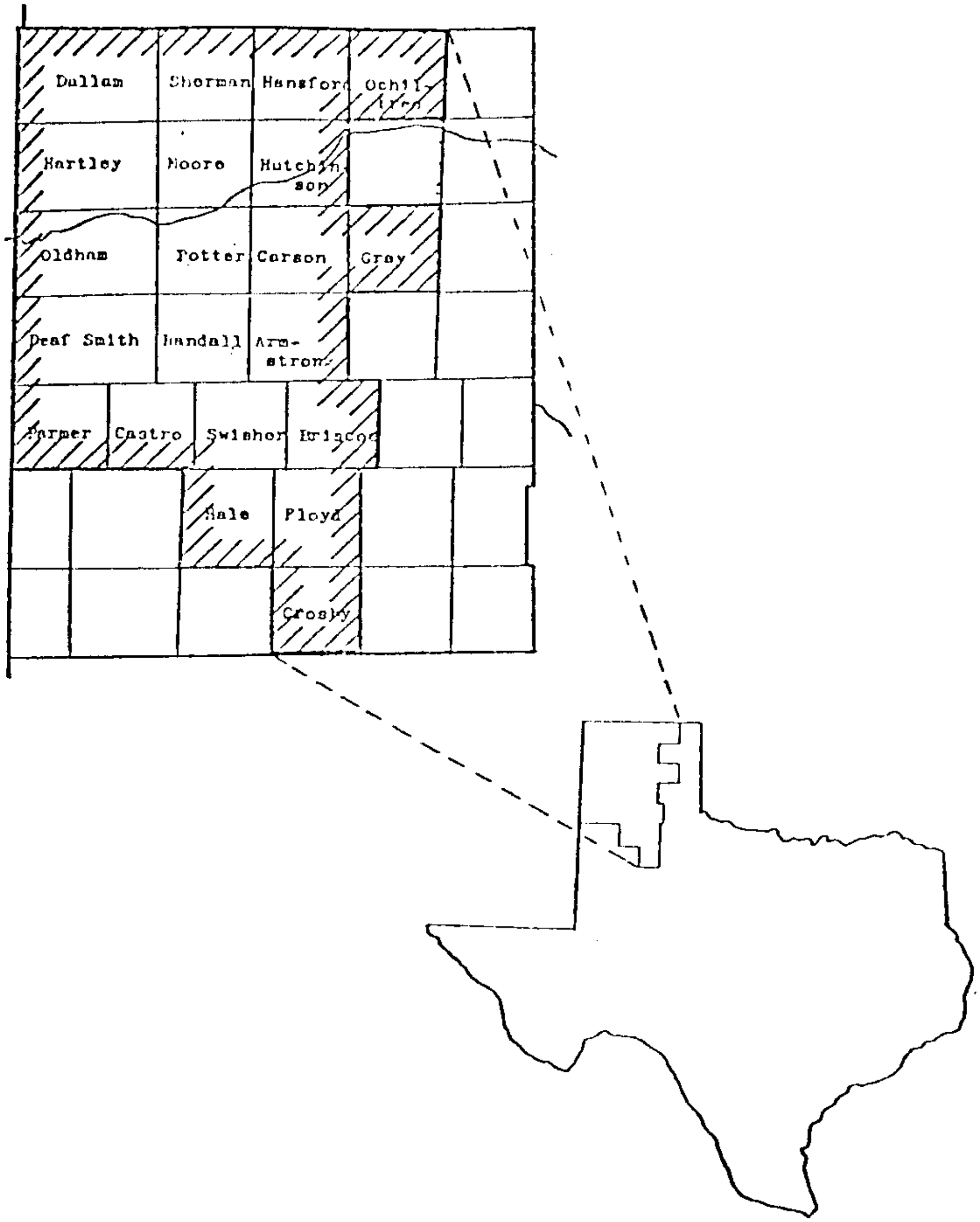

Figure 1. Map of the Study Area -- Texas High Plains.

used, powering 27,323 wells. Ninety-eight percent of the wells lift water from a depth greater than 125 feet, while 73 percent produce less than 700 gallons per minute (New, 1977). Most of the lower yielding wells were situated in the southern part of the region. Surface irrigation methods were used on 90 percent of the irrigated acres, while sprinkler systems were in use on the remaining 10 percent.

Methodology

Since this report is a summarization of two large studies, presentations adhere to the separate studies. Each of the studies relied on a linear programming model for the region. Each linear programming model was linked to an aquifer depletion model. This permitted a temporal analysis whereby water was mined from the Ogallala aquifer. The characteristics of irrigation wells and methods for depleting the aquifer were common to the two studies.

Well yield was established as a function of saturated thickness.[1] Maximum well yield of 800 GPM was assumed to remain constant for all levels of saturated thickness above 210 feet. This is representative of an average well in the region, where the maximum yield is much less than the potential that the aquifer can deliver (Reddell). The well yield relationship for lower levels of saturated thickness is represented by the following equation (Hughes and Harman).

---

[1] Saturated thickness refers to feet of water-bearing sand. The coefficient of storage of the Ogallala is about 15 percent, meaning that 100 feet of saturated thickness yields 15 feet of water (Cronin).

$$GPM = 800 * \left(\frac{ST}{210}\right)^2$$

where

GPM = well yield in gallons per minute,

ST = saturated thickness in feet.

Limitations on seasonal water availability were established by the physical maximum which could be pumped in a critical water period, based on well yield.

$$M = .0044 * GPM * T$$

where

M = maximum acre-feet of water that can be pumped in a critical water period,

T = number of days in each period not used for well repairs and maintenance (assumed to be 8.5 for this study),

.0044 = constant value which translates gallons per minute into acre-feet per day.

Labor restrictions were based on the principle that two men, the operator and one full-time employee, will provide all labor (except part-time hoeing labor) for a 640 acre farm. Labor usage is separated into two-month periods in the model and is charged on an hourly basis. The number of hours available in each two-month period depends on weather patterns and length of days, and will thus be higher in the summer months.

An extension of linear programming was utilized which consolidated a Fortran program with an LP model. The Fortran program functions as a subroutine which modifies the LP model after each year's solution to reflect the farm situation for the following year. The procedure performs as follows:

1. Calculates the decrease in saturated thickness of the aquifer and associated increase in pumping lift based on the amount of water withdrawn in the previous year. The relationship is

$$D = W/(CA * .15)$$

where

D = decline in water level of the aquifer (in feet),

W = acre-feet of water pumped in the previous year,

CA = acres contributing to the aquifer (including non-cultivated acres and dryland)[2]

.15 = coefficient of storage for the Ogallala aquifer.

2. Calculates well yield based on a new saturated thickness.
3. Calculates the amount of energy required to pump an acre-foot of water based on the adjusted pumping lift.
4. Calculates the maximum acre-feet of water which can be pumped in each critical water period based on the adjusted well yield.
5. Calculates the present value of net returns for selected discount rates.
6. Modifies the LP tableau with new irrigation water upper limits and pumping energy requirements.

Input data specifying the scenario being analyzed are read into the

[2]Acres contributing irrigation water are expected to exceed acres irrigated since all acres cannot be cropped, i.e., there is water available beneath land used for turn rows, roads and homesteads.

subroutine, which creates a file to initialize the basic LP matrix. The program is called after each year's solution to perform the updating procedure. A summary table is printed for each year showing the activities in the solution and their level, irrigation pumping and shadow prices by water period, irrigation fuel requirements separated into the amounts purchased and wind-generated by month in addition to cropland acres and their shadow price. At the end of n years the temporal analysis is summarized in tabular form.

With several differences in the model used for each type of analysis and different objectives of the analyzes, each study will be described relative to procedures and results.

Energy and Technology Impact

This study was designed to evaluate, for typical farm situations within a 21-county sub-region of the Texas High Plains, the physical and economic effects of rising natural gas prices, pump efficiency, irrigation distribution efficiencies, tenure arrangements, and the economic effects of credit constraints. This analysis included a center-pivot sprinkler system and a furrow irrigation distribution system.

Procedure

A generalized linear programming/Fortran simulation model was developed for a typical Texas High Plains farm. Three water resource situations were specified. Poor water is defined as 75 feet of lift and 75 feet of saturated thickness, Fair water as 175 feet of lift and 125 feet of saturated thickness, and Good water as a lift of 250 feet and a saturated thickness of

250 feet.

For static analysis, annual computer runs were made using only the LP component of the model. For a temporal analysis, the LP and the Fortran components were employed. The temporal analysis was recursive. Annual farm plans were developed by use of the LP model. Based on quantity of irrigation water applied in the LP farm plan, the Fortran component calculated the decline in the saturated thickness of the aquifer, and resulting new well yield, lift, and fuel required to pump water to the surface. Then the Fortran component updated the LP component with these parameters. This procedure continued automatically for 25 years of analysis or until economic exhaustion of the groundwater supply, whichever occurred first.

The LP component of the model contained production activities for irrigated crops (corn, cotton, grain sorghum, soybeans, wheat, and grazing of wheat by cattle) and dryland crops (cotton, grain sorghum, wheat, and grazing of wheat by cattle). Irrigation activities were included for both furrow or center-pivot sprinkler distribution systems. Cotton was included in the model with furrow irrigation only, since cotton is not traditionally irrigated with sprinkler systems. Since furrow irrigation included cotton, results of the furrow irrigation analysis are not applicable to the north of the Canadian River.

In addition to the production activities, there were separate purchasing activities for inputs, selling activities for crops produced, and borrowing and repaying activities.

Results

Energy Price Impacts

Energy prices were evaluated as to their effects upon a typical Texas High Plains farm. While these energy inputs included natural gas, nitrogen fertilizer, gasoline, and diesel, attention was focused primarily on natural gas.

Natural Gas Price. Expected short-run (static analysis) and longer-run (temporal analysis) effects of increased natural gas prices are summarized for a typical farm in the Texas High Plains. The discussion includes both physical and economic effects.

Static Analysis. For the base situation (which is a natural gas price of $1.50 per mcf), short-run farm returns above variable costs for an owner-operator were the greatest ($90,129) with a combination of shallow lift and lower cost of sprinkler irrigation as shown in Table 1. Annual returns above variable costs were the least with a combination of Good water and furrow irrigation ($62,059).

The price of natural gas was increased parametrically from $1.50 to $10.00 per mcf to evaluate the short-run effects of increased natural gas prices. With sprinkler irrigation and a natural gas price of $1.50 per mcf, the cropping pattern consisted entirely of 640 acres of grain sorghum, of which 533.3 acres were irrigated. As the price of natural gas was increased, irrigation levels were reduced, and in Good water, all acres reverted to dryland production when the price of natural gas reached $7.09 per mcf.

With furrow irrigation, increases in the price of natural gas resulted

Table 1. Annual Returns Above Variable Costs for Selected Natural Gas Prices for 640 Acres, a Typical Farm: Texas High Plains

Water Resource Situation[a]	Price of Natural Gas ($/mcf)		
	1.50	2.00	2.50
Poor			
Sprinkler	90,129	85,982	81,835
Furrow	71,910	70,114	68,330
Fair			
Sprinkler	85,520	79,907	74,294
Furrow	66,152	62,712	59,489
Good			
Sprinkler	82,063	75,350	69,453
Furrow	62,059	57,919	54,511

[a]Poor water has a saturated thickness of 75 feet and a lift of 75 feet, Fair water has a saturated thickness of 125 feet and a lift of 175 feet, and Good water has a saturated thickness of 250 feet and a lift of 250 feet.

in adjustments in irrigation levels and shifts toward crops requiring less water. All acres shifted to dryland production at a gas price of $7.83 per mcf. The adjustments under furrow irrigation were at higher natural gas prices than with the sprinkler, but this was probably due to cotton being included as a crop option under furrow irrigation.

Annual returns above variable costs declined rapidly with increased gas prices. In Poor water, when the gas price was increased from $1.50 to $3.60, annual net returns for the owner-operator were reduced 19 percent, while in Good water, annual net returns were reduced 30 percent. With furrow irrigation and Poor water, a gas price increase from $1.50 to $3.75 per mcf reduced annual net returns 11 percent for an owner-operator, while in Good water, the same gas price increase reduced annual net returns for an owner-operator 26 percent.

Temporal Analysis. This analysis considers returns above all costs (fixed and variable) and includes all the years to economic exhaustion of the water supply or 25 years, whichever occurs first. The base of comparison is a constant $1.50 per mcf for natural gas. The Good and Poor water resource situations were evaluated.

Estimated annual returns above variable and fixed costs in the earlier years are greatest in a Poor water situation, but less water is available in a Poor water situation and is depleted more rapidly than in Good water, as shown in Table 2. With a constant natural gas price ($1.50 per mcf), irrigation can be maintained longer in a Good water situation. Thus, in later years, the annual returns above variable and fixed costs are greater in a Good water situation than in Poor water. In addition, with a constant

Table 2. Expected Effect of a Rising Natural Gas Price for 640 Acres, a Typical Farm: Texas High Plains

Item	Unit	Water Resource Situation[a] Poor	Fair	Good
Present Value of Groundwater				
Sprinkler				
$1.50/mcf gas price	$1000	370.8	490.5	607.0[c]
$0.10/mcf annual rise	$1000	302.8	260.5	237.8
$0.25/mcf annual rise	$1000	201.9	133.2	99.0
Furrow				
$1.50/mcf gas price	$1000	249.0	306.7	348.1[c]
$0.10/mcf annual rise	$1000	223.3	192.5	138.3
$0.25/mcf annual rise	$1000	192.2	112.2	73.3
Years of Irrigation and Ending Saturated Thickness[b]				
Sprinkler				
$1.50/mcf gas price	year(feet)	14(12)	25(19.6)	25(129.2)
$0.10/mcf annual rise	year(feet)	14(12)	20(39)	17(178.5)
$0.25/mcf annual rise	year(feet)	14(12)	10(82.5)	8(216.2)
Furrow				
$1.50/mcf gas price	year(feet)	12(12)	24(10)	25(132.6)
$0.10/mcf annual rise	year(feet)	12(12)	19(40.8)	16(178.5)
$0.25/mcf annual rise	year(feet)	13(10)	11(74.7)	8(214.5)

[a]Poor water has a saturated thickness of 75 feet and a lift of 75 feet, Fair water has a saturated thickness of 125 feet and a lift of 175 feet, and Good water has a saturated thickness of 250 feet and a lift of 250 feet.

[b]The analysis was for 25 years, but irrigation was terminated when saturated thickness was reduced to 10 feet or when irrigation is no longer profitable. Saturated thickness is in parentheses.

[c]Includes a present salvage value of groundwater remaining after 25 years.

natural gas price of $1.50 per mcf, the present value of returns to water are greater in Good water than in Poor water. However, with an initial gas price of $1.50 per mcf that is increased by $0.10 or $0.25 per mcf each year, the present value of returns to water over a 25-year planning horizon are greater in a Poor water situation than in Good water. The water that is available in future years becomes increasingly costly to pump as the water table declines and the price of irrigation fuel increases. With an initial natural gas price of $1.50 per mcf that is increased $0.25 per mcf each year, the economic life of Good water is dramatically shortened from greater than 25 years to only 8 years (Table 2).

With sprinkler irrigation and Poor water, the present value of groundwater decreased 18 percent and 46 percent when the natural gas price (initially $1.50 per mcf) was increased by $0.10 and $0.25 per mcf, respectively. In Good water, the same gas price increases reduced the present value of groundwater by 61 and 84 percent, respectively (Table 2).

With furrow irrigation and Poor water, natural gas price increases of $0.10 to $0.25 per mcf (from an initial $1.50 per mcf) decreased the present value of groundwater by 25 percent and 36 percent, respectively. In Good water, the same gas price increases reduced the present value of groundwater by 60 percent and 79 percent, respectively (Table 2).

Rising natural gas prices resulted in the renter-operator making adjustments in cropping patterns and reducing irrigation levels in similar fashion to the owner-operator but at lower natural gas prices. With natural gas prices increasing yearly $0.10 and $0.25 per mcf (from $1.50 per mcf), annual returns (above variable and fixed costs) to a renter and the present value of those annual returns were estimated to be between 60 to 75 percent below annual returns to an owner-operator.

Energy-Related Input Prices. The base energy prices were: $1.50 per mcf for natural gas, $0.16 per pound for nitrogen fertilizer, and $0.50 per gallon for gasoline and diesel. An energy price increase of a specified magnitude (a price increase of about 60 percent) reduced returns above variable costs over a range of 13 to 27 percent as presented in Table 3. The greatest reduction in returns above variable costs occurred in Good water with sprinkler irrigation. Returns dropped from $82,063 to $59,505 (a 27 percent decrease). At the same time, both natural gas used and the volume of irrigation water applied declined 20 percent. No change in cropping patterns occurred.

In the case of Poor water with furrow irrigation, the higher energy prices decreased annual returns above variable costs from $71,910 to $62,472 (down 13 percent). Natural gas used and water pumped dropped 11 percent, a sizeable shift from irrigated wheat to dryland wheat and irrigated cotton occurred (Table 3).

Crop Prices

The specific crop price scenarios used in the analysis were selected primarily to estimate the sensitivity of the farm organization and net returns under furrow irrigation. Cotton was the dominant crop (under furrow irrigation) prior to the crop price changes. With either a 20-percent decrease in cotton price or a 20-percent increase in grain prices, dramatic shifts occurred away from cotton acres to irrigated grain sorghum and dryland wheat with grazing. In Poor water, these crop price changes decreased annual water use, while in Good water, annual water use was

Table 3. Static Analysis of Increased Prices of Energy Related Inputs with Two Price Scenarios of These Inputs for 640 Acres, a Typical Farm: Texas High Plains

Item	Unit	Poor Water[a] Price Scenarios[b] A	Poor Water[a] Price Scenarios[b] B	Good Water[a] Price Scenarios[b] A	Good Water[a] Price Scenarios[b] B
Sprinkler					
Crops					
Sorghum (dryl)	acres	106.7	106.7	106.7	106.7
Sorghum (irri)	acres	533.3	533.3	533.3	533.3
Level of Inputs					
Gas	mcf	8294	8294	13425	10740
Nitrogen	cwt.	874.70	874.40	874.70	768.10
Gasoline	gal.	2699	2699	2699	2699
Diesel	gal.	3491	3491	3491	3491
Water Pumped	ac ft	666.67	666.67	666.67	666.67
Annual Returns[c]	dol.	90129	70970	82063	59505
Furrow					
Crops					
Wheat (dryl)	acres	80.7	169.7	171.7	168
Cotton (irri)	acres	427.9	455.5	455.3	458
Sorghum (irri)	acres	--	--	--	--
Soybeans (irri)	acres	--	1.8	--	--
Wheat, Grain Only	acres	109.8	13.1	9.6	--
Light Feeders	head	19	--	--	--
Wheat Pasture	aum	--	126.7	122.7	105.9
Level of Inputs					
Gas	mcf	3593	3206	8887	6881
Nitrogen	cwt.	302.90	197.90	198.50	188.10
Gasoline	gal.	2749	3520	3569	3557
Diesel	gal.	6440	7006	7014	6999
Water Pumped	ac ft	832	743	739	572
Annual Returns[c]	dol.	71910	62472	72059	48847

[a]Poor water has a saturated thickness of 75 feet and a lift of 75 feet, and Good water has a saturated thickness of 250 feet and a lift of 250 feet.

[b]Energy price scenarios are: (A) Gas - \$1.50 @ mcf, nitrogen - \$0.16 @ lb., gasoline - \$0.50 @ gal., and diesel - \$0.50 @ gal. compared to (B) Gas - \$2.50 @ mcf, nitrogen - \$0.25 @ lb., gasoline - \$0.80 @ gal, and diesel - \$0.80 @ gal.

[c]Expected annual returns above variable costs.

increased. In both Poor and Good water, annual returns above variable costs decreased (14 percent) with the lower cotton price and increased (15 percent) with the higher grain prices.

Since cotton was not included as a crop option under sprinkler irrigation, the decrease in the cotton price had no effect on the cropping patterns, irrigation levels, or natural gas usage. The 20 percent increase in grain prices (specifically, the increase in the price of grain sorghum from $4.25 to $5.10 per cwt.) resulted only in increased annual returns above variable costs (a 36 percent increase in Poor water and a 39 percent increase in Good water).

Pump Efficiency

The economic and physical implications of pump efficiency were estimated by application of the recursive model with a 50 percent pump efficiency and comparing the results to a 75 percent pump efficiency over a 25-year planning horizon. The results are presented in Table 4.

In the case of sprinkler irrigation and Poor water, the improved pump efficiency had no effect upon cropping patterns, irrigation levels, or ending saturated thickness, but natural gas usage per acre foot of water pumped was reduced 33 percent. The reduction in pumping costs resulted in an increase of $61,940 (17 percent) in the present value of the water supply. The improved pump efficiency slightly increased the rate at which the water supply was being depleted and increased the present value of returns to water by $224,970 or 36 percent (Table 4).

With furrow irrigation and Poor water, the effects of improved pump efficiency upon ending saturated thickness, irrigated acres, and well yield

Table 4. Effects of Improved Pump Efficiency for Two Water Resource Situations with Sprinkler and Furrow Distribution Systems on 640 Acres, a Typical Farm: Texas High Plains

Item	Unit	Poor Water[a] 50% Efficiency	Poor Water[a] 75% Efficiency	Poor Water[a] Difference	Good Water[a] 50% Efficiency	Good Water[a] 75% Efficiency	Good Water[a] Difference
Sprinkler Irrigation							
Ending Saturated							
Thickness	feet	12.0	12.0	0	141.1	137.6	-3.5
Ending Well Yield	gpm	105.0	105.0	0	608.0	597.0	-8.0
Natural Gas Usage:							
Beginning	mcf/af	12.4	8.3	-4.1	20.1	13.4	-6.7
Ending	mcf/af	15.1	10.1	-5.0	24.1	16.1	-8.0
Irrigated Acres:							
Beginning	acres	533.3	533.3	0.0	533.3	533.3	0.0
Ending	acres	428.1	428.1	0.0	533.3	533.3	0.0
Years of Analysis	number	14.0	14.0	0.0	25.0	25.0	0.0
Present Value of:[b]							
Returns	dollars	585636	647576	61940	61940	622318	98118
Returns to Water[c]	dollars	361486	423426	61940	622318	847288	224970
Furrow Irrigation							
Ending Saturated							
Thickness	feet	12.0	12.5	-0.3	146.2	126.0	-20.2
Ending Well Yield	gpm	111.0	109.0	-1.7	623.0	561.0	-62.0
Natural Gas Usage:							
Beginning	mcf/af	4.3	2.9	-1.4	12.0	8.0	-4.0
Ending	mcf/af	6.9	4.6	-2.3	15.5	11.0	-4.5
Irrigated Acres:							
Beginning	acres	468.4	475.3	-6.9	458.4	460.6	2.2
Ending	acres	371.1	365.6	-5.5	458.4	460.6	2.2
Years of Analysis	number	12.0	12.0	0.0	25.0	25.0	0.0
Present Value of:[b]							
Returns	dollars	454874	479869	24995	681736	760833	79097
Returns to Water[c]	dollars	259957	284952	24995	357983	464952	107969

[a]Poor water has a saturated thickness of 75 feet and a lift of 75 feet, and Good water has a saturated thickness of 250 feet and a lift of 250 feet.

[b]The present value of returns do not take into account the costs of well improvement. Cost of well improvement was estimated at $3,000 per well (Lyle 1978). There are 10 wells for the Poor water and 6 for the Good water.

[c]Present value of returns to water includes estimated present value of the remaining water supply after 25 years.

were very small, but natural gas usage was reduced 33 percent (Table 4). In Good water, the physical effects were substantial. Natural gas usage was reduced 33 percent, while irrigation levels were increased. The improved pump efficiency resulted in economic exhaustion of water at a reduced saturated thickness of the aquifer. The improved pump efficiency increased the present value of returns to water by $24,995 (10 percent) and $107,969 (30 percent) in Poor and Good water situations, respectively. Expected cost to improve efficiency of assumed pumps in the Poor water situation would be $30,000, while in the Good water resource situation it would be $12,000. Only in a Poor water situation, with furrow irrigation, does it appear economically infeasible to improve pump efficiency from 50 to 75 percent.

Distribution Efficiency

The purpose of this analysis was to quantify potential economic gains resulting from improved irrigation distribution efficiency.

The recursive model was applied to simulate a mobile trickle system, first, with the same water requirements as for a center-pivot sprinkler system but with pressure reduced from 90 psi to 10 psi, secondly, with 25 percent less water used and, thirdly, with 50 percent less water used. In all cases crop yields were held constant. In Poor water, the present value of returns to water and the distribution system were increased by $100,355 (17 percent), $320,929 (55 percent), and $651,568 (112 percent), for the respective levels of water use (Table 5). In Good water, the present value of returns to water and the distribution system were increased by the mobile trickle system by $176,939 (21 percent), $263,151 (32 percent)

Table 5. A Comparison of Sprinkler and Mobile Trickle Irrigation Systems in a Poor Water Resource Situation at Alternative Rates of Distribution Efficiency for 640 Acres, a Typical Farm: Texas High Plains

Item	Unit	Center-Pivot Sprinkler (90 psi)		Mobile Trickle (10 psi)[a]					
				No Water Saved		25% Less Water		50% Less Water	
		Year 1	Year 14	Year 1	Year 14	Year 1	Year 18	Year 1	Year 25
Poor Water[b]									
Crops:									
Sorghum (dryl)	acres	106.7	211.9	106.7	211.9	106.7	106.7	106.7	106.7
Sorghum (irri)	acres	533.3	428.1	533.3	428.1	533.3	533.3	533.3	533.3
Lift	feet	79.83	138.03	79.83	138.03	78.62	138.83	77.42	135.38
Saturated thickness	feet	70.17	11.97	70.17	11.97	71.38	11.18	72.58	14.62
Water decline	feet	4.83	3.10	4.83	3.10	3.62	2.93	2.92	2.42
Well yield	gpm	388	124	388	125	388	118	388	135
Water pumped	ac ft	667	428	667	428	500	404	333	333
Returns to water and distribution system[c]	dollars	49166	33270	56832	34292	57123	40716	59059	41429
Present value of water and distribution system[c]	dollars	NA	580959	NA	681314	NA	901888	NA	1232527

[a]The analysis is based on maintaining yields with less pressure and the same irrigation level and with 25 to 50 percent less irrigation water.

[b]Poor water has a saturated thickness of 75 feet and a lift of 75 feet.

[c]Annual returns to land and management of $17,870 per year have been deleted. Fixed costs for each distribution system have not been deleted.

and $346,001 (42 percent) for the resepctive levels of water use (Table 6).

The analysis indicated that the water savings, due to improved distribution efficiency of a mobile trickle system, would result in the economic life of the water supply being significantly extended up to 11 years in Poor water. In Good water the increase in the economic life of the water supply was not determined, but at the end of 25 years, saturated thickness of the aquifer was 60 feet greater for the mobile trickle system under the assumption of 50 percent less water used, as compared to a center-pivot system in Good water. Even though the 60 foot greater saturated thickness is not considered in the present value of returns to water, it is recognized as a beneficial factor of irrigation since well yield is greater and lift less.

Static energy comparisons for a single year were made between the irrigation distribution systems as to the total energy used by each distribution system in Good water. Table 7 summarizes these comparisons. Results show that when compared with the center-pivot system, the mobile trickle system reduced total energy by 37, 50, and 64 percent for no water savings, 25 percent savings, and 50 percent savings, respectively. The greatest reduction in energy use resulted with a mobile trickle system and 50 percent water savings. The reduced water use results in reduced irrigation fuel requirements. In addition, irrigation fuel requirements are reduced even further by the lower operating pressure (10 psi as compared to 90 psi) of the mobile trickle system. Such energy savings indicate strong incentives for producers to adjust to the new mobile trickle systems. And the incentives will be increasingly strong as energy becomes more scarce and costly and as irrigation fuel requirements increase due to increased lift.

Table 6. A Comparison of Sprinkler and Mobile Trickle Irrigation Systems in a Good Water Resource Situation at Alternative Rates of Distribution Efficiency for 640 Acres, a Typical Farm: Texas High Plains

Item	Unit	Center-Pivot Sprinkler (90 psi)		Mobile Trickle (10 psi)[a]					
				No Water Saved		25% Less Water		50% Less Water	
		Year 1	Year 25	Year 1	Year 25	Year 1	Year 25	Year 1	Year 25
Good Water[b]									
Crops:									
Sorghum (dryl)	acres	106.7	106.7	106.7	106.7	106.7	106.7	106.7	106.7
Sorghum (irri)	acres	533.3	533.3	533.3	533.3	533.3	533.3	533.3	533.3
Lift	feet	254.80	370.80	254.80	370.80	253.80	340.80	252.40	310.50
Saturated thickness	feet	245.17	129.23	245.17	129.23	246.38	159.42	247.58	189.50
Water decline	feet	4.83	4.83	4.83	4.83	3.62	3.62	2.42	2.42
Well yield	gpm	800	588	800	588	800	673	800	763
Water pumped	ac ft	667	667	667	667	500	500	333	333
Returns to water and distribution system[c]	dollars	41915	30739	50342	31563	53419	35177	56543	38518
Present value of water and distribution system[c]	dollars	NA	828789	NA	1005728	NA	1091940	NA	1174790

[a]The analysis is based on maintaining yields with less pressure and the same irrigation level and with 25 and 50 percent less irrigation water.

[b]Good water has a saturated thickness of 250 feet and alift of 250 feet.

[c]Annual returns to land and management of $17,870 which gives a present value over 25 years of $375,813 have been deleted. Fixed costs for each distribution system have not been deleted.

Table 7. **A Static Energy Use Comparison by Level of Sprinkler Distribution Efficiency for 640 Acres, a Typical Farm in Good Water[a]: Texas High Plains**

Item	Unit	Center-Pivot Sprinkler (90 psi)	Mobile Trickle System (10 psi)[b]		
			No Water Saved	25% Less Water	50% Less Water
Input					
Gasoline	gal.	5228	5228	5228	5228
Diesel	gal.	4771	4771	4771	4771
Natural Gas	mcf.	13425	8007	6020	4003
Nitrogen	lb.	87466	87466	87466	87466
Insecticide	lb.	267	267	267	267
Herbicide	lb.	1200	1200	1200	1200
Energy					
Gasoline[d]	mil BTU[c]	627.4	627.4	627.4	627.4
Diesel[e]	mil BTU	269.8	629.8	629.8	629.8
Natural gas	mil BTU	13425.0	8007.0	6020.0	4003.0
Nitrogen[f]	mil BTU	137.8	137.8	137.8	137.8
Insecticide[g]	mil BTU	.7	.7	.7	.7
Herbicide[g]	mil BTU	3.3	3.3	3.3	3.3
Totals					
Decrease in energy	mil BTU	14824	9406	7419	5402
Decrease in energy	%		37	50	64

[a]Good water has a saturated thickness of 250 feet and alift of 250 feet.

[b]Same as center-pivot sprinkler except with the operating pressure reduced to 10 psi and with no water savings, 25 percent less water used, and 50 percent less water used.

[c]Million British thermal units.

[d]Energy conversion ratio is 120,000 BTU per gallon.

[e]Energy conversion ratio is 132,000 BTU per gallon.

[f]Energy conversion ratio is 6,300 kilocalorie (kcal) per pound, the equivalent of 1575 Btu per pound, based on anhydrous ammonia at 80 percent nitrogen (Pimental, et al. 1973).

[g]Energy conversion ratio is 11,000 kcal per pound of active ingredient, the equivalent of 2750 Btu per pound (Pimental, et al. 1973).

The analysis of the mobile trickle systems was expanded to include 1.69 million acres sprinkler irrigated on the Texas High Plains. It was estimated that the present value of returns to water for the 1.69 million acres could be increased $446 million, $711 million, and $995 million by mobile trickle systems with no water savings but reduced pressure (from 90 psi to 10 psi), 25 percent less water used, and 50 percent less water used, respectively.

Estimates were made of the total energy used by a center-pivot sprinkler system and by a mobile trickle system. According to these estimates, mobile trickle irrigation systems could potentially reduce total energy use on a 640 acre farm by 37, 50, and 64 percent when the level of water use was alternatively the same as with center-pivot sprinklers but only 10 psi of pressure, 25 percent less water used, and 50 percent less water used.

Potential gains that could be realized with furrow irrigation were estimated by reducing row length and applying irrigation water more uniformly, thereby requiring 25 percent less water than long-row furrow irrigation. Results of the analysis as shown in Table 8 indicate that in the short-run the use of shorter rows resulted in smaller net returns, but in the long-run, shorter rows and more carefully applied water resulted in more water being available in future years and increased present value of returns to water. The short-row furrow irrigation increased the present value of returns to water by $48,323 (15 percent) in Poor water and $32,545 (6 percent) in Good water (Table 8). Additionally, it was estimated that for the 4.7 million furrow irrigated acres of the Texas High Plains, the present value of returns to water would be increased nearly $250.4 million by adopting shorter row lengths.

Table 8. The Effects of Water-Use Efficiency under Furrow Irrigation for 640 Acres, a Typical Farm: Texas High Plains

Item	Unit	Water Resource Situations[a]			
		Poor		Good	
		Year 1	Year 8	Year 1	Year 25
Base					
Crops:					
Sorghum (dryl)	acres	--	64.9	--	67.7
Sorghum (irri)	acres	--	287.5	177.7	305.3
Soybeans (irri)	acres	640.0	287.5	463.0	267.1
Acres irrigated	acres	640.0	575.1	640.0	572.3
Lift	feet	83.89	136.62	258.46	430.88
Saturated thickness	feet	66.11	13.38	241.54	69.12
Water pumped	ac ft	1227	767	1168	792
Water decline	feet	8.89	5.56	8.46	5.74
Well yield	gpm	338	146	800	387
Returns	dol.	66780	45672	52609	30236
Returns to water	dol.	48910	27802	34739	12366
Present value of:					
Returns	dol.	NA	447000	NA	918412
Returns to water[b]	dol.	NA	313227	NA	548153
With 25 percent water savings[c]		Year 1	Year 10	Year 1	Year 10
Crops:					
Cotton (irri)	acres	--	357.1	--	511.4
Soybeans (irri)	acres	640.0	282.9	640.0	128.6
Acres irrigated	acres	640.0	640.0	640.0	640.0
Lift	feet	81.68	157.00	256.68	400.73
Saturated thickness	feet	68.32	12.30	243.32	99.26
Well yield	gpm	388	137	800	490
Water pumped	ac ft	922	685	922	666
Water decline	feet	6.68	4.90	6.68	4.83
Returns	dol.	60280	49616	50555	41757
Returns to water	dol.	42410	31816	32685	23887
Present value of:					
Returns	dol.	NA	526350	NA	950957
Returns to water[b]	dol.	NA	361550	NA	580698

[a]Poor water has a saturated thickness of 75 feet and a lift of 75 feet, and Good water has a saturated thickness of 250 feet and a lift of 250 feet.

[b]The present value of returns to water excludes the salvage value of water remaining at the end of 25 years.

[c]The basis of the analysis is that yields can be maintained with 25 percent less water applied due to shorter row lengths.

Credit Constraints

Credit constraints were evaluated to estimate their effect upon a typical farm on the Texas High Plains. With sprinkler irrigation, irrigation levels and annual returns began to decline when credit limits were reduced to $70,000 in Good water ($109 per acre) and $65,000 in Poor water ($102 per acre). With furrow irrigation, irrigation levels, irrigated acres and annual returns began to decline when credit limits were reduced to $75,000 (in both Poor and Good water). At the $60,000 level of borrowing, the marginal value of product (MVP) for credit was $1.29 with Poor water and sprinkler irrigation. This indicates that if available credit was reduced by $1.00, annual net returns would be reduced $1.29. With Good water and sprinkler irrigation, a $1.00 decrease in available credit would result in a $0.40 decrease in annual net returns.

The analysis also considered the cost of credit reserves (unused borrowing capacity) to the farmer. The costs of maintaining credit reserves showed to be much greater with sprinkler irrigation, i.e., credit reserves of $6,896 reduced net returns $4,057, while a credit reserve of $11,896 reduced net returns $10,881. Credit reserves can be of great value to the farmer in coping with the unexpected, but the costs of maintaining credit reserves should be recognized and considered as production plans are made.

Discount Rate

Each stream of annual net returns above variable and fixed costs was discounted first at a rate of 1.5 percent and alternatively at a rate of 6 percent. The increased discount rate reduced the present value of net returns over a range of 22 to 38 percent, the greatest reduction (38 percent) occurring with the combination of Good water, sprinkler irrigation and constant gas price. The least reduction in the present value of returns from using a 6 percent discount rate (as compared to 1.5 percent) was 22 percent and occurred in the situation of Poor water, furrow irrigation, and a natural gas price rising $0.10 per year.

The discount rate had no effect on cropping patterns or irrigation levels. This was because annual returns were maximized for each year individually, without consideration for the discount rate to be used.

Conclusions

The analysis indicated that, in the short-run, increased natural gas prices would impact most heavily upon annual net returns above variable costs. Changes in cropping patterns, irrigation levels, and natural gas usage would be expected if natural gas prices increased beyond $2.00 per mcf. The results indicate that in the short-run, with a natural gas price of $1.50 per mcf or higher, the reduced lift of a small groundwater supply outweighs the benefits of a large, deep groundwater supply.

Temporal analysis indicated that, in the long-run, rising natural gas prices, if unaccompanied by higher crop prices, can reduce annual returns by more than 30 percent and the present value of groundwater by as much as 80 percent. While the effect of rising natural gas prices upon land values was not directly evaluated, economic theory suggests that land values would be lowered and owner equity in farmland would erode. Further, the economic life of deep groundwater can be shortened because of higher gas prices, making less water economically recoverable. Rising natural gas prices have greater impact in a deep water situation due to the greater lift required to pump water to the surface.

With the problem of a declining groundwater supply and rising natural gas prices, producers must develop and adopt new technologies that will enable them to make more efficient use of remaining groundwater, extending the economic life of groundwater, and also to make more efficient use of natural gas so as to minimize irrigation pumping costs. Results of the analysis suggest that substantial economic gains are possible through improved pump efficiency and through irrigation systems which are more efficient in the distribution of water than systems currently in use. The results indicate that improved pump efficiency will not increase the economic life of the water supply, but will improve farm profits over time (increase the present value of net returns) and have a dramatic impact on energy used for irrigation.

Annual returns above variable and fixed costs were significantly increased by the improved distribution efficiency of a mobile trickle system. The present value of returns to water and the distribution system were of such magnitude that large costs could be justified to achieve the improved distribution efficiency of the mobile trickle system.

Similarly, it can be concluded that long-run gains could be realized by using shorter rows (in furrow irrigation) and applying irrigation more uniformly and with less waste. The gains that are thus achieved entail minimal costs and risk.

Thus, energy represents a threat to economic viability of an irrigated farm on the Texas High Plains. However, there are a variety of strategies that will reduce requirements for water and irrigation fuel.

The economic life of the groundwater on the Texas High Plains will be affected by several factors. These include the price of natural gas to the farmer, natural gas requirements, price of crops, and new irrigation techniques. With current irrigation technology, rising natural gas prices could lead to economic exhaustion of deep groundwater (where natural gas requirements are great) in 8 years (decreased from an economic life of over 25 years). The economic life of shallow groundwater would be less affected by rising natural gas prices. New irrigation technologies, if developed and adopted, would tend to offset increasing irrigation costs and extend the economic life of the groundwater.

Limitations in borrowing (whether imposed externally, as by a banker, or internally, as by the farmer himself) can substantially reduce annual net returns. The farmer can justify very high costs for borrowing rather than a reduction of funds available for operating expenses. Additionally, the maintenance of liquidity by means of unused borrowing capacity can be very costly.

Wind Assisted Pumping

One readily abundant renewable source of energy on the Texas High Plains is wind power. The High Plains has as much available wind power as any region in the country. Due to the importance of irrigation in the region, the concept of wind-assisted irrigation pumping could be an important alternative. Wind systems have been developed which are capable of providing supplemental energy to an existing electrical pumping plant. The electric motor is sized to operate the pump on a stand-alone basis. However, when the wind velocity is sufficient, the wind system operates and reduces the load on the electric motor. When pumping is not taking place, electricity can be generated and sold to the electric utility. The purpose of this study was to quantify, on both a static and temporal basis, the benefits of a wind energy system in an irrigation application on the Texas High Plains.

Methodology

The procedure for the static analysis involved determination of an optimal cropping pattern by a linear programming model developed for the Texas High Plains region. The optimal irrigation schedule was used as input to a simulation model. The simulation model matched stochastically generated wind power estimates to the irrigation schedule to estimate the annual value of wind energy.

The production activities in the LP model included dryland and irrigated options for cotton, grain sorghum and wheat along with irrigated corn. To give a broader representation of the choices available to an irrigated producer, activities were included assuming both optimal and non-optimal timing of irrigation applications. The yield reduction effects of non-optimal timing were estimated from experimental data for the region. In addition to the production activities, there were separate purchasing activities for selected inputs, selling activities for crops produced and a cash flow section divided into two-month periods.

Constraining resources included land, labor and irrigation water. Labor restrictions were divided into two-month periods. Irrigation water applications were divided into ten-day periods, with restrictions based on the physical maximum that could be pumped.

The simulation model generates random ("actual") wind speeds by three-hour time periods throughout a year. Random wind speeds are drawn from

Rayleigh distributions, the single parameter of which is mean wind velocity. Frequency distributions were set up by month and time of day (each three-hour interval for which wind speed is recorded), making eight distributions per month. Each three-hour estimate of wind power availability is matched with the amount of irrigation fuel required in that period, as determined by the LP model. Irrigation requirements in excess of wind power are purchased. Surplus generated electricity while pumping is assumed to have no value. If irrigation does not take place, 90 percent of excess wind power is sold to the electric utility for 60 percent of the purchase price. The annual value of wind power is calculated based on irrigation fuel saved and excess power sold. The simulation process is repeated 20 times for each situation analyzed to generate a range of solutions.

Mathematical expectations of available wind power based on single monthly average wind speeds were added to the LP model to test if cropping patterns would change when the availability of wind power was considered in the planning process. If this resulted in a change in cropping patterns, the simulation model was applied to the new irrigation schedule using the same set of random wind speeds.

For the temporal analysis, a Fortran subroutine was added to the LP model to operate the model recursively over the assumed twenty year life of a wind system. Annual farm plans are developed by the LP model. Based on the quantity of irrigation water applied in year t for the LP farm plan, the Fortran subroutine calculates the decline in saturated thickness of the aquifer and associated new well yield, pumping lift and irrigation fuel requirements for year t+1. The LP matrix is then updated with the new coefficients. This procedure continues over the twenty years of analysis.

The benchmark case involved application of the basic LP model. To estimate the value of wind power in the temporal framework, the monthly expectations of wind-generated electricity were added to the model. In both cases, fixed costs appropriate for a long-run analysis are deleted from returns.

The scenarios analyzed consisted of changes in four basic areas. The region was separated into the areas north and south of the Canadian River, with cotton included as a crop option only south of the river, due to the length of the growing season. Four farm situations were specified: (1) a saturated thickness of 100 feet, lift of 125 feet, 32.65 acres of cropland and a 40 KW wind machine; (2) a saturated thickness of 175 feet, lift of 175 feet, 100 acres of cropland and a 40 KW machine; (3) the same as situation 2 with the exception of a 60 KW machine; and (4) a saturated thickness of 225 feet, lift of 200 feet, 144 acres of cropland and a 60 KW wind machine. These are presented in Table 9.

Two sets of crop prices were used, one reflecting 1974-78 averages and the other based on simulated 1985 prices. For the static analysis, electricity purchase prices of \$.05, \$.075 and \$.10 per KWH were analyzed. In the temporal analysis, a constant purchase price of \$.05 per KWH was specified, plus a situation where the price increased by one-half cent per KWH per year.

Results

The randomly generated wind speeds and power output from the Southern High Plains benchmark simulations were aggregated to examine some predicted performance parameters. Average annual output was 67,679.4 KWH for a 40 KW

Table 9. Characteristics of the Farm Situation Scenarios

Farm Situation	Saturated Thickness (feet)	Well Yield (GPM)	Lift (feet)	Cropland (acres)	Power Required for Pumping (KW)	Rated Output of Wind System (KW)
1	100	181	125	32.65	10.4	40
2	175	555	175	100	42.7	40
3[a]	175	555	175	100	42.7	60
4[a]	225	800	200	144	69.3	60

[a]Only Farm Situations 3 and 4 were analyzed for the Northern High Plains.

system and 101,618.6 KWH for the 60 KW machine (Table 10). Over both machines, the average proportion of time producing rated (maximum) output was 4.92 percent, while the average time not operating due to low or high wind speed was 41.5 percent. Value of wind power was estimated assuming all power was sold to the utility. Breakeven investment (on a per KW basis) ranged from $358.42 at a ten percent discount rate and $.03 per KWH electricity to $1,184.43 with three percent discounting and $.06 per KWH electricity. These selling prices are 60 percent of the assumed purchase price of electricity at $.05 and $.10 per KWH, respectively (Table 10).

Static Analysis

Non-Optimal Irrigation Timing. The effect of the inclusion of non-optimal irrigation timings was examined for a specified situation on the Northern High Plains. The model was applied with only optimal irrigation timings included and with non-optimal irrigation timings included. Labor constraints were binding, as land was left idle in both cases, but 5.13 more acres were irrigated where non-optimal timing was allowed (Table 11). Irrigations were applied non-optimally on 28.9 percent of the irrigated acres. The inclusion of non-optimal timings allowed added flexibility in the usage of labor as well as irrigation water, and increased returns over variable costs to the 100 acre farm by $50.50. This was felt to more accurately reflect the situation faced by High Plains producers, thus, non-optimal timing of irrigation was permitted in further analyses.

Cropping Patterns. In the analysis of alternative scenarios for the benchmark solutions, cropping patterns were found to be insensitive to changes

Table 10. Annual Revenue and Breakeven Investment Where All Power Output is Sold to the Utility

Item	Selling Price of Electricity (cents per KWH) 3	4.5	6
	(dollars)		
40 KW Machine			
Annual Revenue:			
Maximum	2000.31	3000.46	4000.61
Minimum	1682.55	2523.83	3365.11
Mean	1827.35	2741.02	3654.69
Breakeven Investment:[a]			
3% Discount Rate	23665.52	35498.21	47330.90
5% Discount Rate	20249.29	30373.88	40498.48
10% Discount Rate	14336.69	21505.00	28673.30
60 KW Machine			
Annual Revenue:			
Maximum	2919.55	4379.32	5839.09
Minimum	2575.05	3862.58	5150.11
Mean	2743.70	4115.55	5487.40
Breakeven Investment:[a]			
3% Discount Rate	35532.92	53299.37	71065.83
5% Discount Rate	30403.58	45605.37	60807.16
10% Discount Rate	21526.02	32289.04	43052.05

[a]Breakeven investment is calculated based on mean annual revenue.

Table 11. Effect of the Inclusion of Non-Optimal Irrigation Timings on Estimated Farm Organization, Northern High Plains, Farm Situation 3[a]

Item	Post-Plants[b]	Rank[c]	Unit	Optimal Timing Only	Non-Optimal Timing Allowed
Crop Acreage:					
Crop					
Corn	5	1	acres	23.15	
Corn	5	2	acres		13.98
Grain Sorghum	1	1	acres	23.15	13.98
Grain Sorghum	2	2	acres		13.98
Grain Sorghum	3	1	acres	39.52	48.69
Wheat	3	1	acres	5.66	5.98
Total Planted Acres			acres	91.48	96.61
Irrigation Water:					
Water Pumped			acre feet	144.8	148.3
Number of Limiting Seasonal Water Periods			number	3	3
Range of Shadow Prices			dollars	11.51-30.77	7.79-26.45
Net Returns[d]			dollars	5797.63	5848.13

[a]This analysis is based on 1974-78 average crop prices and electricity at $.05 per KWH. Wind expectations are not included. Farm situation 3 has a saturated thickness of 175 feet, lift of 175 feet and 100 acres of cropland.

[b]Refers to the number of post-plant irrigations applied.

[c]Refers to the relative yield ranking among all activities of a given crop with a given number of post-plant irrigations.

[d]Returns are net of variable costs only.

in crop prices or electricity prices in the southern region. All acres were planted to irrigated cotton over all farm situations. The specific cropping pattern was identical (in proportion to total acreage) in all cases except in a farm situation with over 200 feet of saturated thickness with electricity at $.10 per KWH and 1974-78 average crop prices, where 37.33 percent of the acreage shifted from one post-plant irrigation to a pre-plant only.

On the Northern High Plains, cropping patterns were insensitive to electricity price changes under 1985 simulated crop prices. Irrigated grain sorghum dominated these solutions, with a small amount of irrigated corn. With 1974-78 average crop prices, land was left idle with electricity at $.05 per KWH. At higher electricity prices, irrigated acreage declined, but sufficient labor was released to allow dryland wheat to use all remaining acreage. Again, irrigated grain sorghum and corn dominated the solution, with a small amount of irrigated wheat in the farm plan except where electricity costs $.10 per KWH. Labor restrictions impacted heavily in this region, actually causing the shadow price of cropland to increase with higher electricity prices.

Returns to Wind Energy. The set of crop prices applied had very little effect on returns to wind. In the northern region, the annual value of a wind system was higher for the average 1974-78 crop prices with electricity at $.05 per KWH. At higher electricity prices, value of wind was higher for 1985 simulated crop prices. No such pattern existed in the south. Any differences in annual returns to wind with respect to crop prices were negligible, less than $100 in most cases.

As expected, returns to wind were higher at higher electricity prices, but by slightly smaller proportions than the increases in electricity price. The addition of a wind system significantly abates the adverse effects of increasing electricity prices. In farm situations where a given wind system is operated on the smaller of the two applicable land units, total returns (returns to wind plus benchmark returns) actually increased with increases in electricity price. On the larger land units, returns did decrease as electricity price was increased, but by a much smaller percentage, where wind power was available, than the decrease in benchmark returns.

Estimated breakeven investment was higher for the Southern High PLains, where cotton was available as a crop option. With electricity at $.05 per KWH, 1985 simulated crop prices and returns discounted at three percent, breakeven investment for the 60 KW machine ranged up to $42,409.88 ($706.83 per KW) in the south compared with $41,707.43 ($695.12 per KW) in the north. The 40 KW machine was analyzed only in the southern region. At the same prices and discount rate cited above, maximum breakeven investment for the 40 KW system was $28,252.40 ($706.31 per KW).

On the 100 acre land unit, where both machines were analyzed in the south, the 40 KW machine (farm situation 2) was found to be the better investment on a per KW basis (Table 12). Each machine had higher value on the larger of the two land units tested, farm situation 2 for the 40 KW machine and situation 4 for the 60 KW system. Table 13 provides estimates of electricity sold and used on the alternative farm situations as well as percent of pumping energy requirements met and percent of generated electricity used for pumping.

Table 12. Comparison of the Value of 40 Kilowatt and 60 Kilowatt Wind Energy Systems on a 100 Acre Farm Unit, Southern High Plains

Item	Purchase Price of Electricity (cents per KWH) 5	7.5	10
	--------(dollars)----------		
1974-78 Average Crop Prices			
Breakeven Investment:[a]			
40 KW Wind System (Farm Situation 2)	609.88	907.56	1215.46
60 KW Wind System (Farm Situation 3)	590.75	888.23	1170.81
1985 Simulated Crop Prices			
Breakeven Investment:[a]			
40 KW Wind System (Farm Situation 2)	604.35	911.87	1224.12
60 KW Wind System (Farm Situation 3)	593.35	887.25	1184.89

[a]Breakeven investment, discounted at 5 percent, is expressed on a per kilowatt of capacity basis.

Table 13. Simulation Results of Electricity Sold and Used for Irrigation

Item	Wind Generated Electricity			
	Sold (KWH)	Used for Irrigation (KWH)	% of Total Requirements[a] (percent)	% of Total Generated[b] (percent)
Northern High Plains				
Farm Situation 3[c]	76994.7	13937.4	23.98	13.80
Farm Situation 4[c]	77339.7	14970.6	16.40	14.84
Southern High Plains				
Farm Situation 1[c]	52095.5	4823.5	42.05	7.16
Farm Situation 2[c]	52518.1	9601.0	20.43	14.13
Farm Situation 3[c]	78444.7	12952.0	27.56	12.73
Farm Situation 4[c]	78677.3	14057.0	18.79	13.86

[a]Represents the average percentage of total irrigation requirements fulfilled by wind power.

[b]Represents the average percentage of wind generated electricity used for irrigaton.

[c]Refer to Table 9 for a description of the farm situations.

Effect of Load Management. The inclusion of wind power expectations in the planning process had little effect on irrigation scheduling, with cropping pattern changes occurring in only four of the 36 situations analyzed. In two of these cases, irrigations were shifted to higher wind speed periods, but this resulted in only a small increase in returns to wind. More significant increases occurred where wind power eased the impact of increasing electricity price, allowing the farm to maintain the irrigation levels estimated without wind power, but which had been decreased due to the price increase.

Temporal Analysis

Only farm situations 2 and 4 were analyzed temporally, as the static analysis results showed each to be the more efficient application of the given size of machine. To reflect the future situation, 1985 simulated crop prices were used.

Cropping Patterns. Wind power had no effect on the optimal farm plan when the price of electricity was held constant through time. Cotton again dominated southern solutions, with a small amount of irrigated grain sorghum planted on the 100 acre unit in the last two years of the analysis. Initial acreage on the Northern High Plains was planted almost entirely to irrigated grain sorghum, with acreage of irrigated wheat and corn increasing through time.

On the Southern High Plains, with electricity price increasing through time, the optimal farm plan remained the same as with constant price for farm situation 4, and changed only minutely in situation 2. In the north, wind power had a significant effect on cropping patterns through time. Acreage reverted to dryland with and without wind power; however, more irrigated acreage was maintained when wind power was available.

Returns to Wind Energy. In contrast to the static results, the estimated breakeven investment was higher on the Northern High Plains where electricity price was held constant, with values on the 60 KW power system as high as $41,772.44 with the three percent discount rate (compared to $41,290.73 in the south). These results are presented in Table 14. This is due largely to the more adverse effect of the declining water level in the north. For the 40 KW machine (analyzed only on the Southern High Plains), breakeven investment on a per KW basis was higher than for the 60 KW machine in either region.

When electricity price increased annually, breakeven investment showed significant increases, as was expected. The increases were as much as 80 percent on the Southern High Plains and up to 75 percent in the north (Table 15). For the 60 KW system, the results were again reversed, with higher investment values in the south. Even with wind power, the increasing electricity price forced land out of irrigation in the north, thus reducing the potential for electricity substitution.

Conclusions and Limitations

With the wind energy industry still in largely a developmental stage, estimates of the initial cost of a wind system can vary considerably. This makes it difficult to draw firm conclusions on the profitability of investment, at least in the short term. As more firms begin mass production of wind systems, prices should decrease and stabilize. Available estimates

Table 14. Temporal Analysis[a] of Breakeven Investment in a Wind Energy System: Constant Electricity Price[b]

Item	Present Value of Returns[c]		Breakeven
	With Wind Power	Without Wind Power	Investment
	(dollars)		
Southern High Plains			
Farm Situation 2[d]:			
3% Discount Rate	344184.81	311975.13	28038.29
5% Discount Rate	289852.75	262933.88	23935.93
10% Discount Rate	200385.06	182089.38	16860.27
Farm Situation 4[d]:			
3% Discount Rate	518283.16	470849.41	41290.73
5% Discount Rate	435580.89	395902.89	35281.19
10% Discount Rate	299706.64	272681.58	24904.78
Northern High Plains			
Farm Situation 4[d]:			
3% Discount Rate	151193.91	103206.79	41772.44
5% Discount Rate	128843.83	88796.64	35609.47
10% Discount Rate	91307.52	64168.39	25009.90

[a] 1985 simulated crop prices are used in all temporal analyses.

[b] Constant electricity price of $.05 per KWH.

[c] Returns are net of variable and fixed costs.

[d] Refer to Table 9 for a description of the farm situations.

Table 15. Temporal Analysis[a] of Breakeven Investment in a Wind Energy System: Increasing Electricity Price[b]

Item	Present Value of Returns[c]		Breakeven
	With Wind Power	Without Wind Power	Investment
	(dollars)		
Southern High Plains			
Farm Situation 2[d]:			
3% Discount Rate	336740.81	278641.25	50575.24
5% Discount Rate	284051.94	237045.88	41797.21
10% Discount Rate	197093.56	167530.75	27243.43
Farm Situation 4[d]:			
3% Discount Rate	499116.91	413561.16	74475.66
5% Discount Rate	420740.14	351483.83	61581.86
10% Discount Rate	291435.27	247815.39	40197.63
Northern High Plains			
Farm Situation 4[d]:			
3% Discount Rate	124383.85	40638.60	72899.63
5% Discount Rate	107739.45	39849.64	60367.14
10% Discount Rate	79076.71	36180.96	39530.31

[a] 1985 simulated crop prices are used in all temporal analyses.

[b] Initial electricity price of $.05 per KWH and increasing by $.005 annually.

[c] Returns are net of variable and fixed costs.

[d] Refer to Table 9 for a description of the farm situations.

of the industry's mature cost range around $500 per KW. Estimated breakeven investment rates for wind-assisted irrigation were greater than $500 per KW in all cases except where electricity was purchased for $.05 per KWH and returns discounted at ten percent. Table 16 presents a summary of the estimated value of wind energy machines under alternative scenarios. The possibility of tax credits for the purchase of a wind system was not explicitly considered. However, for the farm business in a position to take full advantage of the credits, the effective breakeven investment rate could be enhanced by as much as one-third.

This study uses the typical farm approach, thus, the results will likely not apply directly to any specific farm due to the "average" nature of the data. This should be noted particularly in view of the Northern High Plains results, where the assumed labor restrictions had a large effect on the optimal farm plan chosen. A producer able to hire additional summer labor could have a significantly different result. In addition, the producer was assumed to be a strict profit maximizer. Personal preferences or consideration of risk could cause changes in an individual's cropping pattern.

The consideration of non-optimal irrigation timing gives the model additional flexibility that more accurately represents the decision making process of the irrigated producer. However, the yield reductions estimated for this study were based on limited data. Further research is needed regarding the effects of irrigation timing.

The monthly wind power expectations used in the LP model were, in total, slightly less than the averages of output from the simulation model. Thus, the temporal results should be regarded as conservative. These same

Table 16. Comparison of Breakeven Investment Values[a] Derived from Static and Temporal Analysis

Item	Sell-Only Analysis[b]	Static Analysis[c]	Temporal Analysis[d]
	(dollars per KWH)		
Southern High Plains			
40 KW Machine (Farm Situation 2)	591.64	706.31	700.96
60 KW Machine (Farm Situation 4)	592.22[e]	706.83	688.18
Northern High Plains			
60 KW Machine (Farm Situation 4)	592.22[e]	695.12	696.21

[a]All values were discounted at three percent and expressed in dollars per KWH.

[b]Electricity sold at $.03 per KWH.

[c]Electricity purchased at $.05 per KWH and 1985 simulated crop prices.

[d]Electricity purchase price constant at $.05 per KWH and 1985 simulated crop prices.

[e]No distinction was made between regions for the sell-only option.

expectations, as a factor in the planning process, were estimated to have little effect on cropping patterns, contrary to what was expected. The use of wind speed distributions based on averages for each ten-day period could improve the model; however, these data would be difficult to obtain.

The price at which the utility will buy back surplus electricity was assumed to be a constant percentage of the purchase price. In actual practice, this price may vary greatly. Peak load pricing structures, where the price of electricity varies according to the time of use, were not considered. This type of pricing might apply not only to electricity purchases but also to sales, where the utility might pay a premium price for electricity generated at times of peak demand.

The study assumed that normal wind system down time (when the machine does not operate due to insufficient wind speed) could be used for all necessary repairs and maintenance. Major breakdowns could render the system inoperative for longer periods of time; however, data regarding the frequency or duration of such breakdowns were unavailable. The cost of normal repairs and maintenance has not been established on a long-term basis. Available estimates varied considerably and were all based on a percentage of the initial investment rather than on operating time or other performance parameters. This type of data should become more readily available as the industry matures.

Breakeven investment was estimated over a period of 20 years assuming constant levels of technology, crop prices and input costs (except where specified differently). The future values are, of course, unknown. Significant changes in any of these factors could have a great impact on the value of wind energy.

References

Black, A. L. "Water Situation for Agriculture -- The High Plains Ogallala Study." Presented at Crop Production and Utilization Symposium, Texas A&M Research and Extension Center, Amarillo, Texas, February 22, 1979.

Buzenberg, R. J., M. L. David, J. P. Wagner, E. F. Glynn, G. L. Johnson and J. K. Shultis. "Market Potential for Wind Energy Applications in Agriculture." Wind Energy Applications in Agriculture, ed. H. H. Kluter and L. H. Soderholm, U.S. Department of Agriculture, NTI-Conf-7905/109, pp. 22-41, May 1979.

Clark, R. N. and A. D. Schneider. "Irrigation Pumping with Wind Energy." Transactions of the ASAE 23(1980):850-853.

Coble, C. G. and W. A. LePori. "Summary Report on Energy Consumption, Conservation, and Projected Needs for Texas Agriculture." Texas A&M University, Department of Agricultural Engineering, Report S/D-12, Special Project B, December 1974.

Condra, G. D., K. E. Lindsey, C. W. Neeb, and G. L. Philley. "ECONOCOT - A Ray of Hope forthe Pecos Valley." Texas Agricultural Extension Service, TAP-825, 1978.

Elliott, Dennis L. "Synthesis of National Wind Energy Assessments." Battelle Pacific Northwest Laboratories, Richland, Washington, BNWL-2220 WIND-5, July 1977.

Godfrey, Curtis L., Clarence R. Carter and Gordon S. McKee. "Land Resource Areas of Texas." Texas Agricultural Extension Service, B-1070.

Hardin, Daniel C. and Ronald D. Lacewell. "Break-Even Investment in a Wind Energy Conversion System for an Irrigated Farm on the Texas High Plains." Texas Water Resources Institute, TR-116, October 1981.

Hardin, Daniel C. and Ronald D. Lacewell. "Implications of Improved Irrigation Pumping Efficiency for Farmer Profit and Energy Use." Southern Journal of Agricultural Economics 11(1979):89-94.

Hardin, Daniel C., Ronald D. Lacewell and James A. Petty. "The Value of Improved Irrigation Distribution Efficiency with a Declining Groundwater Supply." Texas Agricultural Experiment Station, TA-14294, May 1978.

Hiler, Edward A. "Cricial Issues in the 80's: Alcohol Fuel." In Texas Agriculture in the 80's: The Critical Decade, Texas Agricultural Experiment Station, B-1341, December 1980.

Hughes, William F. and Wyatte L. Harman. "Projected Economic Life of Water Resources, Subdivision Number 1 High Plains Underground Water Reservoir." Texas Agricultural Experiment Station, Technical Monograph 6, December 1969.

Katzman, Martin T. and Ronald W. Matlin. "The Economics of Adopting Solar Energy Systems for Crop Irrigation." American Journal of Agricultural Economics 60(1978):648-54.

Knutson, R. D., R. D. Lacewell, W. A. LePori, D. C. Hardin, E. A. Hiler and C. W. Keese. "Analysis of the National Energy Plan: The Effects on Texas Agriculture." Texas Agricultural Experiment Station, MP-1331, June 1977.

LePori, W. A. and Ronald D. Lacewell. "Energy Potential and Economic Feasibility in Using Agricultural Residues and Crops for Fuels in Texas." Center for Energy and Mineral Resources, Progress Report, Texas A&M University, 1976.

Lyle, William M. "New Irrigation System Design for Maximizing Irrigation Efficiency and Increasing Rainfall Utilization." Texas Water Resources Institute, TR-105, May 1980.

New, Leon. 1977 High Plains Irrigation Survey. Texas Agricultural Extension Service, 1977.

Petty, James A., Ronald D. Lacewell, Daniel C. Hardin and Robert E. Whitson. "Impact of Alternative Energy Prices, Tenure Arrangements and Irrigation Technologies on a Typical Texas High Plains Farm." Texas Water Resources Institute, TR-106, May 1980.

Pimental, D., L. D. Hurd, A. C. Bellotti, M. J. Forester, I. M. Oka, O. D. Sholes and R. J. Whitman. "Food Production and the Energy Crists." Sciences 182(1973):443-449.

Reddell, Donald L. Department of Agricultural Engineering, Texas A&M University. Personal Communication, April 25, 1978.

Skold, Melvin D. "Farmer Adjustments to Higher Energy Prices: The Case of Pump Irrigators." Natural Resource Economics Division, Economic Research Service, U.S. Department of Agriculture, ERS-663, November 1977.

Sprott, J. Michael, R. D. Lacewell, G. A. Niles, J. K. Walker and J. R. Gannaway. "Agronomic, Economic, Energy and Environmental Implications of Short-Season, Narrow-Row Cotton Production." Texas Agricultural Experiment Station, MP-1250, February 1976.

Texas Crop and Livestock Reporting Service. Texas County Statistics. U.S. Department of Agriculture, Austin, 1979.

Texas Department of Water Resources. "Fact Sheet on the Economy of the Texas High Plains." Planning and Development Division, pamphlet, May 1981.

Texas Water Development Board. Continuing Water Resources and Development for Texas. Planning Series Report P34, May 1977.

Wyatt, A. Wayne, Ann E. Bell and Shelly Morrison. "Analytical Study of the Ogallala Aquifer in Deaf Smith County, Texas." Texas Department of Water Resources, Report 213, July 1977.