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Donald Taylor
South Dakota State University

Todd A. Lone

Ardelle A. Lundeen
South Dakota State University

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MIXED INTEGER LINEAR PROGRAMMING MODEL
ELECTRIC RATE STRUCTURE-IRRIGATION STUDY
CLAY-UNION, UNION, CHERRY-TODD, AND CAM-WAL RECs

by

Todd A. Lone, Donald C. Taylor, and Ardelle A. Lundeen*

Research Report 86-2

October 1986

*The senior author, formerly a Research Associate in Economics at SDSU, is currently a Graduate Assistant at Washington State University at Pullman. The second and third authors are Professors of Economics at SDSU.

ACKNOWLEDGEMENT

The authors acknowledge with thanks (1) the most competent and valuable technical assistance from Wayne Ellingson in developing the model and (2) the constructive comments on earlier drafts of the manuscript by Herbert Allen, Wayne Ellingson, and Brian Schmiesing. Responsibility for any remaining errors and shortcomings in communication, of course, rests with the authors.

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This is the second in a series of five Economics Department reports on a research project, "The Economic Impact of Alternative Electric Rate Structures on Energy and Water Use", sponsored by the South Dakota Agricultural Experiment Station. Supplemental funding for the research was provided by the Western Area Power Administration (WAPA), Golden, Colorado.

The purpose of this report is to acquaint the reader with the overall model used in the study and the specific way that the electric rate structures were modeled. This model builds on, but goes beyond, the one developed and used by Robert A. Young and associates[1] in their study of electric rate structures for irrigation in Colorado. The primary way in which this model extends beyond Young's model is that it permits simultaneous (rather than one-at-a-time) attention to all three basic features of electric rate structures for irrigation, namely, annual minimum charges, monthly demand charges, and block rate energy charges. The primary intended audiences for the report are graduate students and research-peers with an interest in analyzing electric rate structures for irrigation.

The other reports in this research report series are as follows:

- No. 1, Enterprise Budgets and Other Data-Sets; Electric Rate Structure-Irrigation Study; Clay-Union, Union, Cherry-Todd, and Cam-Wal RECs;

- No. 3, The Impacts of Alternative Electric Rate Structures for Irrigation, Clay-Union and Union RECs;

- No. 4, The Impacts of Alternative Electric Rate Structures for Irrigation, Cherry-Todd REC; and

- No. 5, The Impacts of Alternative Electric Rate Structures for Irrigation, Cam-Wal REC.

The reports are intended to stand more or less on their own. Readers with a serious interest in Report 2, however, will find it helpful to use Report 2 in conjunction with Report 1. Twenty-six tables are included in the first report. When reference is made in the second report to tables in the

[1] See Energy and Water Scarcity and the Irrigated Agricultural Economy of the Colorado High Plains, Tech. Rep. No. 34, Feb. 1982 and Effects of Alternative Electric Rates and Rate Structures on Electricity and Water Use on the Colorado High Plains, Compl. Rep. No. 134, Oct. 1984; both published by the Colorado Water Resources Research Institute, Colorado State University, Fort Collins.

first report, the nomenclature "Report 1-Table X" is used.[2]

BACKGROUND FOR THE RESEARCH

About 80% of South Dakota's irrigation pumps are energized by electricity. The high cost and under-utilization of recently developed (coal-based) electric power generation facilities have resulted in increased wholesale costs of electric power and, in turn, in higher electric rates for irrigators and other electric power consumers. Operating within an already financially-stressed agriculture, rural electric cooperatives (RECs) that supply electricity to irrigators are exploring possible revisions to rate structures offering prospect of more fully meeting the joint needs of themselves and their irrigator clients.

The objective of the research for which the model described in this report was developed is to estimate the impacts of alternative electric rates and rate structures on (1) the future potential demands for irrigation water and power to energize irrigation pumps, (2) the efficiency of water and energy use in irrigation, and (3) expected levels of (a) farm income earned by irrigators and (b) electric power revenues received by RECs. Attention is focused on both average income/revenue levels and the estimated range in year-to-year income/revenue associated with unusually heavy and light precipitation. Of particular interest in the WAPA component of the study is an examination of electric rate structures that provide incentives for energy conservation.

Several options are open to irrigators in responding to different electric rates and rate structures. Those examined in this study include the use or non-use of two already-present electric power, high pressure center pivots; the conversion of existing center pivots to low pressure and/or diesel power; the purchase of new irrigation systems; water distribution by center pivot sprinklers versus by gated pipe gravity flows; full versus partial crop irrigation; selecting crops with a greater or lesser irrigation water requirement than corn which is generally the most common irrigated crop; and the renting of additional irrigated land.

The research is being implemented in the service areas of each of four case study South Dakota RECs:

- Clay-Union, Vermillion, serving irrigators in Clay and Union counties;

- Union, Elk Point, serving irrigators in Union County;

- Cherry-Todd, Mission, serving irrigators in Todd County (and Cherry County, Nebraska); and

- Cam-Wal, Selby, serving irrigators in Campbell, Walworth, and Potter counties.

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[2] Readers with serious interest in the reports of empirical findings from the study (Reports 3-5) will also undoubtedly find it helpful to consult Reports 1 and 2 for detailed information on the data-sets and modeling, respectively, used in the study.

The discussion in this report applies generally to all four RECs. When illustrations are provided, they pertain to the Union REC.

REPRESENTATIVE FARM MODELS

To accomplish the purpose of the research, a hypothetical farm was identified to represent "typical" irrigator clients served by each REC. A linear programming model was developed to portray as fully as possible the technical, institutional, and economic features associated with each representative farm.

This section consists of two parts: an overall perspective on the circumstances intended to be portrayed in the representative farm models and an overview of the mixed integer linear programming model developed and used in the study.

Perspective surrounding the models

The representative farm models developed in the study are intended to reflect conditions on typical irrigated farms with above-average management in the respective REC service areas in 1985. Irrigator farm managers are presupposed to be in a position to make short-term farm enterprise and irrigation technology adjustments in response to changes in electric rates and rate structures for irrigation announced by their REC electric power suppliers. While the models involve only a single production period, a medium-term (three to five years) decision-making planning horizon is envisioned for the managers of the representative farms. It is thereby presumed that the representative farm managers would reconsider the types of options included in the model once every three to five years, not once every year.

The representative farms are assumed to already be in operation--with specified acreages of land, operator labor, year-round hired labor (only for the Cherry-Todd and Cam-Wal representative farms), and generally adequate machinery and equipment, farm buildings, and breeding herds (where applicable) to make economic use of the land.[3] The available machinery and equipment includes two electric power, high pressure center pivot systems. Because the costs of owning the already-present land, machinery and equipment, and livestock-related resources are "fixed" (i.e., they are the same for all different solutions for each representative farm), these costs are not included in the model. The annualized costs for owning newly purchased irrigation equipment, however, are included in the model. These costs, like those for single-period production inputs, are "variable" to the representative farms. If the irrigation equipment is not purchased, all expenses associated with the equipment could be avoided.

The model for each representative farm is used as follows. Most profitable plans for representative farms with 1985 irrigation electric rate structures are first determined. Most profitable farm organizational adjustments to a series of electric rates and rate structures differing from those used in 1985 are then determined. The implications of the farm organizational adjustments to the levels and efficiency of energy and

[3]As explained in the first report, however, storage facilities for grain and alfalfa are an exception to this general statement.

irrigation water use, farmer profits, and REC revenues are computed. These findings for the individual case study RECs are presented in Study Reports 3-5.

An overview of MILP and its application in the study

Linear programming is an optimization technique for evaluating and selecting the combination of available options to a business-making entity, such as a farm or ranch, which will maximize profits (minimize costs) subject to certain constraints. "Mixed integer linear programming" (MILP) is used to characterize circumstances in which some, but not all, of the input variables are integer in nature. An illustrative non-integer variable is part-time hourly labor that can be hired for any length of time, including partial hours. An illustrative integer variable is a monthly demand electricity charge that is either zero (if an irrigation system is not used during a particular month) or fixed in amount no matter whether the system is used for "one minute" or up to 31 days in a month.

The matrix algebra formulation of the maximization MILP used in this study is as follows. The objective function for each representative irrigated farm, $\underline{P} = \underline{C}' \underline{X}$, is maximized, subject to $\underline{A}\ \underline{X} \leq \underline{B}$, where

- $\underline{P}$ is the surplus of gross revenue over the variable costs of farm, production, or "gross profits" for a representative farm;

- $\underline{C}$ is a scaler matrix (involving a single equation with multiple independent variables) of profit coefficients reflecting the difference between the gross revenue and variable costs for single-period production inputs and annualized costs for newly purchased irrigation equipment for each structural variable;

- $\underline{X}$ is a "full" matrix of structural variables, reflecting the electric rate structure, irrigation alternative, dryland crop production, crop disposition, and resource rental and hiring activities;

- $\underline{A}$ is a "full" matrix of farm production and irrigation input coefficients which consists of variables like "out-of-pocket" costs for producing an acre of corn and the inches of irrigation water required by a crop like alfalfa; and

- $\underline{B}$ is a vector (single column) matrix of right-hand-side constants, reflecting maximum amounts of available land and labor and zeros (as maximum or equality constraints) for all other equations.

One of the most distinctive analytic features of the MILP model used in this study concerns the structural variables constrained to integer values. A brief description of the three categories of integerized structural variables follows.

Three of the four electric rate structure variables are specified in integer form. Each pertains to an irrigation system (130 acre center pivot systems, 160 acre gated pipe systems), not to an irrigated acre or part thereof. An annual minimum charge must be paid regardless of whether an irrigation system is used during an irrigation season.[4] Monthly demand charges--as noted above--are either zero in value or are activated in predetermined amounts during any month in which irrigation water is pumped. The third integerized rate structure variable involves bounded steps in an energy charge block rate structure. Assume, for example, a two-step block rate in which the charge for the first 10,000 kilowatt hours (kWh) is $0.04 per kWh and the charge for all succeeding energy is $0.03 per kWh. In this case, the first step is bounded. An integer variable reflecting the cost of 10,000 kWh at $0.04 per kWh is used to reflect this first-step bounded energy cost component.

A second category of integerized structural variables involves (1) the conversion of already-present electric power, high pressure center pivots to low pressure and/or diesel power and (2) the purchase of new irrigation systems. Again, the unit of analysis is a whole rather than a partial system, and thus these variables are specified in integer form.

The third category of integerized structural variables involves the irrigated crop production activities. Since most farmers irrigate only one crop per irrigation system, the unit specified for the irrigated crop production activities is either 130 acres for center pivot systems or 160 acres for gated pipe systems.

None of the variables other than those in these three categories was constrained to being integer in value.

The SAS/OR-MILP programming package (SAS/OR User's Guide, Version 5 Edition, Cary, N.C.: SAS Institute, 1985) and the South Dakota State University mainframe computer were used in the research analysis.

GENERAL FEATURES OF THE MODEL

The overall features of the model are described in this section. The description is initially in terms of a generalized tableau portraying the Union REC representative farm model. This description is followed by a more detailed discussion of the nature and content of the farm's "gross profit" function, the resources available to the farm and constraints on their use, the overall modeling of the various irrigation alternatives considered, and selected other items.

The generalized model tableau for the Union REC representative farm portrayed in Figure 1 consists of six column-groupings and five row-groupings. The first of the column-groupings reflects the four-part electric rate structure noted above. The second column-grouping consists of four categories of irrigation alternative variables, namely, those involving various irrigation system power conversions, irrigation system purchases, diesel power controls and costing, and the various irrigated crop production options. The third column-grouping is comprised of dryland crop production

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[4]This statement describes "annual minimum charges" as they are interpreted and now used by three of the four case study RECs. Such charges are "fixed" to an irrigator. In some alternative rate structures considered, however, annual minimum charges were not treated as "fixed". For this reason, annual minimum charges were incorporated into the model developed for the study.

options. The fourth reflects crop disposition (via livestock feeding and cash sale), the fifth land rental and part-time labor hiring, and the sixth the maximum permitted land acreages and labor availabilities.

The first of the five row-groupings--the gross profit objective function--reflects the surplus of gross revenues over variable production costs for each production and input purchase activity. The second row-grouping is comprised of the four electric rate structure components. The third row-grouping enables appropriate controls to be exercised over the land, water, and diesel fuel variables. The fourth row-grouping exercises control over labor and the fifth enables transfers of crops from production activities to livestock consumption and cash sale activities.

Each of the six-by-five aggregate cells in Figure 1 which contains non-zero values is assigned a letter designation (A,B,...,U). The subcells within these aggregate non-zero cells, which themselves contain non-zero values, are designated with numerical subscripts [e.g., the A cell consists of four subcells ($A_1,\ldots,A_4$) with non-zero values].

In the following discussion, reference is made to (1) the subcells within the generalized model tableau (Figure 1) into which data were incorporated and (2) the sources from which the data were obtained, namely, the applicable tables in Report 1.

Gross profit function

As indicated above, the optimization of the model involves determining the highest gross profit combination of available options for each representative farm. The components of the gross profit function are as follows:[5]

- Subcells A_1 - A_4: the electric rate charges, as shown in Report 1-Table 20;

- Subcell B_1: the annualized costs of converting existing center pivot systems to low pressure and/or diesel power, as shown in the lower panel of Report 1-Table 19;

- Subcell B_2: the annualized costs of newly purchased irrigation systems, as shown in the lower panels of Report 1-Tables 15-17 and in a footnote to Report 1-Table 18;

- Subcell B_3: the 1985 price of diesel fuel, namely, $1.0227 per gallon;

- Subcell B_4: the sum of (1) the variable crop production costs, per quarter-section (130 acres for center pivots and 160 acres for gated pipe systems) for the irrigated crops, as shown in Budget Tables 2, 4, 6, and 8 and (2) irrigation system repair and maintenance costs, as shown in the lower panel of Report 1-Table 10;

[5] A 5% interest charge is added to the power costs and crop and livestock production variable costs included in the profit function -- to reflect an assumed "average" time cost of money between when operating expenditures are made and when harvests are completed.

- Subcells $\underline{C}_1$ and $\underline{C}_2$: the dryland variable crop production costs per acre, as shown in Report 1-Tables 2-9;

- Subcell $\underline{D}_1$: the gross profit for each livestock production unit, as shown in Report 1-Tables 21-24;

- Subcell $\underline{D}_2$: the per-unit selling prices for the various crops sold, as shown in Report 1-Table 1;

- Subcell $\underline{E}_1$: the per-acre rental rates for irrigated and dryland cropland, as shown in the second panel of Report 1-Table 25; and

- Subcell $\underline{E}_2$: the wage rate for part-time hired labor, namely, $4.50 per hour.

The "gross profit" determined in the model represents the return to (1) the irrigator's land; farm machinery and equipment, including two center pivot systems; farm buildings; and breeding herds; (2) the labor provided by the owner-operator and year-round hired labor; and (3) the management of the farm provided by the irrigator.

Farm resource availabilities and constraints

As indicated above, the representative farms modeled in this study are assumed to already be in operation, with certain already-present assets. The already-present assets explicitly considered in the model are:

- Subcell $\underline{M}_1$: irrigated cropland, dryland cropland, and pasture (rangeland), with the acreages shown in the top panel of Report 1-Table 25;

- Subcell $\underline{M}_1$: two electric power, high pressure center pivot systems, entered as integer values; and

- Subcell $\underline{R}_1$: year-round hours of labor available to the farm, as indicated in the third panel of Report 1-Table 25.

Other assets assumed to be present on the representative farms--but which are not explicitly considered in the model--are farm machinery and equipment, livestock building facilities, and breeding herds (as applicable).[6]

[6] To have modeled individual pieces of farm machinery and equipment would have added greatly to the size of the matrix and the complexity of the analysis. The implicit assumption is that the existing complement of machinery and equipment is adequate to farm the presently available land and up to one rented quarter-section of each of dryland and irrigated land.

Livestock are expected to represent a vehicle, in most runs of the models, for realizing greater returns from home-produced feed than if the feed were to be sold directly for cash. Maximum herd sizes -- based on most commonly found livestock enterprises in the respective study areas -- were placed on the livestock production activities. Because of this and the fact that livestock production is rather incidental to the main purpose of the research, the resources required for financing livestock building facilities and breeding herds were treated as "fixed" in the model.

Upper bounds on possible acres of additional rented land, as shown in the second panel of Report 1-Table 25, are entered into Subcell $\underline{M}_1$. The upper bounds on part-time hired labor shown in the bottom panel of Report 1-Table 25 are entered into Subcell $\underline{R}_2$. Upper bounds on the maximum monthly well-pumping capacities (1,176 acre-inches per month in Cam-Wal; 1,248 acre-inches for the other RECs) were entered for the electric powered systems into Subcell $\underline{H}_1$ [7] and for the diesel powered systems into Subcell $\underline{M}_2$.

Consistent with commonly experienced alfalfa and soybean acreages and livestock numbers in the respective study areas, upper bounds (not portrayed in Figure 1) were placed on crop and livestock enterprises as follows:

Clay-Union REC: (1) one center pivot in alfalfa production; (2) 165 and 44 acres, respectively, of soybeans and alfalfa on dryland; (3) 100 and 26 acres, respectively, of dryland soybeans and dryland alfalfa on the presently irrigated 260 acres that could become unprofitable to irrigate; and (4) 40 sows for the hog farrowing-finishing activity;

Union REC: (1) 150 and 18 acres, respectively, of soybeans and alfalfa on dryland and (2) 88 and 10 acres, respectively, of soybeans and alfalfa on the presently irrigated 260 acres that could become unprofitable to irrigate; and

Cherry-Todd and Cam-Wal RECs: 250 and 125 cows, respectively, for the cow-calf and associated calf-wintering activities.

Finally, cash sale of alfalfa for the Cherry-Todd and Cam-Wal REC representative farms was precluded. The sale of corn silage and sorghum sudan pasture in Cam-Wal was also precluded.

Irrigation alternatives

The eight irrigation alternatives considered in the representative farm models for the different REC service areas are as follows:

	Clay-Union REC	Union REC	Cherry-Todd REC	Cam-Wal REC
Use or non-use of two existing center pivot systems	X	X	X	X
The purchase of new high or low pressure center pivot or gated pipe irrigation systems[8]	X	X	X	X

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[7] The equations controlling the well-pumping capacities have upper limits and right-hand-side values of zero. Demands for pumping capacity are represented by acre-inch irrigation water requirements for various irrigated crops (entered in Subcell $\underline{I}_4$). The supplies of pumping capacity are reflected in Subcell $\underline{H}_1$.

[8] Gated pipe systems are an option only for the Union REC representative farm. Low pressure systems are options for all RECs except Cam-Wal.

	Clay-Union REC	Union REC	Cherry-Todd REC	Cam-Wal REC
The conversion of existing center pivot systems to low pressure and/ or diesel power[8]	X	X	X	X
The use of diesel versus electric energy sources	X	X	X	X
The irrigation of crops with a greater or lesser irrigation requirement than corn	X	X	X	
Full versus partial irrigation water application rates	X	X		
Water distribution by center pivot sprinklers versus by gated pipe, gravity flows		X		
The renting of additional irrigated land	X	X		

Use or non-use of two existing center pivot systems. Data on the irrigated crop options for the various RECs are shown in Report 1-Tables 2, 4, 6, 8, and 10. The variable cost data, as mentioned above, are incorporated into Subcell $\underline{B}_4$. The other irrigated crop production data are incorporated into subcells as follows:

- Irrigated water application rates into Subcells $\underline{I}_4$ and $\underline{I}_6$;

- Labor requirements (for both crop production and the operation of irrigation systems) into Subcell $\underline{N}_1$; and

- Yields into Subcell $\underline{S}_1$.

If irrigated crop production is less profitable than dryland production, the two existing center pivots can be left unused and the land can be farmed as dryland. The dryland crop production data are shown in Report 1- Tables 2-9. The coefficients for the dryland crops are the same, no matter whether the crops are raised on regular (currently non-irrigated) dryland or on irrigated land that reverts to dryland cropping. These two circumstances are differentiated in the model, however, with subscripts $\underline{1}$ and $\underline{2}$ for the following cells reflecting dryland production on regular dryland and formerly irrigated cropland, respectively,

- Variable costs of production, Cells $\underline{C}_1$ and $\underline{C}_2$;

- Regular dryland versus formerly irrigated cropland use, Cells $\underline{J}_1$ and $\underline{J}_2$;

- Labor requirements, Cells $\underline{O}_1$ and $\underline{O}_2$; and

- Yields, Cells $\underline{T}_1$ and $\underline{T}_2$.

The purchase of new high or low pressure center pivot or gated pipe irrigation systems. If irrigated crop production is sufficiently more profitable than dryland production, new high or low pressure center pivot irrigation systems can be purchased for placement on owned and/or rented dryland.[9] The investment requirements for the purchase of new irrigation systems are shown in the upper panels of Report 1-Tables 15-17 and in Report 1-Table 18. The annualized financial and economic costs of ownership of the new irrigation systems are shown in the lower panels and footnotes to the same tables. The annualized ownership costs are entered into Subcell $\underline{B}_1$.

The conversion of existing center pivot systems to low pressure and/or diesel power. Existing electric power, high pressure center pivots can be converted to low pressure and/or diesel power sources. The investment requirements and annual ownership costs for these conversions are shown in the upper and lower panels, respectively, of Report 1-Table 19. The annualized ownership costs for the conversions are shown in Subcell $\underline{B}_1$.

The use of diesel versus electric energy sources. If new or converted irrigation systems involve diesel-powered units, the power costing is via (1) the gallons of diesel fuel required per acre-inch of irrigation water applied, which is entered into Subcell $\underline{I}_5$, and (2) the price of diesel fuel which is entered into Subcell $\underline{B}_3$. The gallons of diesel fuel required per acre-inch of pumped irrigation water are as follows:

1. Clay-Union and Union REC,

    - High pressure center pivots, 2.03;
    - Low pressure center pivots, 1.09;

2. Cherry-Todd REC,

    - High pressure center pivots, 3.05;
    - Low pressure center pivots, 2.21; and

3. Cam-Wal REC high pressure center pivots,

    - Low-lands, 3.05; and
    - Bluffs, 11.1.

The irrigation of crops with a greater or lesser irrigation requirement than corn. In all RECs except Cam-Wal, two or more crops can be irrigated. The irrigation requirements for alfalfa are considerably higher (at least 70% higher) than those for corn. Irrigated soybeans, on the other hand, require slightly less irrigation than irrigated corn (Report 1-Table 10). With higher or lower electricity prices for energizing irrigation pumps and different commodity prices, it is conceivable that the relative economics of producing crops with different intensities of irrigation water application could shift.

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[9] Subcell $\underline{L}_1$ represents the link between the maximum permissible acreages of rented land (entered into Subcell $\underline{M}_1$) and the per-acre charges for the rented land (Subcell $\underline{E}_1$).

Full versus partial irrigation water application rates. One of the potential adjustments to rising energy prices is to irrigate at a level less than that which meets the full consumptive water requirement of a crop. In the Clay-Union and Union REC representative farm models, two levels of partial irrigation, namely, two-thirds and one-third the full application rate, were permitted. Coefficients for these situations are shown in Report 1-Tables 13 and 14.

The irrigated crop options for the Union REC, therefore, include choices not only among (1) corn versus soybeans, (2) high versus low pressure water distribution, (3) center pivot versus gated pipe irrigation, and (4) electric versus diesel power energy sources, but also among full irrigation and two levels of partial irrigation. This complex of factors underlies the 30 irrigated crop production options indicated for the Union REC representative farm in Figure 1.[10]

Water distribution by center pivot sprinklers versus by gated pipe, gravity flow. As indicated above, this option was considered for the Union REC representative farm where the natural topography of some irrigated fields tends to be quite flat.

The renting of additional irrigated land. Provision for renting 130 acres of irrigated land was made, as indicated in Report 1-Table 25, for the Clay-Union and Union REC representative farms.

Other features

The modeling of the electric rate structure (Subcells $\underline{F}_1$ - $\underline{F}_4$) and the interfacing of the electric rate structure with the irrigation alternatives component of the matrix (Subcells $\underline{G}_1$ - $\underline{G}_5$ and $\underline{I}_1$ - $\underline{I}_5$) are discussed in detail in the next major section of the report.

The crops that are produced can be marketed through livestock or sold for cash. The farm-raised feed requirements for the livestock enterprises are shown in Report 1-Tables 21-24. They are entered into Subcell $\underline{U}_1$.[11] Provision is also made for the transfer of harvested crops, via Subcell $\underline{U}_2$, into crop sale activities. The selling prices indicated in Report 1-Table 1 are entered into Subcell $\underline{D}_2$.

If the labor requirements of the crop and livestock production activities exceed the year-round labor supply (entered in Subcell $\underline{R}_1$), provision can be made for meeting the surplus labor requirement from the part-time hired labor supply (Subcell $\underline{R}_2$). The labor goes from Subcell $\underline{R}_2$ via Subcell

[10]The largest number of irrigated crop production options modeled is 36 for the Clay-Union REC representative farm. It is similar to the Union REC representative farm, except that irrigated alfalfa is also an option for it, and gated pipe systems are not. The smallest number of irrigated crop production options modeled is two for the Cam-Wal REC representative farm, namely, high pressure, center pivot irrigated corn grown with electric versus diesel energized pumps.

[11]The pasture/rangeland and labor requirements for the livestock activities are entered into Subcells $\underline{K}_1$ and $\underline{P}_1$, respectively.

Q_2 to meet the surplus requirement in Subcell $\underline{Q_1}$. No more part-time hired labor can be hired, however, than those amounts shown in Subcell $\underline{R_2}$.

To facilitate the interpretation and reporting of data findings, provision was made in the model for several accounting or definitional equations (not portrayed in Figure 1). Examples of the subject matter represented in these accounting rows are:

- Irrigation energy costs;

- Kilowatts of energy used;

- Acre-inches of irrigation water pumped;

- The value of crops produced; and

- Livestock sales.

The "irrigation energy cost" accounting equation was structured, for example, so as to reflect the sum of the annual minimum, monthly demand, first step bounded energy, and second step energy charges associated with the irrigated crop production activities comprising the optimal (most profitable farm organizational) solution.

DESIGN OF THE "ELECTRIC RATE STRUCTURE-IRRIGATION ALTERNATIVES" COMPONENT OF THE MILP MODEL

The purpose of this section is to explain the "inner-workings" of the "electric rate structure-irrigation alternatives" component of the generalized model tableau for the Union REC representative farm. Rather detailed attention is given to Cells A, B, F, G, H, I, and M in Figure 1. To simplify discussion, only 37 of the 73 columns and 35 of the 57 rows covered by those cells are selected for consideration here. The full set of matrix coefficients for the 37 columns and 35 rows is presented in Figure 2.

Each of the 36 structural variables represented in Figure 2 is constrained to an integer (0 or 1) value -- as explained in the "MILP overview" section -- except for those in the "second step energy charge" and "diesel power" sections. These exceptions involve per-unit (kWh of electricity and gallons of diesel fuel) energy charges and per-acre-inch-of-water energy requirements. The 37th column represents a vector matrix of right-hand-side constants.

Within-matrix linkages: electric power, high pressure, fully irrigated corn production and the electric rate structure

Modeling the electric rate structure for irrigation for the Union REC required the establishment of four linkage relationships--one for each of the annual minimum charge, the monthly demand charges, the first step bounded energy charge, and the second step energy charge. The costs represented by each of these types of charges for the Union REC representative farm are shown in the second panel of Report 1-Table 20 and are incorporated into the first 15 columns of the profit function in Figure 2.

Electric power, high pressure, fully irrigated corn--shown in Col 31 in Figure 2--is used to illustrate the inner-workings of the matrix. The linkages between this production activity and each of the four electric rate structure components are now described. As an aid to understanding (not because the computer necessarily proceeds to solve the matrix in the manner indicated), the descriptions are in terms of one-by-one sequential steps. The locations of the coefficients in the Figure 2 matrix are designated by the respective row-column positions of the coefficients in the matrix.

Annual minimum charge (see the "▬▬" guide-line in Figure 2). The initial impetus for activating the annual minimum charge is an indication of the need for 130 acres of electric power, high pressure irrigated land on which the corn is grown (Row 21-Col 31). This requirement is transmitted through Equation 21 to Col 19 which represents the first already-present center pivot.[12] The linkage is via (Row 20-Col 19) which denotes the first center pivot, (Row 21-Col 19) which denotes the supply of the 130 acres, and (Row 2-Col 19) which shows the need for one unit of an annual minimum charge.

This requirement is transmitted through Equation 2 to Column 1 which accounts for the high pressure, annual minimum charge. The linkage is via (Row 2-Col 1) which denotes the supply of one unit of the annual charge and then on to (Row 1-Col 1) which represents the dollar value of the annual minimum charge. Thus, a necessary condition for the selection of a center pivot irrigated quarter-section of corn is the payment of an annual minimum charge of $1,212.75.[13]

Monthly demand charges (see the "■■■" guide-line in Figure 2).[14] The monthly demand charges for irrigated corn are triggered by (Row 5-Col 31) and (Row 6-Col 31) which indicate a need for one unit of the July demand charge and one unit of the August demand charge. These needs are transmitted via Equations 5 and 6 to Col's 4 and 5 which can supply the respective monthly demand charges. Through (Row 5-Col 4) and (Row 6-Col 5), linkages are established with (Row 1-Col 4) and (Row 1-Col 5) which require demand payments of $602.91 for each of July and August.

Equations 28 and 29 insure that the maximum monthly pumping capacities are not exceeded. The acre-inch needs for irrigated corn during July (468) and August (572) are shown in (Row 28-Col 31) and (Row 29-Col 31). If these values were to exceed the maximum monthly pumping capacity of 1,248

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[12]In the complete matrix, four additional columns analagous to 19-22 are provided for the second already-present center pivot.

[13]Even if an irrigated crop activity does not enter an optimal solution, however, the annual minimum must be paid. This was modeled through the establishment of unity (1.00) coefficients in Equation 26 for the dryland crops grown on already-present irrigated quarter-sections, which link through (Row 26-Col 31) to (Row 21-Col 31) and then on to (Row 1-Col 1) as explained above.

[14]In the complete matrix, monthly demand charges for May through September are provided for each of high pressure, low pressure, and gated pipe water distribution. In Figure 2, the monthly demand charges for only July and August are provided.

acre-inches shown in (Row 28-Col 4) for July and (Row 28-Col 5) for August, the potential solution represented therein would be infeasible.

First step energy charge (see the " ***** " guide-line in Figure 2). The first step bounded energy charge for irrigated corn is triggered by (Row 11-Col 31) which represents the need for one unit of the first step energy charge. This need is transferred via Equation 11 to Col 10 which can supply the first step energy charge. Through (Row 11-Col 10), a linkage is established with (Row 1-Col 10) which requires the payment of $207.90 as the first step energy payment.

Second step energy charge (see the ". . . " guide-line in Figure 2). The second step (unbounded) energy charge for irrigated corn is triggered by (Row 14-Col 31) which indicates a need for 1,040 acre-inches of water. This need is transmitted via Equation 14 to Col 16 which denotes that, for every acre-inch of water (Row 14-Col 16), 28.69 kWh of power (Row 17-Col 16) is required. The computer calculates the product of 1,040 and 28.69, and then deducts from this, via Equation 17, 6,300 kWh (Row 17-Col 31) which represents the amount of power already paid for through the first step energy charge.

The remainder of the kWh need is then transferred to Col 13 which supplies second step electric power. The linkage is via (Row 17-Col 13) and ultimately to (Row 1-Col 13) which requires the payment of $0.0158 for each remaining kWh.

Within-matrix linkages to accommodate other irrigation alternatives

The model is structured so that first consideration is given to the provision of irrigation by the already-present, electric power high pressure center pivot (Col 19) or by conversion of the pivot to (1) electric, low pressure (Col 20), (2) diesel, high pressure (Col 21), or (3) diesel, low pressure (Col 22). Attention is then given to the irrigation system purchase options (Col's 23-27).

The possibilities of greater profitability of partial irrigation are considered in the model. The coefficients for fully irrigated corn (Col 31) shown in Figure 2 are analagous to those for two-thirds irrigation (Col 32) and one-third irrigation (Col 33), except for fewer acre-inches of irrigation water applied (Equations 14, 28, and 29) and lower variable production costs (Equation 1). Not shown in Figure 2 are lower yields with partial irrigation (as shown in Report 1-Table 14). In determining the competitiveness of the partial irrigation alternatives with full irrigation, joint consideration is given to (1) the reduced irrigation needs (and hence reduced energy costs) and reduced variable production costs versus (2) the reduced yields with partial irrigation.

The inner-workings of the model for electric power, low pressure irrigated corn (Col 34) and electric power, gated pipe irrigated corn (Col 35) are analagous to those for electric power, high pressure irrigated corn (Col 31), except that the costs of converting currently owned systems to low pressure (Col 20) and/or purchasing of low pressure (Col 24) or gated pipe (Col 25) systems must also be borne.

The option of diesel power, high pressure irrigated corn (Col 36) requires the conversion of the already-present center pivot to diesel power (Col 21) or the purchase of a new diesel irrigation system (Col 26). The energy requirement for diesel power, high pressure irrigated corn is handled through Equations 34 and 35 in which 1,040 acre-inches of irrigation water are required (Row 34-Col 36) and each acre-inch of pumped water requires 2.03 gallons of diesel fuel (Row 35-Col 29). The fuel cost is met through Col 28, which shows that the cost of diesel fuel is $1.0227 per gallon (Row 1-Col 28).

Not shown in Figure 2 are the 15 options associated with irrigated soybeans; the dryland options on currently owned irrigated land (or dryland) of corn, soybeans, alfalfa, oats, and spring wheat; and the option of renting irrigated land. The basic linkages to the electric rate structure for the soybean options are identical to those described for irrigated corn. The general linkages for the other two options are indicated in the prior section.

LIMITATIONS TO THE MODEL

The analytic model employed in this study, as with any other study, fails to accommodate all pertinent features of the real-world environment being studied. Those features believed to most limiting in this regard are the following.

The actual farmer decision-making process is only crudely incorporated into the MILP model. The only farmer managerial objective explicitly considered in the model is the maximization of revenues over and above variable production costs (and the annualized ownership costs of newly purchased irrigation equipment). No attention is given to other economic objectives (e.g., cash-flow management, risk management) and non-economic objectives (e.g., preferences regarding family involvement with the farm, farmer involvement in the home, leisure time). Neither is attention given to the investment credit and tax deduction dimensions of irrigation investments.

The model covers only a single production period; yet, many decisions are made by farmers within the context of several production periods. Crops are considered individually; yet, many farmers plan cropping patterns with rotational considerations in mind. Specific assumptions (e.g., center pivots that cover only 130 acres of land each, fixed rather than towable center pivots, land and labor resource availabilities, insurance rates, commodity storage and marketing practices) may apply to some farms, but certainly not to all farms. The same is true for the assumed crop and livestock production coefficients and irrigation technologies.

Because of these limitations, the findings from the study need to be interpreted with caution. In some instances, sensitivity analysis is undertaken to determine over what ranges of variation for particular coefficients solutions remain stable. In all cases, however, the results should not be interpreted as absolutely definitive.

The applicability of the findings from the study to particular RECs also depends on the cost structures and managerial philosophies for the individual RECs. Inspite of the limitations to the study, we believe that the decision-making process on appropriate electric rate structures can be facilitated because of the existence of the findings from the study. The alternative of no systematic study of some of the key issues involved in the establishment of appropriate electric rate structures is considered to be inferior.

SUMMARY

This report contains a description of the mixed integer linear programming (MILP) model that was developed and used in a study of electric rate structures for irrigation in four case study rural electric cooperatives (RECs) in South Dakota. Particular emphasis is placed on the design of the model that permits simultaneous attention to all three basic features of electric rate structures for irrigation, namely, annual minimum charges, monthly demand charges, and block rate energy charges. The primary intended audiences for the report are graduate students and research-peers with an interest in analyzing electric rate structures for irrigation.

FIGURE 1. GENERALIZED MODEL TABLEAU, UNION REC REPRESENTATIVE FARM, ELECTRIC RATE STRUCTURE-IRRIGATION STUDY[a]

Matrix rows		Matrix Columns														
		Electric rate structure				Irrigation alternatives				Dryland crop production options		Crop disposition		Resource rental		
		Annual minimum charges (3)	Monthly demand charges (15)	First step energy charges (3)	Second step energy charges (6)	Irrigation system conversion options (8)	Irrigation system purchase options (5)	Diesel power controls and costing (3)	Irrigated crop production options (30)	On dryland (5)	On formerly irrigated land (5)	Live-stock feeding (0)	Crop sales (5)	Land rental (2)	Labor hiring (6)	Right hand side (1)
Objective function	Gross profit	A_1	A_2	A_3	A_4	B_1	B_2	B_3	B_4	C_1	C_2	D_1	D_2	E_1	E_2	
Electric rate structure	Annual minimum charge controls (3)	F_1				G_1	G_2									
	Monthly demand charge controls (15)		F_2						G_3							
	First step energy charge controls (3)			F_3					G_4							
	Second step energy charge controls (7)				F_4				G_5							
Water, land, and diesel power	Center pivot and land controls (11)					I_1	I_2		I_3	J_1	J_2	K_1		L_1		M_1
	Maximum monthly pump capacity controls (15)		H_1						I_4							
	Diesel water and energy controls (2)							I_5	I_6							M_2
Farm/ ranch labor controls	Year-round labor (6)								N_1	O_1	O_2	P_1			Q_1	R_1
	Hired hourly labor (6)														Q_2	R_2
Crop transfer rows (5)									S_1	T_1	T_2	U_1	U_2			

[a]The number following each row heading reflects the number of equations (rows) in the Union REC representative farm model that pertain to that row heading. The number below each column subheading reflects the number of variables (columns) in the model associated with that heading. The value of all coefficients in the non-letter-labeled cells in the matrix is zero.