Economic feasibility of using crop residues to generate electricity in Iowa

Center for Agricultural and Rural Development, Iowa State University

Burton C. English  
_Iowa State University_

Cameron C. Short  
_Iowa State University_

Earl O. Heady  
_Iowa State University_

Steven K. Johnson  
_Iowa State University_

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Economic Feasibility of Using Crop Residues to Generate Electricity in Iowa

CARD Report 88
ECONOMIC FEASIBILITY OF USING CROP RESIDUES
TO GENERATE ELECTRICITY IN IOWA

by
Burton C. English
Cameron C. Short
Earl O. Heady
Steven K. Johnson

This research study was completed under a grant from the RANN
Program (Research Applied to National Needs) of the National
Science Foundation (GI-32990). Any opinions, findings, conclu-
sions, or recommendations expressed in this paper are those
of the authors and do not necessarily reflect the view of NSF.

CARD Report 88

The Center for Agricultural and Rural Development
Iowa State University
Ames, Iowa  50011

January 1980
Energy production from renewable resources is currently under intensive discussion and examination. New technologies are being developed to use these renewable resources in the production of usable fuel.

This study examines the economic feasibility of using Iowa's crop residues to generate electricity. Iowa was chosen because of the high crop residue densities and the dispersed nature of Iowa's power plants. If the use of crop residue is not economically feasible in Iowa, then it is likely that it will not be feasible elsewhere.

The study is made possible by a grant from the National Science Foundation (NSF), Research Applied Needs (RANN) program. The study assumes an already proven technological method (direct firing of crop residue) and examines the economic feasibility of crop residue use by Iowa's existing power plants.

Numerous individuals have helped in the preparation of this research. Appreciation goes to Bill Boggess and Elaine White for programming help; Paul Sidles and Wes Buchele for the initial help in designing the project; William Shrader and Regis Voss for their help on the agronomic aspects of crop residue; Alfred Joensen for his advice on power plants; Harvey Funk and Dan Morroni for their help in processing plant design; Phillip Baumel, Tom Drinka, and Craig O'Riley for their data and help concerning coal transportation and coal benefication; Allan Carpenter (Iowa's
Department of Environmental Quality) and Fred Rezazadeh for their help on sulfur oxide; and Jeff Goebels for his help on the crop residue transportation design.¹

¹Many of the above people conduct research at Iowa State University. Those who do not include Harvey Funk and Dan Morrioui who work for Henningson, Durham, and Richardson, Omaha, Allan Carpenter who works at Iowa's Department of Environmental Quality, Des Moines, and Paul Sidles who works at the Ames Lab with the Department of Energy, Ames.
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THE ECONOMIC FEASIBILITY OF USING CROP RESIDUES TO GENERATE ELECTRICITY IN IOWA

INTRODUCTION

The United States is a nation rich in domestic energy resources. Yet it depends on the importation of large quantities of fossil fuels. This situation provides the crux of the nation's energy problem. Today, over 75 percent of the nation's energy demand is filled by petroleum and natural gas. Reliance on imported oil has left the nation in a vulnerable position which affects all facets of American lifestyle. The threat of oil embargos and rising energy prices has disturbed the American public. We have in the space of a few short years moved from a position of self-sufficiency to one of net imports on energy.

Fossil fuels provide all but 4 percent of the energy consumed in the United States. Nonfossil fuel sources are a small and decreasing proportion of U.S. energy consumption. Wood, at one time, was the predominant fuel source, then coal replaced wood and oil replaced coal. Each of these substitutions took approximately 60 years. At present, most of our energy needs are met by natural gas, petroleum, and coal [Tables 1, 2]. Natural gas consumption continued to increase through 1972, but its rise in the share of total energy has tapered off. Fuels produced in the United States have increasingly been insufficient to supply the rapidly rising domestic needs [Table 3]. So, energy imports have been increasing as described by Bohin and Russell [1973]: "The
Table 1. U.S. total energy consumption 1970-1976

<table>
<thead>
<tr>
<th>Year</th>
<th>Natural Gas</th>
<th>Coal</th>
<th>Crude Petroleum</th>
<th>Total</th>
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<tr>
<td>1970</td>
<td>21,795</td>
<td>12,698</td>
<td>29,537</td>
<td>66,090</td>
</tr>
<tr>
<td>1971</td>
<td>22,469</td>
<td>12,043</td>
<td>30,570</td>
<td>68,348</td>
</tr>
<tr>
<td>1972</td>
<td>22,698</td>
<td>12,423</td>
<td>32,966</td>
<td>71,609</td>
</tr>
<tr>
<td>1973</td>
<td>22,512</td>
<td>13,294</td>
<td>34,852</td>
<td>74,555</td>
</tr>
<tr>
<td>1974</td>
<td>21,733</td>
<td>12,889</td>
<td>33,467</td>
<td>72,668</td>
</tr>
<tr>
<td>1975</td>
<td>19,948</td>
<td>12,814</td>
<td>32,742</td>
<td>70,598</td>
</tr>
<tr>
<td>1976</td>
<td>20,344</td>
<td>13,748</td>
<td>35,086</td>
<td>74,372</td>
</tr>
<tr>
<td>1977a</td>
<td>19,613</td>
<td>14,117</td>
<td>36,956</td>
<td>75,836</td>
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</tbody>
</table>

*aEstimated.


adjustment to these changes has been painful for Americans, and is likely to become more painful still before it is completed."

Exxon Corporation [Annonymous, 1978b] examined the world's energy outlook. It found that a significant shift in the shares of energy supplies by fuel source is needed by 1990 for non-Communist countries. It is estimated that nuclear power will increase its share as a source of energy by 2 to 8 percent; coal will maintain its current 19 percent share; hydroelectric and geothermal power is projected to maintain their
Table 2. U.S. per capita energy consumption 1970-1976

<table>
<thead>
<tr>
<th>Year</th>
<th>Natural Gas (Million BTU's)</th>
<th>Coal</th>
<th>Crude Petroleum</th>
<th>Total</th>
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<tr>
<td>1970</td>
<td>106</td>
<td>62</td>
<td>144</td>
<td>327</td>
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<tr>
<td>1971</td>
<td>109</td>
<td>58</td>
<td>148</td>
<td>330</td>
</tr>
<tr>
<td>1972</td>
<td>109</td>
<td>60</td>
<td>158</td>
<td>344</td>
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<tr>
<td>1973</td>
<td>108</td>
<td>64</td>
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<td>1974</td>
<td>103</td>
<td>61</td>
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<td>1975</td>
<td>94</td>
<td>60</td>
<td>154</td>
<td>331</td>
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<td>95</td>
<td>64</td>
<td>163</td>
<td>346</td>
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<td>1977a</td>
<td>91</td>
<td>65</td>
<td>171</td>
<td>351</td>
</tr>
</tbody>
</table>

*Estimated.


7 percent share; the synthetics, solar, and other new energy forms will have a 2 percent share. But, Exxon continues by suggesting that synthetics, solar, and other energy forms could be the base for a rapid rate of expansion.

Crops capture solar energy, a flow resource, and combines it with other elements such as plant nutrients and water inherent in the soil, and carbon dioxide from the air. These ingredients are combined to form grains, fruits, and fibers.
Table 3. Net exports of selected mineral fuels, 1970-1976<sup>a</sup>

<table>
<thead>
<tr>
<th>Year</th>
<th>Natural Gas</th>
<th>Crude Oil</th>
<th>Coal</th>
<th>Petroleum Products</th>
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<tbody>
<tr>
<td></td>
<td>(Trillion BTU's)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1970</td>
<td>-774</td>
<td>-2,688</td>
<td>1,990</td>
<td>-4,153</td>
</tr>
<tr>
<td>1971</td>
<td>-881</td>
<td>-3,428</td>
<td>1,566</td>
<td>-4,508</td>
</tr>
<tr>
<td>1972</td>
<td>-971</td>
<td>-4,540</td>
<td>1,545</td>
<td>-5,108</td>
</tr>
<tr>
<td>1973</td>
<td>-985</td>
<td>-6,861</td>
<td>1,446</td>
<td>-6,142</td>
</tr>
<tr>
<td>1974</td>
<td>-903</td>
<td>-7,354</td>
<td>1,570</td>
<td>-5,323</td>
</tr>
<tr>
<td>1975</td>
<td>-899</td>
<td>-8,676</td>
<td>1,751</td>
<td>-3,851</td>
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<tr>
<td>1976</td>
<td>-917</td>
<td>-11,206</td>
<td>1,594</td>
<td>-3,982</td>
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<tr>
<td>1977&lt;sup&gt;b&lt;/sup&gt;</td>
<td>-959</td>
<td>-13,798</td>
<td>1,425</td>
<td>-4,312</td>
</tr>
</tbody>
</table>

<sup>a</sup>A positive number indicates net exports.

<sup>b</sup>Predicted.


The primary purpose of U.S. agriculture has always been to provide food and fiber desired by consumers. The incentive for achieving these goals is an adequate return on the resources employed in producing these commodities. A secondary purpose of U.S. agriculture may be, in addition to supplying food and fiber, to provide energy. Significant amounts of energy from U.S. agriculture, in excess of our basic food and fiber requirements and other needs may come from energy crops,
agricultural by-products, crop residues, and animal wastes. These materials are known as biomass. Biomass consists of carbon to carbon bonds. It is from these bonds that energy originates. The Project Independence Task Force estimated that, if an accelerated implementation plan were followed, biomass through bioconversion processes could provide up to 8 percent of our energy requirements by 2000 [Alich and Inman, 1976]. A further speculation under this scenario is that bioconversion would be the most important solar energy concept.

Biomass energy conversion may be an answer to providing crucial energy, an idea that has existed for numerous years. People burned wood for warmth and protection until the present century. As wool lots decreased, the people of the developed countries turned away from wood burning to that of coal and oil [Table 4] while sources of heat for cooking and home heating in underdeveloped countries remained wood, charcoal, animal wastes, etc. In essence, the developed areas have increased reliance on stock fuel resources existed while underdeveloped areas continue to rely more heavily on flow fuel resources.

There are a number of renewable energy sources that may become available. Included in this are energy resulting from wind, daily tides, ocean thermal gradient, bioconversion from municipal, and agricultural wastes, grains, kelp, algae, sugar crops, and geothermal. Exxon [Anonymous, 1978] states that these possibilities will probably be geographical in nature and generally on a small scale. Their collective impact, however, may become significant. For this to occur, improvements in costs or encouragement through government policies for
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<th>Wood Quantity (quads)</th>
<th>Wood Proportion (percent)</th>
<th>Coal Quantity (quads)</th>
<th>Coal Proportion (percent)</th>
<th>Petroleum Quantity (quads)</th>
<th>Petroleum Proportion (percent)</th>
<th>Natural Gas Quantity (quads)</th>
<th>Natural Gas Proportion (percent)</th>
<th>Other Quantity (quads)</th>
<th>Other Proportion (percent)</th>
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<td>1860</td>
<td>2.6</td>
<td>83.5</td>
<td>--</td>
<td>--</td>
<td>16.4</td>
<td>0.5</td>
<td>--</td>
<td>--</td>
<td>--</td>
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<tr>
<td>1880</td>
<td>2.9</td>
<td>57.0</td>
<td>2.0</td>
<td>41.1</td>
<td>0.5</td>
<td>1.9</td>
<td>0.1</td>
<td>1.9</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>1900</td>
<td>2.0</td>
<td>21.1</td>
<td>6.8</td>
<td>71.3</td>
<td>0.5</td>
<td>0.5</td>
<td>1.9</td>
<td>0.5</td>
<td>2.6</td>
<td>3.6</td>
</tr>
<tr>
<td>1920</td>
<td>1.6</td>
<td>15.5</td>
<td>7.5</td>
<td>72.8</td>
<td>3.4</td>
<td>0.5</td>
<td>1.9</td>
<td>0.5</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>1940</td>
<td>1.4</td>
<td>5.3</td>
<td>12.5</td>
<td>50.1</td>
<td>10.2</td>
<td>40.9</td>
<td>0.9</td>
<td>0.9</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>1950</td>
<td>1.2</td>
<td>3.3</td>
<td>12.9</td>
<td>36.7</td>
<td>19.7</td>
<td>73.5</td>
<td>0.9</td>
<td>0.9</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>1960</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>1970</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>1975</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>1976</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

**SOURCE:** [Iowa Energy Policy Council, 1977].

2. A quad is defined as a quadrillion British Thermal Units.
certain energy forms would appear to be necessary if renewable resources are to capture a larger share of total energy used.

Presently, the Department of Energy (DOE) is examining the fuels from biomass. Their program's objectives are to "investigate and demonstrate the feasibility of utilizing agricultural, forest and animal residues to produce clean fuels and petrochemical products" [Ward, 1977]. Being examined are different conversion processes using various technologies so that they might be economically as well as technologically feasible. The various conversion processes include anaerobic digestion, pyrolysis, hydrogenation, hydrogasification, and direct combustion [Figure 1]. Any of these approaches involve the flow of residues through a sequence of processing and energy recovery activities. The economic feasibility of one possible approach is examined in this study. More specifically, the direct combustion of crop residues in electrical generating power plants in Iowa and the conditions in which this would be economically viable are evaluated.

Crop residues consist principally of the stalks and leaves of crops such as corn grown for grain. Presently, some of these residues are removed or used in situ for livestock feed. For the most part, crop residues are incorporated into the soil. For every 16 kilocalories (kcal) produced through the capturing of energy plants, 3.9 kcal are within crop residues [Nelson, Burrows, and Stickler, 1975]. These materials, when left in the field are useful for soil conservation, but they also have some future potential for use as a renewable energy source.
Figure 1. Bioconversion methods

Processes

Direct Combustion

Hydrocarbom-
ization

Pyrolysis

Hydrogeneration

Thermo-chemical

Anaerobic digestion

Outputs

Electricity

Oil

Gas

Biomass
The purpose of using crop residues is two-fold. First, crop residues are a renewable resource unlike the fossil fuels, and secondly, crop residues are virtually sulfur-free. Therefore, mixing crop residues with coal would allow power plants to meet increasingly stringent environmental constraints. Crop residues could be a substitute for coal, natural gas, and other petroleum products used in power plants.


1. There are enough residues in the United States to fire 130,1000 megawatt electric power plants. This is equivalent to 30 percent of the nation's current gas demand.

2. Crop residues are not restricted by geography because they occur whenever crops are grown.

3. The cost of producing crop residues is partially offset by the sales value of the food or fiber crop.

4. Crop residues represent an added source of income to farmers.

5. Use of crop residues would eliminate costly and environmentally sensitive disposal problems.

6. There would be no land or water development necessary.

There also are several disadvantages in using crop residue. Crop residue is already used as livestock feed, field mulch, and soil tilth improvement measures. The defused nature of crop residue also presents
a problem. Thus, costs of collection and transportation may exceed the value of residue as a feedstock to power plants. Another disadvantage is that crop residue is available with great seasonal and random variability. Residue produced locally will vary from year to year so a discontinuity of supply may result.

Study Area

To examine the economic feasibility of using crop residues as a fuel source in the production of electricity, Iowa is selected as a representative study area for two reasons: (a) Iowa has a high density of crop residues, and (b) the electricity-producing utilities are of a disperse nature.

Agriculture

Iowa is primarily an agricultural state. In 1975, cash receipts from farm marketing contributed 6.6 billion dollars to the state's economy. Iowa, in 1975, ranked first in the nation in combined total acres of principal crops harvested\(^1\) [Iowa Crop and Livestock Reporting Service, 1976].

Almost 26 million acres were harvested on the state's 136,000 farms. Primary crops, which are produced on 92 percent of the acres harvested, include corn, oats, soybeans, sorghum, wheat, and hay, [Table 5]. The total value of these crops is difficult to determine, as much of what is grown is not directly sold at the market place, but used as

\(^1\)Crop acres included are corn, sorghum, oats, barley, wheat, rice, soybeans, flaxseed, peanuts, popcorn, cotton, hay, dry beans, dry peas, potatoes, sweet potatoes, tobacco, sugar cane and sugarbeets.
Table 5. Acres and quantity of corn, oats, soybeans, sorghum, and wheat harvested in Iowa, 1970, 1975

<table>
<thead>
<tr>
<th>Crop</th>
<th>Acres Harvested for:</th>
<th>Quantity Harvested for:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1970</td>
<td>1975</td>
</tr>
<tr>
<td></td>
<td>(thousands of acres)</td>
<td>(millions of bushels)</td>
</tr>
<tr>
<td>Corn, All Purposes</td>
<td>10,004</td>
<td>13,040</td>
</tr>
<tr>
<td></td>
<td>857.9</td>
<td>1,091.7</td>
</tr>
<tr>
<td>Oats</td>
<td>1,657.6</td>
<td>1,540.0</td>
</tr>
<tr>
<td></td>
<td>89.9</td>
<td>78.5</td>
</tr>
<tr>
<td>Soybeans</td>
<td>5,618</td>
<td>6,970.0</td>
</tr>
<tr>
<td></td>
<td>182.6</td>
<td>237.0</td>
</tr>
<tr>
<td>Sorghum</td>
<td>19.0</td>
<td>26.0</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>1.6</td>
</tr>
<tr>
<td>Wheat</td>
<td>27.8</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>0.9</td>
<td>2.6</td>
</tr>
<tr>
<td>Hay</td>
<td>2,451.2</td>
<td>2,350.0</td>
</tr>
<tr>
<td></td>
<td>NAa</td>
<td>NA</td>
</tr>
</tbody>
</table>

*aNA Data are not available.


feed for livestock. Assuming 1975 prices for corn, oats, soybeans, sorghum, and wheat, the total value of these crops would be $3.83 million. This value does not include the value of other crops such as rye, popcorn, white corn, potatoes, and red clover and timothy seed.

Average 1970-1975 yields for the six major crops are presented in Table 6. Using the crop residue coefficients developed by Alrich, Inman, and Ernest [1976], the total amount of crop residues produced in the state is determined [Table 6]. There are more than 52.9 million tons of residues produced annually in Iowa. This residue, if collected and burned, would provide an estimated 687,440 million BTU's of input energy. Not all of this residue is available for energy production. Some land requires residue for erosion control, residue is used
Table 6. Average state crop yields and total crop residue produced by corn type

<table>
<thead>
<tr>
<th>Crop</th>
<th>Average State Yields 1970 - 1975 (bushels)</th>
<th>Crop Residue Coefficient&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Total Crop Residue Produced (thousand tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn for grain</td>
<td>93.8</td>
<td>1.1</td>
<td>33,624.4</td>
</tr>
<tr>
<td>Oats</td>
<td>54.2</td>
<td>3.01</td>
<td>3,784.5</td>
</tr>
<tr>
<td>Sorghum</td>
<td>73.2</td>
<td>1.57</td>
<td>63.3</td>
</tr>
<tr>
<td>Soybeans</td>
<td>32.3</td>
<td>2.14</td>
<td>15,213.6</td>
</tr>
<tr>
<td>Wheat</td>
<td>34.4</td>
<td>2.53</td>
<td>197.3</td>
</tr>
<tr>
<td>Hay&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2.6</td>
<td>NONE</td>
<td>NONE</td>
</tr>
</tbody>
</table>


<sup>a</sup> In terms of tons of residue per ton of grain.

<sup>b</sup> Average state yield is in tons.

for livestock feed and bedding, and finally, some residue is presently sold.

Electric utility sector

Iowa's electric utility producing sector consumed 4.9 million tons of coal, 720 thousand barrels of oil, and 46.9 trillion cubic feet of natural gas in the production of 15.9 million megawatts hours of electricity [Iowa Energy Policy Council, 1977]. There are 36 power plants located in Iowa, generating from 3.9 to 2,506.1 million kwh in 1975. Of these 36, eight had a 1975 net generation of less than 40 million
kwh. These power plants are deleted from the study because crop residue processing costs are prohibitive for power plants of this size. Thus, 28 power plants are included in the study. In addition, several power plants are located in the same vicinity. For instance, Cedar Rapids has three power plants; Ames has two, and Sioux City has three. Power plants included in the model are listed in Table 7 along with the amount of coal each facility used. Figure 2 shows the power plant sites and fuel used by site. In some cases, as with Cedar Rapids, there is an aggregation of two or more power plants.

Study's Objectives

The purpose of this study is to examine the economic feasibility of using crop residues in existing Iowa power plants. Four different scenarios are examined -- The Base Run, Soil Constrained, Increased Energy Prices, and Sulfur Constrained. Under each of these options, crop residues are required by the power plant at 0, 20, 40, and 60 percent levels of the coal used in 1975 (Table 8).

The costs of crop residue are divided into three stages: on-the-farm, transportation, and processing. The on-the-farm stage includes agronomic and harvesting costs. The transportation stage is self-explanatory and the processing stage includes the costs required to size the residues into a usable fuel feedstock in existing boilers and the cost of boilers design adjustments. In addition to the costs, the energy used in collecting, transporting, and processing the residues is examined. This is necessary to examine the energy balance. Are we saving or losing energy in the system examined?
Table 7. 1975 coal use and maximum allowable sulfur emissions both in 1975 and the proposed standard by power plant location

<table>
<thead>
<tr>
<th>Power Plant Location</th>
<th>1975 Coal Consumption(^a) (Million BTU's)</th>
<th>Sulfur Oxide Constraint(^b) (Million pounds per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Creston</td>
<td>11,342,053</td>
<td>90.7 34.0</td>
</tr>
<tr>
<td>Dubuque</td>
<td>2,969,318</td>
<td>17.8  8.9</td>
</tr>
<tr>
<td>Clinton</td>
<td>11,626,693</td>
<td>69.8 34.9</td>
</tr>
<tr>
<td>Lansing</td>
<td>3,068,601</td>
<td>36.8  9.2</td>
</tr>
<tr>
<td>Boone</td>
<td>304,839</td>
<td>3.7   1.8</td>
</tr>
<tr>
<td>Cedar Rapids</td>
<td>11,416,854</td>
<td>57.1 34.3</td>
</tr>
<tr>
<td>Marshalltown</td>
<td>3,139,298</td>
<td>25.1  9.4</td>
</tr>
<tr>
<td>Bettendorf</td>
<td>9,196,985</td>
<td>55.2 27.6</td>
</tr>
<tr>
<td>Council Bluffs</td>
<td>6,564,312</td>
<td>52.5 19.7</td>
</tr>
<tr>
<td>Des Moines</td>
<td>7,496,344</td>
<td>37.5 22.5</td>
</tr>
<tr>
<td>Sioux City/Salix</td>
<td>18,300,929</td>
<td>131.8 54.9</td>
</tr>
<tr>
<td>Eddyville</td>
<td>1,147,545</td>
<td>9.2   6.9</td>
</tr>
<tr>
<td>Burlington</td>
<td>15,998,558</td>
<td>96.0  6.9</td>
</tr>
<tr>
<td>Ames</td>
<td>1,314,800</td>
<td>15.8  3.9</td>
</tr>
<tr>
<td>Cedar Fall/Waterloo</td>
<td>2,549,455</td>
<td>15.3  7.6</td>
</tr>
<tr>
<td>Muscatine/Montpelier</td>
<td>7,289,380</td>
<td>43.7 21.9</td>
</tr>
<tr>
<td>Pella</td>
<td>1,711,074</td>
<td>20.5 10.3</td>
</tr>
<tr>
<td>Humboldt</td>
<td>1,407,615</td>
<td>12.7  4.2</td>
</tr>
<tr>
<td>Spencer</td>
<td>1,064,000</td>
<td>12.8  3.2</td>
</tr>
</tbody>
</table>

\(^a\)SOURCES: [Anonymous, 1976, and the state of Iowa's Commerce Commission files].

\(^b\)See Appendix A.
Figure 2. Power plant location in Iowa
Table 8. Alternative scenarios examined in the study and the assumptions under each scenario

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Level of Crop Residue at</th>
<th>1975 Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>Base</td>
<td></td>
<td>1975 Costs</td>
</tr>
<tr>
<td>Soil Constrained</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Double Energy</td>
<td>Doubled energy prices relative to 1975 costs, at-the-mine coal cost doubled.</td>
<td></td>
</tr>
<tr>
<td>Double Coal and Energy Price</td>
<td>Same as Double Energy Price except coal price to the power plant is doubled.</td>
<td></td>
</tr>
<tr>
<td>Sulfur Constrained</td>
<td>Same as Double Coal and Energy Price except sulfur emitted is constrained to the projected environmental standards.</td>
<td></td>
</tr>
</tbody>
</table>

\(^{a}\)This solution is identical with the Base at 0 percent residue demand.

The Base Run scenario is based on 1975 costs and is used as a comparison to all other scenarios. The Soil Constraint scenario is similar to the Base Run except soil loss is constrained to the 0 percent crop residue use in the Base Run solution. Three scenarios are run under increased energy prices. The first (Doubled Energy Prices) assumes the energy derived from diesel, natural gas, LPG, and electrical sources are doubled with the at-the-mine price of coal being doubled. The doubled coal and energy price scenario assumes that all fuel prices are doubled, including the cost of coal to the power plant. In the sulfur constrained scenario, these increased prices are combined with projected environmental sulfur emission standards.
II. MODEL DESCRIPTION

The linear programming model used in this study, to evaluate the feasibility for each residue situation and level of crop residue utilization, can be divided into three separate sectors: the crop production sector, the crop residue sector, and the power plant sector. These sectors are interrelated through land use of crop residue transfer constraints. The LP maximizes the selection of crops and farming practices, and minimizes the cost of supplying fuel to meet the power plant's fuel demands. This maximization procedure is subject to a set of primary constraints explained later.

Regional Delineation

Iowa is divided into 12 producing areas (PA). These regions are consistent with Iowa's soil conservancy districts and used initially by Nagadevra, Heady, and Nicol [1977] (Figure 3).

The Objective Function

The objective function is maximized subject to the cost of agricultural production, the gross return of endogenous crops, and the cost of coal for electrical generation by power plants located in Iowa. Thus, agricultural returns can be derived by adding to the objective function's value the cost of fuel to each individual power plant. Costs of producing agricultural commodities included in the model are labor, machinery, pesticides, energy, and fertilizers.
The objective function is subject to predetermined livestock demands, availability of land resources, and 1975 fuel and sulfur requirements by the power plants. The profit maximization objective function is of the form:

\[
\text{Max OBJ} = \sum_{i} \sum_{j} p_{ij} c_{ij} s + \sum_{i} \sum_{k} t_{ikl} l_{ikl} - p^N Q^N B - \sum_{e} \sum_{e}^E \sum_{m}^C c_{mn} q_{mn}^C
\]

\(i = 1\) to 12 for the producing areas;
\(j = 1\) to 8 for the crop produced;
\(k = 1\) to 12 for the 12 conservation tillage practices;
\(l = 1\) to 48 for the crop rotations in producing area \(i\);
\(e = 1\) to 4 for the type of fuel used in crop production and coal transportation;
\(n = 1\) to 19 for the 19 power plant locations included in the model; and
\(n = 1\) to 7 for the source and type of coal consumed.

where:

\(p_{ij} c_{ij} s\) is the return received for selling crop \(c_{ij}^s\) at price \(p_{ij}\) in PA \(i\);

\(t_{ikl} l_{ikl}\) is the cost of production \(T\), dollars per acre, of rotation \((1)\) with conservation tillage practice \(k\) in producing area \((i)\) times the level of the crop activity \((L)\);
\( P^N_{QNB} \) is the price of nitrogen \((P^N)\) times the quantity of nitrogen purchased \((Q^{NB})\):

\( P^E_{Q^e} \) is the price of fuel \((e)\) times the quantity of fuel purchased \((Q^e)\); and

\( C^C_{Q^m} \) is the cost of coal \((n)\) to power plant \((m)\) times the quantity of coal \((n)\) power plant \((m)\) consumes.

In addition, when crop residues are used by the power plant, three additional components are added to the objective function:

\[
\text{max OBJ} = \text{OBJ} - \sum_i \sum_k \sum_l T_{ikl} L_{ikl} C^CR_{Q^m} - P^N_{Q^{NBCR}} (2)
\]

where:

\( \text{OBJ} \) is the objective function previously states in equation (1);

\( T_{ikl} C^CR_{L_{ikl}} \) is the least cost of producing the crop plus the costs in harvesting and the cost of replacing nonnitrogen nutrients of crop residue for crop residue activity \((1)\) with conservation tillage practice \((k)\) in producing area \((i)\) times the level of the crop residue activity.

\( P^N_{Q^{NBCR}} \) is the discounted price of nitrogen times the quantity of nitrogen replaced.

\( C^CR_{Q^m} \) is the transportation and processing cost of crop residue to power plant \((m)\) times the quantity of crop residue power plant \((m)\) consumes.
Constraints

There are constraints at both PA and state levels. In addition, there are two sets of constraints for each power plant specified in the model and a third constraint for power plants located within Iowa but near either the Missouri or Mississippi rivers.

Constraints at the producing area level

There are six different sets of constraints at the PA level. These include land availability by land class for both crop and crop residue production, crop transfer rows, crop residue production and both livestock and power plants, and nitrogen replacement due to crop residue removal.

There are two different categories of land, one used for crop production and the other which is within a predetermined distance from a given power plant. Under each category, five different land classes represent an aggregation of the 29 class-subclasses in the Conservation Needs Inventory (CNI). The data from the 1967 base are then updated to 1975.

The quantity of land available for supplying power plants with crop residue is predetermined assuming the power plant demand is a given percentage of BTU's demanded to be replaced by crop residues, 50 percent harvest of crop residues, and 1970-1975 average density

1In the CNI there are eight major capability land classes. Classes II through VII are further subdivided to reflect the most severe hazard which prevents the land from being available for unrestricted use. These hazards include erosion, subsoil exposure, drainage problems, and climatic conditions [Conservation Needs Inventory Committee, 1971].
within the county where the power plant is located. Also, assumed is a diamond-shaped collection area with a homogeneous crop residue density. (For further explanation see Chapter III).

Crop transfer rows simulate the marketplace for the following endogenous commodities: corn grain, corn silage, legume hay, nonlegume hay, oats, sorghum grain, soybeans, and wheat. The producing areas supply these commodities directly to the crop purchase activities once livestock demands are met.

Livestock demands are derived using suggested rations developed by the Iowa State Cooperative Extension Service [1976a]. The commodities included within the rations are corn, corn silage, legume and non-legume hay, and crop residues. Thus, the commodity transfer rows, for each of the endogenous crops, take the form:

\[ \sum_{i} \sum_{k} Y_{ikl} L_{ikl} = C_{i} > LSTK^{D}_{i} \]  

where \( Y_{ikl} \) is the per acre yield of crop activity (1) with conservation-tillage practice (k) in PA (i) and \( LSTK^{D}_{i} \) is the quantity of crop required by livestock in PA (i).

The crop residue constraints exist for each PA. The first crop residue constraint supplies crop residue to meet the livestock demand within PA i and is in the form of:

\[ \sum_{i} \sum_{k} Y^{CR}_{ikl} L_{ikl} \geq LSTK^{CR}_{i} \]  

where: \( i, k, l \) and \( L_{ikl} \) have previously been defined; \( Y^{CR}_{ikl} \) is the crop residue yield of crop activity (1) with conservation-tillage
practices (k) in PA (i); and \( LSTK_{i}^{CR} \) is the quantity of crop residue required by livestock in PA (i).

The second constraint which supplies crop residue to power plants is in the form of:

\[
\sum_{k} \sum_{l} y_{ijl}^{CR} L_{ikl}^{CR} - \sum_{n} Q_{in}^{CR} > 0 \tag{5}
\]

where: \( i, k, l, y_{ijl}^{CR} \) and \( L_{ikl}^{CR} \) have been previously defined; \( z \) is the number of power plants in PA (i); and \( Q_{in}^{CR} \) is the quantity of crop residue used by these power plants.

As crop residue is removed from the land, nitrogen must be added. To account for this, an additional constraint for each PA of the form:

\[
\sum_{k} \sum_{l} N_{ikl}^{CR} L_{ikl}^{CR} - N_{BCR} > 0 \tag{6}
\]

where \( i, k, l, \) and \( L_{ikl}^{CR} \) have been previously defined; \( N_{ikl}^{CR} \) is the added quantity of nitrogen for crop residue activity (1) with conservation-tillage practice (k) in PA (i) (pounds per acre) and \( N_{BCR} \) is the quantity of additional commercial nitrogen purchased in (pounds). The above constraint acts as a marketplace for the supply and demand of commercial fertilizers required for maintaining future crop productivity.

**Constraints at the state level**

There are three state-wide constraints in the model. Two of them, nitrogen used for crop production and soil lost through production of crops and crop residues, correspond to the agricultural sectors of the model. The third constraint limits the quantity of Iowa and Wyoming coal available to Iowa power plants to the 1975 level of use.
The nitrogen fertilizer transfer constraint acts as a marketplace for the supply and demand of commercial fertilizers used for the production of crops. For the state, the general form of the nitrogen constraint is:

\[ - \sum_{i,k,l} N_{ikl} L_{ikl} - \sum_{i,k,l} N_{ikl} L_{ikl}^{CR} + Q_{i}^{MB} \geq 0 \]  

(7)

where: \( i, k, l, L_{ikl}, L_{ikl}^{CR}, \) and \( A_{i}^{MB} \) have been previously defined; and \( N_{ikl} \) is in the quantity of commercial nitrogen for crop activity (1) with conservation-tillage practice (k) in PA (i) (pound per acre).

The last set of state-wide constraints limits the quantities of Iowa and Wyoming coal to the 1975 level or use. Thus, the form of this constraint is:

\[ \sum_{q=1,2,...,19} C_{pq} < Q_{p}^{C} \]  

(8)

where \( q=1,2,...,19 \) for the number of power plants in the model; \( p \) is the coal type; \( C_{pq} \) is the quantity of type (p) coal used by power plant (q); and \( Q_{p}^{C} \) is the maximum amount of (p) type coal available to Iowa's utility power plants.

**Constraints at the power plant level**

There are two sets of constraints for each power plant represented in the model. These constraints require the power plants to meet the minimum 1975 sulfur dioxide (SO\(_2\)) requirements (Appendix A) and to consume a given amount of fuel expressed in BTU's.\(^1\)

\(^1\)British thermal units.
The amount of BTU's to be replaced by crop residues is a percentage of the amount of BTU's supplied by coal. If a plant uses 3 million BTU's in a year and 2 million BTU's are derived from coal, then the model will require, under a 1975 coal replacement scenario, the plant to use 2 million BTU's of fuel with a mix of coal and residues.

Activities

For the purpose of this report, activities are divided into two sections: agriculture and power plant activities. In addition, the agriculture sector is divided into crop production, crop production and crop residue production, crop sell, nitrogen purchase, and energy purchase activities.

Agricultural activities

Crop production activities: The crop production variables or activities simulate rotations producing corn grain, corn silage, legume and nonlegume hay, oats, sorghum grain, soybeans, and wheat. The crop production activities represent crop management systems incorporating rotations of one to four crops. Each rotation is defined for four conservation methods: straight-row, strip cropping, contour, and terrace. Each conservation method is associated with three tillage practices: conventional tillage, residue management, and reduced tillage. Each of these combinations is defined on the land class to which they would apply. Thus, each rotation combined with specific conservation-tillage practice define a unique crop management system.
Coefficients defined for each activity include the cost of production, the land used (one acre), the quantity of nitrogen required, the yield adjusted for conservation-tillage practice, the energy by type required, and the average number of tons of soil leaving the field during a one-year period.

Gross soil loss for the major Land Resource Areas in Iowa is determined using the Universal Soil Loss Equation developed by Wischmeier and Smith [1965]. These soil loss data are then weighted to the producing areas and attached to the appropriate crop management system.

Crop yields are estimated using 1970 to 1975 average county yields [Iowa Crop and Livestock Reporting Service, 1970-1976]. These yields are then weighted by average production; thus providing the PA yields. These yields are adjusted for land classes and conservation-tillage practices, with the exception of hay yields, the yields are adjusted for land class and conservation tillage practice. Hay yields are derived from the 1974 Agricultural Census [Bureau of Census, 1977]. There are four energy types used in the model: diesel, natural gas, liquid petroleum gas, and electricity. For each type of energy and endogenous crop, energy requirements are determined from data estimated by the Economic Research Service [1976]. These data are then weighted into the rotations.

The commercial nitrogen fertilizer coefficients are derived from a combination of sources. Total Iowa and county 1974 acreage by crop and that portion of land that was fertilized by crop is derived from the 1974 Agricultural Census [Bureau of Census, 1977]. The 1974 state proportion of nitrogen, (N_P) phosphorous (P_P), and potassium (K_P) per
acre is determined from Energy and U.S. Agriculture [Economic Research Service, 1976]. For further details see Appendix B.

The objective function is derived in part from the Firm Enterprise Data System (FEDS) [Economic Research Service, 1976a]. Costs are based on 1975 cost data. Where FEDS budgets are not available, the Iowa State's Cooperative Extension Services budgets [1976] are used. These crops are then adjusted for land class and conservation-tillage practice and incorporated into the rotations.

**Crop production and crop residue production activities:** These sets of activities consist of the same rotations as in the crop production activities. All five land classes are represented; however, only four conservation-tillage practices are included because residue is removed and the residue left and reduced tillage practices are no longer viable production methods. Coefficients included within these activities are the same as in the crop production activities with several additional coefficients. These additional coefficients include coefficients for the additional nitrogen required when residues are removed, coefficients estimating crop residue yields, and coefficients for the available crop residue land.

Crop residue yields are determined for four different crops: corn, sorghum, soybeans, and wheat. Any rotation having one or more of these crops has a crop residue yield defined. This crop residue yield is a function of the crop yield and a crop residue factor. The crop yield is determined from the crop production activities and the crop residue factor is assumed from Alrich, Inman, and Ernest [1976]. (See Table 6).
For example, assuming 100 bushels of corn per acre and 56 pounds per bushel, it can be shown that the estimated crop residue is 3.08 tons per acre.¹

Costs attributed to these activities include not only the costs of crop production incurred but also the costs inherent in the removal of residue. These costs are further discussed in Chapter III. They include the costs of replacing the nutrients lost and the costs of harvesting. These costs are then added to the cost of producing the crop rotation. Thus, the crop residue and crop production activities objective function includes the cost of producing the crop, the discounted value of phosphorous and potassium, and the cost of harvesting. No cost is assumed for on-farm-storage.

Energy coefficients from the crop production activities are adjusted for the crop residue and crop production activities. Additional energy used for P and K nutrient replacement are determined from Appendix C. Additional harvesting consumes 0.8 gallons of diesel fuel per ton of crop residue, 0.5 gallons for actual harvesting and 0.3 gallons for moving the stacks from the field to on-farm-storage [Iowa State Cooperative Extension Service, 1976].

\[
\begin{align*}
3.08 &= \frac{100 \text{ bushels}}{\text{acre}} \times 56 \frac{\text{pounds}}{\text{bushels}} \times \frac{1}{2000} \frac{\text{tons}}{\text{lb}} \\
1.1 &= \frac{\text{tons of residue}}{\text{tons of crop}}
\end{align*}
\]
Power plant activities: The activities incorporated in the utility sector of the model include only fuel supplies for each of the power plants identified in the model including power plants located in Ames, Bettendorf, Boone, Burlington, Cedar Rapids, Clinton, Council Bluffs, Creston, Des Moines, Dubuque, Eddyville, Humboldt, Lansing, Marshalltown, Muscatine, Pella, Salix, Spencer, and Waterloo. The plants at Montpelier and Cedar Falls were assumed to be located in the same residue demand areas as Muscatine and Waterloo, respectively. They are, therefore, combined in the study. In addition, the three power plants located at Cedar Rapids are combined. Thus, for each of the forementioned power plant locations, seven coal activities (coal originating in Wyoming, Iowa, Illinois, and Kentucky plus washed coal activities coals from Iowa, Illinois, and Kentucky) and a crop residue activity are defined.

The power plant's objective function for the coal types includes the cost of transporting and handling the coal as well as the at-the-mine price of coal. Transportation costs are derived from Baumel, Drinka, and Miller [1978]. Handling costs are estimated to be 1.30 dollars per ton. The 1975 cost of coal is determined from Division of Fuels Data and Division of Coal [1976].

Coefficients derived within the coal activities include BTU and sulfur content of the coal. The values assumed in this study are shown in Table 9.

1Personal interview with Craig O'Riley, Iowa State University, September 1977.
Table 9. Coal characteristics by coal type

<table>
<thead>
<tr>
<th>Type of Coal</th>
<th>Heating Value (MMBTU per ton)\textsuperscript{a}</th>
<th>Sulfur Dioxide (pounds per ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illinois</td>
<td>22.10</td>
<td>100.0</td>
</tr>
<tr>
<td>Illinois Washed</td>
<td>25.01</td>
<td>80.0</td>
</tr>
<tr>
<td>Iowa</td>
<td>23.402</td>
<td>293.2</td>
</tr>
<tr>
<td>Iowa Washed</td>
<td>24.40</td>
<td>196.4</td>
</tr>
<tr>
<td>Kentucky</td>
<td>23.98</td>
<td>132.0</td>
</tr>
<tr>
<td>Kentucky Washed</td>
<td>24.68</td>
<td>108.0</td>
</tr>
<tr>
<td>Wyoming</td>
<td>19.2</td>
<td>16.0</td>
</tr>
</tbody>
</table>

Sources: [Anonymous, 1976 and Division of Fuels Data and Division of Coal, 1976].

\textsuperscript{a} Million British thermal units per ton of coal.

The crop residue transfer activity for each power plant transfers residues from the agricultural sector to the utility sector. The objective function's value for these activities includes the estimated costs of transporting and processing the residues. These costs are further explained in Chapter III. The BTU content of the residues is assumed to be 13 MMBTU\textsuperscript{1} per ton with the sulfur content being fixed at 0 percent.

\textsuperscript{1} Million British thermal units.
III. COSTS OF CROP RESIDUES

The purpose of this chapter is to evaluate the costs of using the residues as a source of energy for providing steam to be used as an input to electricity production. The costs of crop residue are divided into three stages: 1) on-the-farm costs, 2) transportation costs, and 3) processing costs. The on-the-farm stage includes agronomic and harvesting costs. The transportation stage accounts for costs of moving the residues from the farm to the power plant. Finally, the processing stage includes the costs required to size the residues into a usable fuel feedstock in existing boilers and the cost of boiler design adjustments.

On-The-Farm Costs

Agronomic

Increased soil erosion, lost nutrients, reduced soil organic matter, and decreased moisture-holding capacity of the soil are possible results of crop residue removal. These effects may impose short- and long-run costs when the residue is removed from the soil. Recent studies indicate that some of these costs may not be factors in the farmer's decision-making framework. For a successful analysis of costs incurred because of the removal of crop residues, however, both primary and indirect costs must be considered.
Organic matter: Organic matter plays several roles. Organic matter serves as a source of nutrients, food for soil organisms, and as a soil conditioner. It acts as a general amendment and is a desirable soil constituent. In addition, it promotes granulation of soil particles and effects the rate of water infiltration [Mariakulandai and Manickan, 1975]. The Corn Belt is characterized by a mineral soil with a good supply of bases and large areas of siltloams containing 20 to 30 percent clay. These soils are easily tilled even with little or no organic matter.

Several studies have been conducted which show the agronomic effect of residue removal. In a 13-year study of continuous corn, Marachan, Moldenhauer, and Larson [1972] obtained ambiguous results. In the early part of their study they experienced lower yields with the removal of crop residues. In the latter part of their study, they found that with additional phosphorous, yields of continuous corn with crop residues and those without residues were similar. Adams, Morris, and Dawson [1970] found that the removal of stalks had no effect on yields for continuous corn with and without a cover crop and for corn grown in rotation. Triplett and Mannering [1977] conclude that non-legume crop residues seem to have little value except in controlling erosion. Bauer [1942] actually found that adding residues had either no effect or a slightly depressing effect on yields. According to Shrader [1977], in soils such as those which characterize the Corn Belt, there is no relationship between organic matter and yields as long as adequate fertilizer is present. Therefore, we assumed no penalty or other costs are incurred because of reduced organic matter in the soil.
Nutrients: Substantial costs are incurred because of the loss of fertilizer when residues are removed. Additional amounts of the major plant nutrients (nitrogen, phosphorous, and potassium) have to be applied to maintain yields. The estimated amounts of these nutrients removed are presented in Table 10. In addition to these major nutrients, small amounts of other nutrients are also removed while crop residue removal may cause a deficiency to occur with respect to these other nutrients. This study does not include the costs incorporated with micronutrient removal.

According to Mariakulandai and Manickan [1975], there are five sources of nitrogen -- mineral deposits, addition through rainfall, soil organic matter, nitrogen fixing organism activity, and industrial. Only a small amount (4 to 6 pounds per acre per year) of nitrogen is added through rainfall. The main "natural" source of nitrogen is the soil organic matter. The quantity of this source depends on the quality and quantity of organic matter in the soil. Nitrogen is lost through many methods. It is lost by removing the crop, by grazing animals, through leaching or drainage (only in nitrate form), by erosion, and by denitrification occurring only under abnormal conditions [Mariakulundia and Manickan, 1975].

Phosphorous is required for the formation of phospholipids, nucleo proteins, nucleic acid, adenosine diphosphates, pyridine nucleotides, and the prosthetic group of enzymes. It is required for energy transfer within the plant and is essential for photosynthesis to take place. Losses of this important element can occur through crop removal, animal grazing, and erosion.
Table 10. Amount of nutrients removed with removal of crop residue

<table>
<thead>
<tr>
<th>Crop Residue</th>
<th>Crop Yield</th>
<th>Residue Yield</th>
<th>Nitrogen</th>
<th>P$_2$O$_5$</th>
<th>K$_2$O</th>
<th>Calcium</th>
<th>Magnesium</th>
<th>Sulfur</th>
<th>Copper</th>
<th>Manganese</th>
<th>Zinc</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>bushel/acre</td>
<td>tons/acre</td>
<td>(lbs. per residue yield)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barley Straw</td>
<td>40</td>
<td>1</td>
<td>15</td>
<td>5</td>
<td>30</td>
<td>8</td>
<td>2</td>
<td>4</td>
<td>0.01</td>
<td>0.32</td>
<td>0.05</td>
</tr>
<tr>
<td>Corn Stover</td>
<td>150</td>
<td>4.5</td>
<td>100</td>
<td>37</td>
<td>145</td>
<td>26</td>
<td>20</td>
<td>14</td>
<td>0.05</td>
<td>1.50</td>
<td>0.30</td>
</tr>
<tr>
<td>Oat Straw</td>
<td>80</td>
<td>2</td>
<td>25</td>
<td>15</td>
<td>80</td>
<td>8</td>
<td>8</td>
<td>9</td>
<td>0.03</td>
<td>--</td>
<td>0.29</td>
</tr>
<tr>
<td>Rice Straw</td>
<td>80</td>
<td>2.5</td>
<td>30</td>
<td>10</td>
<td>70</td>
<td>9</td>
<td>5</td>
<td>--</td>
<td>--</td>
<td>1.58</td>
<td>--</td>
</tr>
<tr>
<td>Rye Straw</td>
<td>30</td>
<td>1.5</td>
<td>15</td>
<td>8</td>
<td>25</td>
<td>8</td>
<td>2</td>
<td>3</td>
<td>0.01</td>
<td>0.14</td>
<td>0.07</td>
</tr>
<tr>
<td>Sorghum Stover</td>
<td>60</td>
<td>3</td>
<td>65</td>
<td>20</td>
<td>95</td>
<td>29</td>
<td>18</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Wheat Straw</td>
<td>40</td>
<td>1.5</td>
<td>20</td>
<td>5</td>
<td>35</td>
<td>6</td>
<td>3</td>
<td>5</td>
<td>0.01</td>
<td>0.16</td>
<td>0.05</td>
</tr>
</tbody>
</table>

SOURCE: [Eakin, 1976].
The effect of removing these nutrients through crop residue removal is not fully understood. Triplett and Mannering [1976] state that removal of nonlegume crop residues seems to have little value except in controlling erosion. This finding is backed by Bauer [1942] who in his studies found that nonlegume residues when added alone had either a slightly depressing effect or no effect on crop yields. Finally, they conclude that growth of a crop on a "short-term basis is insensitive to the amount of residue left if that residue is buried by plowing and it is not important for nitrogen nutrition of the crop." In addition, mulch cover may be detrimental or of no importance for satisfactory crop production. The amount of mulch necessary is determined by soil characteristics, climatic regime, tillage practices, and time of the year.

Willard [1959] found that on high clay content soils, soil structures deteriorated, pore space decreased, and crop yields declined with intensive cropping. In addition, the decline in yields was not corrected by adding fertilizer. Neither removing nor leaving crop residues in the field had any impact on the yield.

Adams, Morris, and Dawson [1970] found that removal of stalks from the land had no effect on yield. In this study, they examined continuous corn with a rye or vetch cover crops, corn in rotation, and continuous corn with no cover crop.

Morachan, Moldenhauer, and Larson [1972] found varied results in their 13-year study when examining the effects of increasing amounts of various residue types on continuous corn. During the initial years, a
continuous corn crop with all of the residues removed experienced lower yields than those with residues. However, they speculate that this was probably caused by a slight phosphorous deficiency. In the latter stages of the experiment, yields of continuous corn with no crop residues were as high as those with residues. They also found that adding cornstalks significantly depressed yields (Figure 4). However, four years after the residue treatments were discontinued, corn yields were higher on the high residue plots compared to the lower residue plots. This increased yield, they speculated, was due to a higher nutrient state, since no fertilizer was applied.

Because of the long-run implications of crop residue removal, this study assumes that the major nutrients -- phosphorous, potassium, and nitrogen must be replaced if removed. When crop residues are incorporated into the soil, not all of the nutrients become available to the following crop. The residues decay gradually over a period as long as 20 years, releasing only a fraction of the nutrients in any year. Indeed, some of the nutrients are leached or lost through bacterial action and never become available to succeeding crops. The fertilizer value of crop residues, therefore, is calculated as the discounted present value of the nutrients.

A decay schedule giving the amounts of nutrients mineralized in each year is used to estimate the discounted present value of the flow of nutrients. Broadbent [1971], in a review of the literature on rates of mineralization or organic nitrogen present a range of rates from less

---

1 The value of trace elements lost due to residue removal is assumed to be zero.
Figure 4. The effect of crop residue additions on corn grain yields, average 1963-1966

SOURCE: [Morachan, Moldenhauer, and Larson, 1972]
than 1 to 10 percent. We assumed that 5 percent of the remaining nitrogen becomes available in each year following incorporation. The same rate of decay is assumed for phosphorous.¹ Potassium, however, is not discounted because it is readily washed out of crop residues and becomes available to the succeeding crop.² The discounted present value of the nutrients removed is given in Table 11 by crop.

Table 11. Discounted present value of nutrients per ton of crop residue removed by crop

<table>
<thead>
<tr>
<th>Crop</th>
<th>Value of nutrients for:</th>
<th>Total value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nitrogen</td>
<td>Phosphorous</td>
</tr>
<tr>
<td>----------</td>
<td>----------</td>
<td>-------------</td>
</tr>
<tr>
<td>Corn</td>
<td>1.39</td>
<td>0.32</td>
</tr>
<tr>
<td>Sorghum</td>
<td>1.35</td>
<td>0.24</td>
</tr>
<tr>
<td>Soybeans</td>
<td>2.88</td>
<td>0.38</td>
</tr>
<tr>
<td>Wheat</td>
<td>0.76</td>
<td>0.10</td>
</tr>
</tbody>
</table>

¹Present value calculated in 1975 dollars using a 10 percent discount rate and prices per pound of 0.18, 0.26, and 0.10 dollars per pound of nitrogen, phosphorous, and potassium, respectively.

Soil erosion: Conflicting opinions prevail on the effectiveness of crop residues in controlling soil erosion. Mannering, et al. [1968] found that the return of large amounts of crop residue is not as effective in reducing soil erosion as is the inclusion of a meadow crop in the rotation. Shrader [1975] states that vegetation acts to decrease

¹Personal communication with T. Nakashima, Department of Land, Air and Water Resources, University of California, Davis, Jan. 24, 1978.

²Personal communication with W. D. Shrader, Department of Agronomy, Iowa State University, August 1977.
soil erosion by protecting the surface from rain drop impact. In addition, vegetative cover decreases the amount of rain that reaches the soil and prevents surface sealing [Shrader, 1975].

There is a methodological difficulty in estimating the value of crop residues for erosion control. Even if the amount of soil per acre lost annually due to residue removal could be quantified, it is not apparent how this loss should be valued. Thus, it is assumed that the value of the soil lost when residue is used is equal to the agricultural revenues foregone when the base solution's level is maintained.

The cost is estimated from the regional linear programming model described in Chapter II. The model is used to select the optimal pattern of production in Iowa, including rotations and conservation-tillage practices for various levels of crop residue collection for energy conversion. Alternative solutions of the model are obtained with soil loss unconstrained and constrained to the level of soil loss that occurs without crop residue collection. The lower level is obtained by forcing in different rotations and conservation-tillage practices to satisfy the soil loss constraint. This analysis is conducted by comparing the results, presented in Chapter IV, of the second scenario to those of the Base Run. For additional information, see Appendix D.

**Harvesting**

A large number of studies have been made of the costs of harvesting plant materials using a variety of harvesting systems. Five basic packaging systems are identified: 1) small rectangular bales, 2) cubing, 3) large round bales, 4) large rectangular bales, and 5) stacks.
Harvesting small rectangular bales requires many machine operations (such as mowing, raking, and baling), and a significantly greater amount of labor than the other systems considered. Although it is recognized that equipment which reduces the labor input is available, this equipment is costly and not widely used in Iowa.

Cubing of cornstalks is presently in the development stage and no cost estimates are available, but California alfalfa hay cubing information is available [Dobie, Parsons, and Curley 1976]. This study found that the initial investment in cubing equipment is three or four times greater than investing in small rectangular baling equipment. At an output of 10,000 tons per year, cubing costs are approximately $4 per ton higher than the cost of small rectangular bales. A portion of this high cost can be justified due to the ease of transporting and handling cubes. But, the size of operations required, the need for a storage facility, and the higher cost practically eliminates cubing of Iowa's crop residues.

A large rectangular baler is now marketed that forms 4x8x4.5-foot bales. The advantages of a bale this size is that it will easily fit standard truck beds without overhang. Flat-bed trucks now in use could be used for hauling this size of bale without the need for specialized equipment. In addition, oversized load permits would not be necessary. There are several apparent disadvantages to square bales including: 1) they must be stored either indoors or in stacks covered with plastic because the square shape does not provide any weather protection, 2) they must be loaded onto trucks or trailers by either forklifts or tractors
equipped with front-end loaders and grapple-forks, 3) they are not widely used in Iowa, and 4) they are costly (8.28 to 10.18 dollars per ton). The higher cost is due to the large initial investment for the bailer. It is concluded, therefore, that a large square bale system is not feasible at this time.

Many Iowa farmers have access to a large round baler and they are popular for hay harvesting. Only one-half of the large baler owners in Iowa use their machine for cornstalk harvesting (Herr, 1977). Disadvantages in baling cornstalks into large round bales include: 1) cornstalks must be shredded and raked before baling, 2) the condition of the stover is more critical for baling than for stacking, and 3) bales tend to expand and break the twine during storage. Herr [1977] concludes that large bales do not work as well as stackers for packaging corn stover. Thus, while the large round bales are economically feasible, it is believed that the drawbacks previously mentioned will probably keep them from being used in the harvesting of crop residues.

By using large stackers, the crop residue can be harvested in one trip across the field and then the stack is moved to the roadside to await transportation to the powerplant. The advantages of stacks include: 1) labor and time savings easily offset the higher initial investment, 2) stacks are the most economical system to use under conditions of high output (1,000 tons or more annually), 3) stacks, because of their shape, can be stored outdoors and not deteriorate, and 4) truck-mounted and trailer stack movers have been developed to facilitate transportation. Thus, large stacks appear to be the best system for harvesting crop residue.
A wide variety of estimates of hay and forage harvesting costs are available but few have been estimated for crop residues. Some comparable estimates for hay and forage harvesting costs using a stack harvester and a stack mover are given in Table 12. The costs in Table 12 assume that windrowing would not be necessary and that an annual output of 1,000 tons per stack harvester would result. Most sources indicate that the harvesting costs per ton show economies of scale with annual outputs of less than 1,000 tons per year but costs decline slowly at greater levels of output [Buchele, 1977; Herr, 1977; Ayres, 1975]. Because six-ton stacks are easier to transport, we assume these are used even though they are most costly. Harvesting costs are assumed to be 7.27 dollars per ton which is an average of the values given in Table 12 for the six-ton stack harvesting system.

Transportation Costs

Transportation costs are a small but important portion of total costs. These costs are an increasing function of transportation distances. There are two components in developing the transportation costs for delivering crop residue to the power plant from the farm. The first objective is to determine the cost per ton-mile of material; the second is to estimate the average distance that crop residue must be transported.

Formulation of transportation costs

Since determining that harvesting of crop residue would be done through formation of 6-ton stacks, it is necessary to estimate the cost
Table 12. Costs of stack harvesting forages assuming an annual output of 1000 tons

<table>
<thead>
<tr>
<th>Source</th>
<th>Cost in Current Dollars</th>
<th>Cost in 1975 Dollars&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Three Ton System</td>
<td>Six Ton System</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Three Ton System</td>
</tr>
<tr>
<td></td>
<td>(dollars per ton)</td>
<td></td>
</tr>
<tr>
<td>Buchele&lt;sup&gt;b&lt;/sup&gt;</td>
<td>N.A.</td>
<td>7.65</td>
</tr>
<tr>
<td>Herr&lt;sup&gt;c&lt;/sup&gt;</td>
<td>4.46</td>
<td>N.A.</td>
</tr>
<tr>
<td>Successful Farming</td>
<td>7.19</td>
<td>7.29</td>
</tr>
<tr>
<td>Ayres&lt;sup&gt;d&lt;/sup&gt;</td>
<td>6.50</td>
<td>7.28</td>
</tr>
<tr>
<td>Edwards &amp; Stoneberg&lt;sup&gt;f&lt;/sup&gt;</td>
<td>6.73</td>
<td>N.A.</td>
</tr>
</tbody>
</table>

<sup>a</sup>Costs converted to 1975 dollars using cost index "Farm Production Items, Interest, Taxes, and Wage Rates" [Crop Reporting Board, 1975, 1977].

<sup>b</sup>Personal communication with Dr. Wesley F. Buchele, Department of Agricultural Engineering, Iowa State University, Ames, Iowa. The estimate is for a 5 1/2 ton system rather than a 6 ton system.

<sup>c</sup>[Herr, 1977].

<sup>d</sup>Costs for implements are from [Eftink and Rider, 1977]. Method for calculating harvesting costs followed the procedure developed by [Ayres, 1976].
of a mode of transportation capable of handling these large stacks. The transportation equipment assumed to be used includes a truck with a mounted stack-mover towing a trailer-mounted stack-mover. This transportation system is capable of delivering 2 stacks or 12 tons per trip. To determine costs, three cost components are estimated. These categories include annual variable costs ($C_V$) which are associated with distance, annual fixed costs ($C_F$) and annual transfer costs ($C_{TR}$) which are a function of the cost of loading and unloading the truck and trailer. Total annual costs ($C_T$) therefore, can be represented by

$$C_T = C_F + C_V M + C_{TR}$$

where $M$ is the total miles per year.

**Variable costs:** Variable costs include fuel, oil and oil filters, tires, and driver's wages. Fuel cost is determined by dividing the 1975 per gallon cost of diesel estimated at $0.49 per gallon [Agricultural Statistics, 1976] by the number of miles per gallon (5.5) [Eldridge, 1977]. Oil costs are derived by dividing the cost per oil change over the number of miles per change. It is assumed that the cost per change is $11.84 and the oil is changed every 4,500 miles. Driver's per mile wage is determined by dividing the hourly wage by expected number of miles per hour. It is assumed the driver's hourly wage will be $5.47 including fringe benefits [Eldridge, 1977]. Per mile tire cost is calculated by dividing the tire cost times the number of tires on the vehicle by the average number of miles over which the tire will last. There are six tires on the truck at a new purchase
price of $738 per tire and four tires on the trailer at a cost of $100 per tire. It is assumed that the life expectancy of both types of tires is 80,000 miles.

The per mile variable cost $C_{VM}$, therefore is equal to:

$$
C_{VM} = \frac{.49}{5.5} = \frac{11.84}{4,500} + \frac{100(4)}{80,000} + \frac{5.47}{MPH}
$$

where MPH is determined from the speed-distance matrix (Table 13).

**Fixed costs:** Included in fixed costs are interest, depreciation-capital recovery, license fees, highway use taxes, overhead expense, and maintenance and repairs (Table 14). An annual interest of 9 percent is assumed for this analysis. In addition, no provision for the effects of income or corporate taxes are included.

Interest and depreciation costs are based on an average investment cost at an annual interest rate of 9 percent. An 8-year life expectancy for both the truck and trailer is assumed with the truck purchase price less tires being $16,488 and the purchase price for the trailer less tires is $6,216 [Hesston, 1977]. Salvage values for the truck and the trailer are $4,287 and $1,405, respectively.

Other fixed costs are the license fee, highway use tax, insurance cost, maintenance and repair cost and management and overhead costs. The license fee is estimated to be $275 per year and the highway use tax is $165 per year [United States Department of Commerce, 1978].

---

1 Personal interview with Firestone personnel, February 1978.

2 The truck has a 366-cubic-inch V-8 engine, a 5-speed transmission, a power pack, and a track-bed stack mover.
Table 13. Speed-distance matrix for crop residue transportation by truck

<table>
<thead>
<tr>
<th>Round Trip Distance (miles)</th>
<th>Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>14</td>
</tr>
<tr>
<td>1.00</td>
<td>18</td>
</tr>
<tr>
<td>1.50</td>
<td>21</td>
</tr>
<tr>
<td>2.00</td>
<td>25</td>
</tr>
<tr>
<td>3.00</td>
<td>32</td>
</tr>
<tr>
<td>4.00</td>
<td>34</td>
</tr>
<tr>
<td>10.00</td>
<td>40</td>
</tr>
<tr>
<td>15.00</td>
<td>42</td>
</tr>
<tr>
<td>20.00</td>
<td>45</td>
</tr>
<tr>
<td>30.00</td>
<td>46</td>
</tr>
<tr>
<td>50.00</td>
<td>47</td>
</tr>
<tr>
<td>100.00</td>
<td>48</td>
</tr>
<tr>
<td>150.00</td>
<td>49</td>
</tr>
<tr>
<td>200.00</td>
<td>51</td>
</tr>
<tr>
<td>250.00</td>
<td>52</td>
</tr>
<tr>
<td>300.00</td>
<td>53</td>
</tr>
<tr>
<td>350.00 and above</td>
<td>55</td>
</tr>
</tbody>
</table>

SOURCE: [Eldridge, 1977].

Insurance costs vary greatly with coverage. In this analysis, liability and collision are assumed at an annual cost of $624.56. Annual maintenance and repair costs is assumed to be 6.7 percent of the equipment's purchase price. Finally, management and overhead costs are assumed to be $3,189.47 for the truck-trailer combinations.

---

Table 14. Average cost per mile and per ton mile for hauling crop residue by round trip distance interval

<table>
<thead>
<tr>
<th>Round Trip Distance Interval (miles)</th>
<th>Cost$^a$ (dollars per mile)</th>
<th>Cost$^a$ (dollars per ton-mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>.5</td>
<td>15.97</td>
<td>1.33</td>
</tr>
<tr>
<td>1.0</td>
<td>8.24</td>
<td>0.69</td>
</tr>
<tr>
<td>1.5</td>
<td>5.64</td>
<td>0.47</td>
</tr>
<tr>
<td>2.0</td>
<td>4.30</td>
<td>0.36</td>
</tr>
<tr>
<td>3.0</td>
<td>2.95</td>
<td>0.25</td>
</tr>
<tr>
<td>4.0</td>
<td>2.30</td>
<td>0.19</td>
</tr>
<tr>
<td>10.0</td>
<td>1.12</td>
<td>0.09</td>
</tr>
<tr>
<td>15.0</td>
<td>0.85</td>
<td>0.07</td>
</tr>
<tr>
<td>20.0</td>
<td>0.71</td>
<td>0.06</td>
</tr>
<tr>
<td>30.0</td>
<td>0.58</td>
<td>0.05</td>
</tr>
<tr>
<td>50.0</td>
<td>0.47</td>
<td>0.04</td>
</tr>
<tr>
<td>100.0</td>
<td>0.39</td>
<td>0.03</td>
</tr>
</tbody>
</table>

$^a$Based on 1975 costs.

Transfer costs: Transfer costs are based on the assumption that the loading operation would take 30 minutes with unloading requiring 15 minutes. Transfer costs, then, are the costs of the driver's waiting time to load and unload, and are estimated by

$$C_{TR} = TWN$$  \hspace{1cm} (11)

where: $C_{TR}$ is previously defined; $N$ is the annual number of trips; $T$ is the transfer time in hours per trip; and $W$ is the driver's wage.

The number of trips per year is based on trip distance, speed,
transfer time, and the number of working days per year assumed to be 248. Equation (12) is used to estimate the number of trips per year.

\[ N = \frac{H}{(D/S) + T} \]  

(12)

where \( N \) and \( T \) have been defined previously; \( D \) is the round-trip expressed as miles per trip; \( S \) is the speed in miles per hour; and \( H \) is the total working hours per year of the vehicle.

The three components of annual cost are derived, summed, and divided by the estimated number of miles that the truck annually covers. An average cost per mile is determined (see Table 14). This is then converted to average cost per ton-mile by dividing by the payload of 12 tons per trip (see Table 14).

**Determining average round trip distance**

The average round trip distance depends upon the size and shape of the collection area which, in turn, depends on the total quantity of crop residues required by the power plant and those power plants nearby, the density of crop residues produced in the area, the demand for crop residues by competing uses and as livestock, and the proportion of farmers that would participate in the crop residue market.

This study assumes that 50 percent of the acres within a power plant demand market will be harvested 50 percent of the time. In addition, the study assumes an average density determined from 1970-1975 county yields along with the crop residue factors derived by the Alich, Inman, and Ernest [1976].
Shape of the collection area: Starr, Finn-Carlson, and Nachtsheim [1977] in their work concerning direct firing of crop residues assume a circular collection area with a radius (R). In most of the Midwest, however, the road system is a grid with roads running east and west, north and south. The loci of points on equal transportation distance from a power plant form a diamond-shaped area. This type of road system implies that the feasible transportation set for power plants can be described best by a series of straight lines rather than curves. Another assumption is that crop residue can occur at any point within the diamond. Thus, the diamond is assumed to be characterized by a homogeneous density.

With these two assumptions, we can determine an average hauling distance through integration. Assume a right quadrant [Figure 5]

![Figure 5](image)

Figure 5. A right quadrant of a hypothetical homogeneous collection area

with an equation $x + y = r_2$. The goal is to derive the average distance ($D$). Setting up the integrand, we find that

$$
\int_0^{r_2} \int_0^{r_2-x} Cdydx = 1
$$

(13)
where:

l is the probability of collecting within the area; and

C is the probability density function for a random selection from anywhere within the perimeter.

Solving for C, we find that

\[ C = \frac{2}{r_2^2} \]  

(14)

Now integrating to determine \( \bar{D} \), we find

\[ \bar{D} = \int_0^{r_2} \int_0^{r_2-x} (x + y) C \, dy \, dx \]  

(15)

and solving,

\[ \bar{D} = \frac{2}{3} r_2 \]  

(16)

where \( r \) is the perimeter distance.

Size of collection area: The size of the collection area is a function of \( \bar{D} \), the density, and demand for crop residues. The area of the diamond is \( 2r_2^2 \). Thus, to fulfill the demand for residues by the power plant, we have:

\[ \text{CR}_m^D = 2 r_2^2 d_c \]  

(17)

where \( r_2 \) has been previously defined; \( \text{CR}_m^D \) in the quantity of crop residues demanded by power plant (m); and \( d_c \) in the density of crop residues in county (c). Thus, since \( \text{CR}_m^D \) and \( d_c \) are known, \( r_2 \) can be solved for by:

\[ r_2 = \left( \frac{\text{CR}_m^D}{2 d_c} \right)^{.5} \]  

(18)
Once $r_2$ is known, $D$ can be derived substituting $r_2$ from equation (23) into equation (21). Then through interpolation of Table 13, we can find the average cost per ton-mile.

Crop Residue Processing Plant Costs

The costs of processing crop residue are estimated by engineering methods from hypothetical processing plants as no facilities exist that are designed and built to prepare crop residue for energy conversion. There is considerable leeway in how processing plants may be designed and therefore in possible costs. There is no way of knowing whether the design selected is optimal or even close to an optimum. The preconceptions of the researcher are necessarily heavily incorporated into the design.

The costs estimated here are all based on designs that envisage the continuous combustion of crop residue. The blending of crop residue with coals is then a viable sulfur oxide emission control strategy. The intermittent use of crop residue would probably lower processing and storage costs. However, crop residue would then be valued for its BTU value only, or for its BTU value and the variable costs of other sulfur emission control technologies employed. The continuous combustion of a blend of crop residue and coals that satisfy emission standards results in the shadow price of crop residue reflecting both the energy value of crop residue and the opportunity cost of having to use another pollution control alternative.
The flowline

The flowline of the hypothetical processing plants is based primarily on the design of the Ames Solid Waste Recovery System at Ames, Iowa. Other municipal solid waste treatment plants, the handling of forage crops, and the forest industry's processing of wood residues are all additional sources of insights into possible processing and storage methods for crop residue energy conversion.

The flowline, as shown in Figure 6, has four main elements: the tipping floor where the crop residue is received, the size reduction equipment (hog) which reduces the material to a homogeneously sized product, the storage facilities, and finally the boilers modified to permit the introduction of crop residue. Mechanical conveyors are used both in and out of the hog, and pneumatic conveyors are used between the storage bin and the boilers.

It is envisaged that crop residue is delivered to the processing plant by truck. The trucks delivering the crop residue are weighed and then their loads are dumped on an enclosed tipping floor. The size of the tipping floor is sufficient to hold one day's supply of crop residue. A front-end loader then pushes the residue onto a mechanical conveyor that feeds the hog.

A hog is a machine used in the forest industry to reduce hog fuel (waste wood and bark) used to feed a boiler. Shredders and forage harvesters are two alternative types of machines that could be used. The former is designed to accommodate such things as refrigerators and automobile crankshafts found in municipal solid waste
Figure 6. The flowline for a hypothetical processing plant.

- Tipping floor
- Storage Silos
- Pneumatic conveyor
- Boiler
- Steam
- Stack
- Ash
- Electricity

Figure 6. The flowline for a hypothetical processing plant.
and the latter for mobile operation on live fibers. The hogs are designed for a purpose most similar to that needed for crop residue processing plants.

From the hog, the crop residue is transported by mechanical conveyors to storage bunkers. Storage is necessary for a continuous supply or residue to the power plant. It is assumed that a storage capacity for a three day supply is necessary to accommodate long weekends.

An essential feature of storage systems used for municipal solid waste are the "live bottoms," which are necessary to prevent municipal solid waste from clogging outflow conveyors. A simpler and less costly system would work for crop residue. The storage bunkers are envisaged as cylindrical concrete silos.

From the storage bunkers, the residue is conveyed pneumatically to the boilers, moving from the storage bunkers to the pneumatic pipes through air lock feeders. The crop residue is driven through the pipe by the compressed air from blowers. This residue then enters the boilers above the main combustion area where the combustion of crop residue is used to produce electricity.¹

Estimated costs

Cost estimates in dollars per ton are made for a range of processing plant sizes. The size of the processing plant is determined by its output in tons per day. The main elements of the flow line are selected to accommodate the daily output and hours of operation per day. Plant

¹The experience at Ames has shown that small suspension boilers would need modifications in the grate system to accommodate municipal solid waste. These types of modifications are not incorporated in this portion of the study.
sizes are 100, 300, 600, 900, and 1,200 tons per day. In addition, the flow line is modified to estimate processing costs for three small scale processing plants of 50, 100, and 200 tons per day capacity. For these plants a simpler processing plant is assumed. A pneumatic conveyor is used between the hog and storage bins. It is assumed that the tipping floor is not enclosed so that buildings are required only for the hog and a small office. Many of the capital items such as landscaping are deleted from the estimates.

The traditional distinction between fixed and variable costs is used in classifying different types of costs. Variable costs are those which vary directly with the level of output of an established processing plant while fixed costs are independent of the level of output of an established plant. Five subclassifications are used for fixed costs: capital costs for the processing plant, capital costs for energy conversion, land costs, operating and maintenance costs, and labor costs. The first three fixed costs may be described as inevitable in that they represent the opportunity costs of capital invested. The last two are annual costs incurred in operating the processing plant but are independent of the level of output within the relevant range for which the processing plant would be operated.

The first step in estimating costs is the selection of the hog and associated equipment. The hog and space needed to store one day's supply of crop residues determine building size, site work and associated capital costs. Where possible, manufacturers were contacted and the figures they quoted incorporated. For a great many items, unit
costs are used. For example, the cost of mechanical conveyors is based on a unit cost in dollars per lineal foot. For others, cost assumptions were made on the basis of a single datum or suggestion made by engineers.

The three types of inevitable costs are given in Table 15. The capital costs for the processing plant are given in aggregations used by Funk and Morrioni. Land costs represent the value of land assumed to be required. The capital costs (energy conversion are the costs for the pneumatic conveying system and boiler modifications incurred at the Ames Power Plant in adapting to municipal solid waste.

The three categories of inevitable costs have different useful lives assumed for capital equipment. The processing equipment and buildings are assumed to have a life span of 20 years. The pneumatic systems are assumed to have a useful life of six years. Land has an infinite life span. Both types of capital are assumed to be operational at full capacity and have no use thereafter. Salvage value is assumed to equal dismantling costs. The costs for the three categories of inevitable costs are then annualized by multiplying by the appropriate capital recovery factor from Table 16. The result is the capital and land costs per year for the three inevitable costs shown in Table 17.

There are two categories of fixed costs that are not inevitable. Operating and maintenance costs are determined as a percentage of the capital costs in Table 17 according to the expenditure item. The costs of power used for lighting is also included. Labor costs are the annual

---

1 Personal interview at Henningson, Durham, and Richardson, Omaha, Nebraska, September 1977.
Table 15. Capital costs by plant size

<table>
<thead>
<tr>
<th>Plant size (tons per day)</th>
<th>50&lt;sup&gt;a&lt;/sup&gt;</th>
<th>100&lt;sup&gt;a&lt;/sup&gt;</th>
<th>100</th>
<th>200&lt;sup&gt;a&lt;/sup&gt;</th>
<th>300</th>
<th>600</th>
<th>600&lt;sup&gt;b&lt;/sup&gt;</th>
<th>900</th>
<th>900&lt;sup&gt;b&lt;/sup&gt;</th>
<th>1,200</th>
<th>1,200&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost (Processing)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sitework</td>
<td>14,974</td>
<td>16,242</td>
<td>127,360</td>
<td>18,312</td>
<td>152,928</td>
<td>164,292</td>
<td>164,228</td>
<td>173,388</td>
<td>172,452</td>
<td>180,540</td>
<td>179,648</td>
</tr>
<tr>
<td>Buildings &amp; Structures</td>
<td>69,500</td>
<td>69,500</td>
<td>188,110</td>
<td>111,000</td>
<td>413,425</td>
<td>755,240</td>
<td>749,640</td>
<td>1,140,805</td>
<td>1,052,000</td>
<td>1,547,925</td>
<td>1,463,610</td>
</tr>
<tr>
<td>Equipment</td>
<td>204,510</td>
<td>233,555</td>
<td>751,547</td>
<td>292,760</td>
<td>1,073,279</td>
<td>1,297,820</td>
<td>1,217,784</td>
<td>1,568,394</td>
<td>1,366,893</td>
<td>1,728,079</td>
<td>1,480,177</td>
</tr>
<tr>
<td>Rolling Steele</td>
<td>26,000</td>
<td>26,000</td>
<td>43,000</td>
<td>41,000</td>
<td>58,000</td>
<td>108,000</td>
<td>108,000</td>
<td>108,000</td>
<td>108,000</td>
<td>108,000</td>
<td>108,000</td>
</tr>
<tr>
<td>Engineering</td>
<td>5,344</td>
<td>63,682</td>
<td>249,107</td>
<td>86,868</td>
<td>372,883</td>
<td>507,775</td>
<td>486,631</td>
<td>661,880</td>
<td>597,573</td>
<td>777,940</td>
<td>698,879</td>
</tr>
<tr>
<td>Total</td>
<td>368,405</td>
<td>408,979</td>
<td>1,362,204</td>
<td>549,140</td>
<td>2,070,515</td>
<td>2,833,127</td>
<td>2,726,283</td>
<td>3,298,868</td>
<td>3,298,868</td>
<td>4,342,484</td>
<td>3,930,314</td>
</tr>
<tr>
<td>Land</td>
<td>2,000</td>
<td>2,000</td>
<td>2,000</td>
<td>2,000</td>
<td>3,000</td>
<td>4,000</td>
<td>4,000</td>
<td>5,000</td>
<td>5,000</td>
<td>6,000</td>
<td>6,000</td>
</tr>
</tbody>
</table>

<sup>a</sup>Modified flowtime, simple plant.

<sup>b</sup>Double shift plant.
Table 16. Capital recovery factors used to annualize inevitable costs

<table>
<thead>
<tr>
<th>Useful Life (years)</th>
<th>8%</th>
<th>10%</th>
<th>12%</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>.21632</td>
<td>.22961</td>
<td>.24323</td>
</tr>
<tr>
<td>20</td>
<td>.10185</td>
<td>.11746</td>
<td>.13388</td>
</tr>
<tr>
<td>∞</td>
<td>.08</td>
<td>.10</td>
<td>.12</td>
</tr>
</tbody>
</table>

SOURCE: [Smith, 1973].

salaries of individuals assumed employed in the processing plant. These two costs are added to the annualized inevitable costs to give total fixed costs per year as shown in Table 17. The total fixed costs per year are divided by annual production based on 248 operating days per year to give total fixed costs per ton shown in Table 18.

Variable costs are those directly associated with hogs and other equipment. The hogs selected have sufficient capacity to absorb a reasonable amount of downtime. Because of lumpiness in hog capacity, the proportion downtime assumed is not a smooth function of plant size. In general, a greater proportion of downtime is assumed for the smaller plants.

The costs of operating the front-end loaders and the energy required by the other equipment on an hourly basis is divided by the hourly output of the hog (rather than multiplied by the number of hours per day). Therefore, these costs are variable and are included in Table 18. In addition, Table 18 shows total processing and storage costs which is the sum of the fixed and variable costs. From the costs given it is apparent that there
Table 17: Annual Fixed Costs by plant size

<table>
<thead>
<tr>
<th>Item</th>
<th>Discount Rate</th>
<th>50%</th>
<th>100%</th>
<th>1000</th>
<th>2000</th>
<th>3000</th>
<th>6000</th>
<th>6000b</th>
<th>9000</th>
<th>9000b</th>
<th>12000</th>
<th>12000b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Costs (Processing)</td>
<td>8%</td>
<td>37,522</td>
<td>41,654</td>
<td>138,740</td>
<td>56,011</td>
<td>210,882</td>
<td>288,554</td>
<td>279,672</td>
<td>372,004</td>
<td>335,990</td>
<td>442,282</td>
<td>459,302</td>
</tr>
<tr>
<td></td>
<td>10%</td>
<td>43,273</td>
<td>48,039</td>
<td>160,004</td>
<td>64,596</td>
<td>243,203</td>
<td>332,779</td>
<td>320,229</td>
<td>429,019</td>
<td>387,485</td>
<td>510,068</td>
<td>561,655</td>
</tr>
<tr>
<td></td>
<td>12%</td>
<td>49,322</td>
<td>54,754</td>
<td>182,372</td>
<td>73,626</td>
<td>277,201</td>
<td>379,299</td>
<td>364,995</td>
<td>488,992</td>
<td>441,652</td>
<td>581,372</td>
<td>526,190</td>
</tr>
<tr>
<td>Capital Costs</td>
<td>8%</td>
<td>33,374</td>
<td>33,374</td>
<td>33,374</td>
<td>33,374</td>
<td>33,374</td>
<td>33,374</td>
<td>33,374</td>
<td>33,374</td>
<td>33,374</td>
<td>33,374</td>
<td>33,374</td>
</tr>
<tr>
<td></td>
<td>12%</td>
<td>37,526</td>
<td>37,526</td>
<td>37,526</td>
<td>37,526</td>
<td>37,526</td>
<td>37,526</td>
<td>37,526</td>
<td>37,526</td>
<td>37,526</td>
<td>37,526</td>
<td>37,526</td>
</tr>
<tr>
<td>Land</td>
<td>8%</td>
<td>160</td>
<td>160</td>
<td>160</td>
<td>160</td>
<td>240</td>
<td>320</td>
<td>320</td>
<td>400</td>
<td>400</td>
<td>400</td>
<td>480</td>
</tr>
<tr>
<td></td>
<td>10%</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>300</td>
<td>400</td>
<td>400</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>12%</td>
<td>240</td>
<td>240</td>
<td>240</td>
<td>240</td>
<td>360</td>
<td>480</td>
<td>480</td>
<td>600</td>
<td>600</td>
<td>600</td>
<td>720</td>
</tr>
<tr>
<td>Operating &amp; Maintenance</td>
<td>N.A.</td>
<td>21,831</td>
<td>23,429</td>
<td>52,714</td>
<td>26,718</td>
<td>77,943</td>
<td>101,862</td>
<td>97,150</td>
<td>125,593</td>
<td>113,037</td>
<td>152,311</td>
<td>194,639</td>
</tr>
<tr>
<td>Labour</td>
<td>N.A.</td>
<td>24,000</td>
<td>24,000</td>
<td>65,500</td>
<td>24,000</td>
<td>68,500</td>
<td>95,000</td>
<td>154,000</td>
<td>107,000</td>
<td>166,000</td>
<td>107,000</td>
<td>166,000</td>
</tr>
<tr>
<td>Total Fixed Costs</td>
<td>8%</td>
<td>116,887</td>
<td>122,617</td>
<td>290,488</td>
<td>140,263</td>
<td>390,939</td>
<td>519,110</td>
<td>562,516</td>
<td>638,371</td>
<td>648,801</td>
<td>735,447</td>
<td>794,795</td>
</tr>
<tr>
<td></td>
<td>10%</td>
<td>124,728</td>
<td>131,092</td>
<td>313,842</td>
<td>150,938</td>
<td>425,370</td>
<td>565,465</td>
<td>607,203</td>
<td>697,536</td>
<td>702,446</td>
<td>805,403</td>
<td>858,318</td>
</tr>
<tr>
<td></td>
<td>12%</td>
<td>132,919</td>
<td>139,949</td>
<td>338,352</td>
<td>162,110</td>
<td>461,530</td>
<td>614,107</td>
<td>654,151</td>
<td>759,711</td>
<td>758,815</td>
<td>878,929</td>
<td>925,075</td>
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</table>

- **Modified flowline.**
- **Double shift.**
- **Discount rate not applicable.**
Table 18. Total processing costs by plant size

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<th>Item</th>
<th>Discount Rate</th>
<th>50a</th>
<th>100a</th>
<th>100a</th>
<th>200a</th>
<th>300</th>
<th>600</th>
<th>600b</th>
<th>900</th>
<th>900b</th>
<th>1200</th>
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<td>8</td>
<td>9.43</td>
<td>4.94</td>
<td>11.71</td>
<td>2.83</td>
<td>5.25</td>
<td>3.49</td>
<td>3.78</td>
<td>2.86</td>
<td>2.91</td>
<td>2.47</td>
<td>2.67</td>
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<td></td>
<td>10</td>
<td>10.06</td>
<td>5.29</td>
<td>12.65</td>
<td>3.04</td>
<td>5.72</td>
<td>3.80</td>
<td>4.08</td>
<td>3.13</td>
<td>3.15</td>
<td>2.71</td>
<td>2.88</td>
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<td>12</td>
<td>10.72</td>
<td>5.64</td>
<td>13.64</td>
<td>3.27</td>
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<td>3.40</td>
<td>2.95</td>
<td>3.11</td>
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<td>Variable Costs</td>
<td>N.A.</td>
<td>1.44</td>
<td>1.04</td>
<td>1.14</td>
<td>1.06</td>
<td>0.93</td>
<td>0.83</td>
<td>0.96</td>
<td>0.80</td>
<td>0.89</td>
<td>0.78</td>
<td>0.85</td>
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<td>Total Costs</td>
<td>8</td>
<td>10.87</td>
<td>5.98</td>
<td>12.85</td>
<td>3.89</td>
<td>6.18</td>
<td>4.32</td>
<td>4.74</td>
<td>3.66</td>
<td>3.80</td>
<td>3.25</td>
<td>3.52</td>
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<tr>
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<td>10</td>
<td>11.50</td>
<td>6.33</td>
<td>13.79</td>
<td>4.10</td>
<td>6.65</td>
<td>4.63</td>
<td>5.04</td>
<td>3.93</td>
<td>4.04</td>
<td>3.49</td>
<td>3.73</td>
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<tr>
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<td>12</td>
<td>12.16</td>
<td>6.68</td>
<td>14.78</td>
<td>4.33</td>
<td>7.13</td>
<td>4.96</td>
<td>5.36</td>
<td>4.20</td>
<td>4.29</td>
<td>3.73</td>
<td>3.96</td>
</tr>
</tbody>
</table>

*Modified flow line.

*Double shift.

*Discount rate not applicable.
are considerable economies of scale. A more labor intensive system (using double shifts) is more attractive at larger scales of operation. Although these costs represent the best estimates based on data available, they remain largely conditional until a demonstration plant is designed and built.

An equation is estimated in the form:

$$\log C = B_0 + B_1 \log S$$  \hspace{1cm} (24)

where $S$ is the size of the plant; $C_x$ is the cost of power plant of size $x$; and $B_0$, $B_1$ are regression coefficients. The coefficients were estimated using the total costs presented in Table 18 assuming a 10 percent discount rate. The regression equation is:

$$\log C = 5.013 - .53264 \log S$$  \hspace{1cm} (25)

This equation is then used to determine the crop residue processing costs of plants between 100 and 1,200 tons per day. The cost of a 1,200 tons per day plant is assumed to hold for those plants greater than 1,200 tons per day.
IV. RESULTS

This chapter presents the results of the study. Included is a review of the scenarios examined, the changes in crops produced and resources used under each of the scenarios, and the impact of these scenarios on the returns to agricultural production.

Scenarios Examined

Under each of the scenarios (see Table 1) crop residues replace coal use by 0, 20, 40, and 60 percent of the energy supplied by coal.\footnote{Some power plants within the study area used oil and natural gas as a fuel source in 1975. It is assumed that the level of use of these fuels does not change.} Thus, for each option there are four different solutions.

The Base scenario is used as a comparison for all other options. It assumes energy prices remain at their 1975 level and that the sulfur emitted by the power plants is at the levels consistent with Iowa's sulfur emission regulations in effect in 1975. Production cost for both the crops and residues are estimated in 1975 dollars. The results of this alternative reflects the expected changes in production and resource use due to increased crop residue use.

The Soil Constrained scenario is identical to the Base scenario with the exception that total Iowa soil loss is restricted to the level indicated in the Base with no crop residues produced. Thus, changes in methods of producing crops, and the actual level of crops produced as well as changes in resources used due to the soil loss constraint is reflected in the solutions of this alternative.
The Doubled Energy Price scenario assumes that the 1975 energy prices for diesel, natural gas, liquid petroleum gas, and electricity are doubled. In addition, the at-the-mine 1975 coal price is doubled. This option, therefore, increases the costs of production crops, residues, transporting coal, and the actual costs of coal to the power plant. These costs tend to increase the costs of production of residues, but less than the increase in the costs of coal providing the energy balance is positive.

In the Double Coal and Energy Prices, coal as well as the other energy types have their prices doubled. This results in a higher cost of coal to the power plant than in the previous scenario as not only the mine cost is doubled but also the costs of transporting the coal to the mine and the costs of handling that coal at the plant are doubled. Thus, coal prices are most expensive in this option and should reflect a greater benefit from use of crop residues than in the other previous scenarios.

Finally, the Sulfur Constrained scenario examines the impacts of not only double coal and energy prices but also the impacts of presently proposed sulfur constraints (Appendix A). By enforcing the stricter constraints, a lower-in-sulfur coal mix must be used to meet these constraints.

Crop Production

The total value of crops sold exceeds three billion dollars in all alternatives examined (Table 19). The Soil Constrained scenario shows a small decrease in the gross value of crops marketed when 20 and 40 percent of BTU's are supplied as residues. At the 60 percent level, however, a decrease in crop value greater than a 1.2 percent occurs.
Table 19. Gross value of crops marketed and percentage changes between and within alternatives by scenario

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Gross value of crops marketed (million dollars)</th>
<th>Change from Base (percentage)</th>
<th>Change from no residues (percentage)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0^b</td>
<td>3,461.5</td>
<td>NA^c</td>
<td>NA</td>
</tr>
<tr>
<td>20</td>
<td>3,467.4</td>
<td>NA</td>
<td>0.17</td>
</tr>
<tr>
<td>40</td>
<td>3,475.1</td>
<td>NA</td>
<td>0.39</td>
</tr>
<tr>
<td>60</td>
<td>3,483.3</td>
<td>NA</td>
<td>0.63</td>
</tr>
<tr>
<td><strong>Soil Constrained:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0^b</td>
<td>3,461.5</td>
<td>No change</td>
<td>0.15</td>
</tr>
<tr>
<td>20</td>
<td>3,466.7</td>
<td>-0.02</td>
<td>0.15</td>
</tr>
<tr>
<td>40</td>
<td>3,473.8</td>
<td>-0.041</td>
<td>0.36</td>
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<tr>
<td>60</td>
<td>3,439.4</td>
<td>-1.26</td>
<td>-0.54</td>
</tr>
<tr>
<td><strong>Double Energy Prices:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0^b</td>
<td>3,399.9</td>
<td>-1.78</td>
<td>NA</td>
</tr>
<tr>
<td>20</td>
<td>3,404.6</td>
<td>-1.81</td>
<td>0.14</td>
</tr>
<tr>
<td>40</td>
<td>3,383.8</td>
<td>-2.63</td>
<td>-0.47</td>
</tr>
<tr>
<td>60</td>
<td>3,381.7</td>
<td>-2.92</td>
<td>-0.54</td>
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<tr>
<td><strong>Double Coal and Energy Prices:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0^b</td>
<td>3,399.9</td>
<td>-1.78</td>
<td>0.14</td>
</tr>
<tr>
<td>20</td>
<td>3,404.6</td>
<td>-1.81</td>
<td>-0.47</td>
</tr>
<tr>
<td>60</td>
<td>3,381.7</td>
<td>-2.92</td>
<td>-0.54</td>
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<tr>
<td><strong>Sulfur Constrained:</strong></td>
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<tr>
<td>0^b</td>
<td>3,399.9</td>
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<tr>
<td>60</td>
<td>3,381.7</td>
<td>-2.92</td>
<td>-0.54</td>
</tr>
</tbody>
</table>

^aChange that occurs within the scenario with 0 percent as Base.

^bPercentage BTU replacement of crop residue for coal.

^cNot applicable.
This is primarily due to a decrease in oil meals (soybeans) produced (Table 20). Under the Energy Price Increase and Sulfur Constrained scenarios these decreases range from 1.78 to 2.92 percent. Within the options, crop residue causes only, at the most, a 0.64 percent decrease in the gross value of crops produced.

Energy

Three types of activities consume energy—agriculture, transportation, and electrical generation. The agricultural sector consumes energy in producing crops and crop residues; and manufacturing fertilizers, pesticides, and herbicides. Transportation is defined in the model for both crop residues and coal. Each of these transfer activities require diesel fuel purchases. Finally, the amount of energy by fuel type (electricity and diesel) is quantified for crop residue processing and coal beneficiation.

For each sector, the amount of energy is determined. The amount of energy used in transporting fuel to the power plants is then summed to the energy used in the electrical generator sector. In addition, the energy used for producing additional fertilizers, harvesting the crop residues, transporting the residues to the power plant, and processing these residues is determined so that a crop residue energy balance can be illustrated.

The power plants included in the crop residue model consume a fixed amount (118 trillion BTU's) of coal in all options when no crop residues are consumed for electrical generation. This decreases to 94, 71, and 47 trillion BTU's for 20, 40, and 60 percent coal replacement. All of
<table>
<thead>
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<th>Scenario</th>
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<th></th>
<th></th>
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<td>Corn</td>
<td>Hay</td>
<td>Oats</td>
<td>Oilmeals</td>
<td>Sorghum</td>
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<td>Total</td>
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<td>(million</td>
<td>(million</td>
<td>(million</td>
<td>(million</td>
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<td>(million</td>
<td>Value</td>
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<td></td>
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<td>tons)</td>
<td>bushels)</td>
<td>bushels)</td>
<td>bushels)</td>
<td>dollars)</td>
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<td>2.9</td>
<td>2.0</td>
<td>3,483.3</td>
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<td><strong>Soil Constrained:</strong></td>
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</tr>
<tr>
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<td>67.0</td>
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<td>67.0</td>
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<td>67.1</td>
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</tr>
<tr>
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<td>8.1</td>
<td>67.0</td>
<td>124.0</td>
<td>1.7</td>
<td>1.9</td>
<td>3,398.2</td>
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<td>67.0</td>
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<td>1.7</td>
<td>2.0</td>
<td>3,404.6</td>
<td></td>
</tr>
<tr>
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<td>1,129.5</td>
<td>8.1</td>
<td>67.1</td>
<td>118.3</td>
<td>2.9</td>
<td>1.8</td>
<td>3,383.8</td>
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<tr>
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<td>8.1</td>
<td>67.2</td>
<td>115.8</td>
<td>2.9</td>
<td>1.8</td>
<td>3,381.7</td>
<td></td>
</tr>
<tr>
<td>Sulfur Constrained:</td>
<td>Corn (million bushels)</td>
<td>Hogs (million tons)</td>
<td>Oats (million tons)</td>
<td>Oilmeals (million bushels)</td>
<td>Sorghum (million bushels)</td>
<td>Wheat (million bushels)</td>
<td>Total Value (million dollars)</td>
<td></td>
</tr>
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<td>--------------------</td>
<td>---------------------------</td>
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<td>67.0</td>
<td>121.4</td>
<td>2.9</td>
<td>1.8</td>
<td>3,383.8</td>
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<tr>
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<td>67.0</td>
<td>121.4</td>
<td>2.9</td>
<td>1.8</td>
<td>3,404.6</td>
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<td>1.129.5</td>
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<td>8.1</td>
<td>67.0</td>
<td>115.8</td>
<td>2.9</td>
<td>1.8</td>
<td>3,381.7</td>
<td></td>
</tr>
</tbody>
</table>

Includes crops produced to meet exogenous livestock demands. They are constant throughout the alternatives and included in production data.

\(^{\text{a}}\) Percentage BTU replacement of crop residue for coal.
the other fuels vary somewhat, however, and the total changes in energy use do not vary significantly when comparing one scenario with another (Table 21). In examining the energy used when residues are used, however, the quantity of energy used in supplying the fuel is less than that quantity saved through coal replacement (Table 22).

**Power plant's energy consumption**

Coal consumption is based on the 1975 demands for BTU's consumed by the Iowa utilities. Five different coals came into solution under the five scenarios -- Iowa, Iowa-washed, Illinois, Illinois-washed, and Wyoming (Table 23). The Base and Soil Constrained scenarios have identical coal consumption patterns, so only the Base is represented in Table 23. As energy prices increase, the quantity of Illinois coal used decreases somewhat. The biggest change, however, occurs when sulfur is constrained to the proposed levels. Iowa coal quantities decrease as it is high in sulfur and low sulfur coal can be used only to meet the sulfur constraint; however, as the amount of crop residues increase so does the amount of Iowa coal used. In addition, under this same option, washed coals become important. Very little change occurs in the quantity of Wyoming coal used. At 0 and 20 percent, Wyoming coal consumed increases when compared to the Base under the Sulfur Constraint scenario. Use of Wyoming coal decreases from the Base at 40 and 60 percent residue demanded.

The average cost of the coal mix also is determined (Table 24). In all alternatives, as the percentage of residue used increases, the
Table 21. Energy use by scenario and type of energy excluding coal consumption

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Total energy used by type</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diesel</td>
<td>Natural Gas</td>
<td>Electricity</td>
<td>LPG</td>
</tr>
<tr>
<td></td>
<td>(million gallons)</td>
<td>(million cu. feet)</td>
<td>(million kwh)</td>
<td>(million gallons)</td>
</tr>
<tr>
<td>Base Run:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0(^a)</td>
<td>295.09</td>
<td>34,192.58</td>
<td>393.07</td>
<td>138.92</td>
</tr>
<tr>
<td>20</td>
<td>301.31</td>
<td>35,129.17</td>
<td>438.23</td>
<td>140.34</td>
</tr>
<tr>
<td>40</td>
<td>312.40</td>
<td>36,154.97</td>
<td>484.56</td>
<td>142.04</td>
</tr>
<tr>
<td>60</td>
<td>328.65</td>
<td>37,060.22</td>
<td>525.66</td>
<td>143.48</td>
</tr>
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</table>

| Soil Constraint:|                               |       |       |       |
|                 |                           |       |       |       |
| 0\(^a\)         | 295.09                    | 34,192.58 | 393.07 | 138.92 |
| 20              | 300.93                    | 35,107.89 | 437.94 | 140.30 |
| 40              | 312.10                    | 36,101.07 | 484.18 | 142.01 |
| 60              | 328.92                    | 36,979.65 | 525.35 | 143.60 |

| Double Energy Prices: |                               |       |       |       |
|                      |                           |       |       |       |
| 0\(^a\)             | 292.54                    | 31,144.13 | 363.52 | 128.13 |
| 20                  | 297.37                    | 32,125.11 | 409.13 | 129.65 |
| 40                  | 310.03                    | 33,196.04 | 456.05 | 131.51 |
| 60                  | 325.53                    | 34,089.33 | 496.86 | 132.97 |

| Double Coal and Energy Prices: |                               |       |       |       |
|                                |                           |       |       |       |
| 0\(^a\)                       | 291.94                    | 31,144.13 | 363.52 | 128.13 |
| 20                             | 296.85                    | 32,116.23 | 409.06 | 129.64 |
| 40                             | 309.85                    | 33,196.04 | 456.05 | 131.96 |
| 60                             | 325.44                    | 34,102.51 | 497.99 | 133.02 |

| Sulfur Constraint:            |                               |       |       |       |
|                               |                           |       |       |       |
| 0\(^a\)                       | 294.85                    | 31,144.13 | 368.20 | 128.13 |
| 20                             | 298.73                    | 32,116.22 | 409.12 | 129.64 |
| 40                             | 310.19                    | 33,196.04 | 456.13 | 131.96 |
| 60                             | 325.67                    | 34,102.51 | 497.99 | 133.07 |

\(^a\) Percentage BTU replacement of crop residue for coal.
Table 22. Total energy use by scenario and type of energy

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Coal</th>
<th>Diesel</th>
<th>Gas</th>
<th>Electricity</th>
<th>LPG</th>
<th>Total</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Natural</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(trillion BTU's)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Base Run:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0  (^a)</td>
<td>118</td>
<td>41.3</td>
<td>35.0</td>
<td>1.3</td>
<td>13.3</td>
<td>208.9</td>
</tr>
<tr>
<td>20</td>
<td>94</td>
<td>42.2</td>
<td>36.0</td>
<td>1.5</td>
<td>13.4</td>
<td>187.1</td>
</tr>
<tr>
<td>40</td>
<td>71</td>
<td>43.7</td>
<td>37.0</td>
<td>1.7</td>
<td>13.6</td>
<td>167.0</td>
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<td>1.8</td>
<td>13.7</td>
<td>146.4</td>
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<tr>
<td>0  (^a)</td>
<td>118</td>
<td>41.3</td>
<td>35.0</td>
<td>1.3</td>
<td>13.3</td>
<td>208.9</td>
</tr>
<tr>
<td>20</td>
<td>94</td>
<td>42.1</td>
<td>36.0</td>
<td>1.5</td>
<td>13.4</td>
<td>187.0</td>
</tr>
<tr>
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<td>71</td>
<td>43.7</td>
<td>37.0</td>
<td>1.7</td>
<td>13.6</td>
<td>167.0</td>
</tr>
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<td>60</td>
<td>47</td>
<td>46.0</td>
<td>37.9</td>
<td>1.8</td>
<td>13.7</td>
<td>146.4</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0  (^a)</td>
<td>118</td>
<td>41.0</td>
<td>31.9</td>
<td>1.2</td>
<td>12.2</td>
<td>204.3</td>
</tr>
<tr>
<td>20</td>
<td>94</td>
<td>41.6</td>
<td>32.9</td>
<td>1.4</td>
<td>12.4</td>
<td>182.3</td>
</tr>
<tr>
<td>40</td>
<td>71</td>
<td>43.4</td>
<td>34.0</td>
<td>1.6</td>
<td>12.6</td>
<td>162.6</td>
</tr>
<tr>
<td>60</td>
<td>47</td>
<td>45.6</td>
<td>34.9</td>
<td>1.7</td>
<td>12.7</td>
<td>141.9</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0  (^a)</td>
<td>118</td>
<td>40.8</td>
<td>31.9</td>
<td>1.2</td>
<td>12.2</td>
<td>204.3</td>
</tr>
<tr>
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<td>94</td>
<td>41.6</td>
<td>32.9</td>
<td>1.4</td>
<td>12.4</td>
<td>182.3</td>
</tr>
<tr>
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<td>71</td>
<td>43.3</td>
<td>34.0</td>
<td>1.6</td>
<td>12.6</td>
<td>162.5</td>
</tr>
<tr>
<td>60</td>
<td>47</td>
<td>45.5</td>
<td>34.9</td>
<td>1.7</td>
<td>12.7</td>
<td>141.8</td>
</tr>
<tr>
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<td></td>
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<td></td>
</tr>
<tr>
<td>0  (^a)</td>
<td>118</td>
<td>41.3</td>
<td>31.9</td>
<td>1.3</td>
<td>12.2</td>
<td>204.9</td>
</tr>
<tr>
<td>20</td>
<td>94</td>
<td>41.8</td>
<td>32.9</td>
<td>1.4</td>
<td>12.4</td>
<td>182.5</td>
</tr>
<tr>
<td>40</td>
<td>71</td>
<td>43.4</td>
<td>34.0</td>
<td>1.6</td>
<td>12.6</td>
<td>162.6</td>
</tr>
<tr>
<td>60</td>
<td>47</td>
<td>45.6</td>
<td>34.9</td>
<td>1.6</td>
<td>12.7</td>
<td>141.8</td>
</tr>
</tbody>
</table>

\(^a\)Percentage BTU replacement of crop residue for coal.
Table 23. Consumption of coal by alternative scenario and coal type

<table>
<thead>
<tr>
<th>Scenario&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Coal Type</th>
<th>Iowa</th>
<th>Illinois</th>
<th>Wyoming</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Washed</td>
<td>Washed</td>
<td></td>
</tr>
<tr>
<td><strong>Base:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0&lt;sup&gt;b&lt;/sup&gt;</td>
<td>620</td>
<td>0</td>
<td>3,553.5</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>620</td>
<td>0</td>
<td>2,714.2</td>
<td>0</td>
</tr>
<tr>
<td>40</td>
<td>620</td>
<td>0</td>
<td>1,875.0</td>
<td>0</td>
</tr>
<tr>
<td>60</td>
<td>620</td>
<td>0</td>
<td>1,027.5</td>
<td>0</td>
</tr>
<tr>
<td><strong>Double Energy Prices:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0&lt;sup&gt;b&lt;/sup&gt;</td>
<td>620</td>
<td>0</td>
<td>3,054.0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>620</td>
<td>0</td>
<td>2,356.8</td>
<td>0</td>
</tr>
<tr>
<td>40</td>
<td>620</td>
<td>0</td>
<td>1,740.6</td>
<td>0</td>
</tr>
<tr>
<td>60</td>
<td>620</td>
<td>0</td>
<td>1,027.1</td>
<td>0</td>
</tr>
<tr>
<td><strong>Double Coal and Energy Prices:</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0&lt;sup&gt;b&lt;/sup&gt;</td>
<td>620</td>
<td>0</td>
<td>3,539.7</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>620</td>
<td>0</td>
<td>2,700.5</td>
<td>0</td>
</tr>
<tr>
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<td>620</td>
<td>0</td>
<td>1,861.2</td>
<td>0</td>
</tr>
<tr>
<td>60</td>
<td>620</td>
<td>0</td>
<td>1,027.2</td>
<td>292.7</td>
</tr>
<tr>
<td><strong>Sulfur Constrained:</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0&lt;sup&gt;b&lt;/sup&gt;</td>
<td>9.1</td>
<td>29.4</td>
<td>2,091.1</td>
<td>1,381.6</td>
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<td>291.6</td>
<td>47.4</td>
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<td>410.0</td>
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<td>528.1</td>
<td>6</td>
<td>1,099.3</td>
<td>292.7</td>
</tr>
</tbody>
</table>

<sup>a</sup> Soil Constrained scenario is identical to the Base.

<sup>b</sup> Percentage BTU replacement of crop residue for coal.
Table 24. Cost of coal for the alternative scenarios

<table>
<thead>
<tr>
<th>Scenario&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Coal Type</th>
<th>Iowa-washed</th>
<th>Illinois-Sparta</th>
<th>Illinois-washed</th>
<th>Wyoming</th>
<th>Average</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Iowa</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Base Run:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
<td>0.75</td>
<td>NA&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.86</td>
<td>NA</td>
<td>0.85</td>
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<td>20</td>
<td></td>
<td>0.75</td>
<td>NA</td>
<td>0.85</td>
<td>NA</td>
<td>0.85</td>
</tr>
<tr>
<td>40</td>
<td></td>
<td>0.75</td>
<td>NA</td>
<td>0.85</td>
<td>NA</td>
<td>0.85</td>
</tr>
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<td>0.74</td>
<td>NA</td>
<td>0.83</td>
<td>NA</td>
<td>0.85</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
<td>1.24</td>
<td>NA</td>
<td>1.35</td>
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<td></td>
<td>1.25</td>
<td>NA</td>
<td>1.35</td>
<td>NA</td>
<td>1.25</td>
</tr>
<tr>
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<td>1.25</td>
<td>NA</td>
<td>1.35</td>
<td>NA</td>
<td>1.22</td>
</tr>
<tr>
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<td>1.26</td>
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<td>1.33</td>
<td>NA</td>
<td>1.19</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
<td>1.51</td>
<td>NA</td>
<td>1.72</td>
<td>NA</td>
<td>1.69</td>
</tr>
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<td>20</td>
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<td>1.38</td>
<td>NA</td>
<td>1.71</td>
<td>NA</td>
<td>1.69</td>
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<td>1.49</td>
<td>NA</td>
<td>1.69</td>
<td>NA</td>
<td>1.69</td>
</tr>
<tr>
<td>60</td>
<td></td>
<td>1.48</td>
<td>NA</td>
<td>1.66</td>
<td>1.487</td>
<td>1.62</td>
</tr>
<tr>
<td><strong>Sulfur Constrained:</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>1.36</td>
<td>1.72</td>
<td>1.77</td>
<td>2.55</td>
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<td>1.71</td>
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<tr>
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<td>1.48</td>
<td>1.72</td>
<td>1.73</td>
<td>NA</td>
<td>1.81</td>
</tr>
<tr>
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<td></td>
<td>1.51</td>
<td>NA</td>
<td>1.70</td>
<td>1.49</td>
<td>1.92</td>
</tr>
</tbody>
</table>

<sup>a</sup>The Soil Constrained scenario used the same coal mix as the Base.

<sup>b</sup>Percentage BTU replacement of crop residue for coal.

<sup>c</sup>NA indicated that this coal is not used by the power plants and, thus, no price is available.
average cost of a MM$	ext{B} 	ext{T} 	ext{U}^1$ if coal decreases. This change is most pronounced in the Sulfur Constrained scenario where, at 0 percent crop residue use, the cost to the power plant is $2.12 per MM$	ext{B} 	ext{T} 	ext{U}$. When 60 percent of the coal is replaced by the residues, the average cost decreases to $1.63 per MM$	ext{B} 	ext{T} 	ext{U}$.

As might be expected, the quantity of diesel fuel used to transport the coal from the coal mines to the power plant decreases as the percentage of residues demanded increases (Table 25). When sulfur is constrained and residue use increases from 0 to 60 percent, energy used for coal transportation increases by 45.2, 37.2, 8.7, and 3.3 percent over the Base and its corresponding residue use levels. In addition, electrical use increases due to the introduction of beneficiated coal.

When energy prices increase, the results are not consistent. There are some increases and some decreases in fuel used for coal transportation in the energy price increases.

Crop production's energy consumption

Doubled Energy Prices, Doubled Coal and Energy Prices, and Sulfur Constrained scenarios all show a decrease in the amount of energy used (Table 26) for Iowa's agricultural production. In addition, in all three of these options, the ratio of BTU's per dollar of output decreases 3.6, 3.3, 2.4, and 2.3 percent when residues replace coal by 0, 20, 40, and 60 percent, respectively, when compared to the Base solutions (Table 27). As the quantity of crop residue increases, this ratio also increases.

---

$^1$Million British Thermal Units.
Table 25. Energy used for transporting and processing coal by scenario and type of energy

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Diesel (thousand gallons)</th>
<th>Electricity (thousand kwh)</th>
<th>Total Energy (trillion BTU's)</th>
<th>Change in Energy Use from Base Run (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base Run:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0a</td>
<td>6,648.3</td>
<td>0</td>
<td>0.931</td>
<td>NA</td>
</tr>
<tr>
<td>20</td>
<td>5,120.6</td>
<td>0</td>
<td>0.717</td>
<td>NA</td>
</tr>
<tr>
<td>40</td>
<td>3,684.7</td>
<td>0</td>
<td>0.516</td>
<td>NA</td>
</tr>
<tr>
<td>60</td>
<td>2,361.2</td>
<td>0</td>
<td>0.331</td>
<td>NA</td>
</tr>
<tr>
<td><strong>Soil Constraint:</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>0a</td>
<td>6,648.3</td>
<td>0</td>
<td>0.931</td>
<td>No change</td>
</tr>
<tr>
<td>20</td>
<td>5,120.6</td>
<td>0</td>
<td>0.717</td>
<td>No change</td>
</tr>
<tr>
<td>40</td>
<td>3,684.7</td>
<td>0</td>
<td>0.516</td>
<td>No change</td>
</tr>
<tr>
<td>60</td>
<td>2,361.2</td>
<td>0</td>
<td>0.331</td>
<td>No change</td>
</tr>
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<td><strong>Double Energy Prices:</strong></td>
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<td></td>
<td></td>
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<tr>
<td>0a</td>
<td>7,240.1</td>
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<tr>
<td>20</td>
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<td>0</td>
<td>0.784</td>
<td>+ 9.34</td>
</tr>
<tr>
<td>40</td>
<td>3,849.8</td>
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<td>0.539</td>
<td>+ 4.46</td>
</tr>
<tr>
<td>60</td>
<td>2,293.5</td>
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<td>0.321</td>
<td>- 3.02</td>
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<td></td>
</tr>
<tr>
<td>0a</td>
<td>6,644.7</td>
<td>0</td>
<td>0.930</td>
<td>- c</td>
</tr>
<tr>
<td>20</td>
<td>5,105.8</td>
<td>0</td>
<td>0.715</td>
<td>-</td>
</tr>
<tr>
<td>40</td>
<td>3,670.0</td>
<td>0</td>
<td>0.514</td>
<td>-</td>
</tr>
<tr>
<td>60</td>
<td>2,185.1</td>
<td>971.8</td>
<td>0.309</td>
<td>-</td>
</tr>
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<td><strong>Sulfur Constraint:</strong></td>
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<td></td>
<td></td>
</tr>
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<td>0a</td>
<td>9,546.1</td>
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<td>1.352</td>
<td>+45.22</td>
</tr>
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</tr>
<tr>
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</tr>
<tr>
<td>60</td>
<td>2,418.8</td>
<td>971.8</td>
<td>0.342</td>
<td>+ 3.32</td>
</tr>
</tbody>
</table>

a Percentage BTU replacement of crop residue for coal.

b NA indicates not applicable.

c - indicates less than .005 percent change.
| Scenario<sup>a</sup> | Type of Energy Used:<br> | | Natural Gas | Electricity | LPG |
|---|---|---|---|---|
| | Diesel<sup>b</sup> | (million gallons) | (million cu. ft.) | (million kwh) | (million gallons) |
| **Base Run:** | | | | | |
| 0<sup>c</sup> | 288.44 | 34,192.58 | 393.07 | 138.92 |
| 20 | 290.06 | 34,590.32 | 398.57 | 140.34 |
| 40 | 292.14 | 35,074.01 | 401.97 | 142.04 |
| 60 | 295.12 | 35,474.34 | 408.17 | 143.48 |
| **Double Energy Prices:** | | | | | |
| 0<sup>c</sup> | 285.30 | 31,144.13 | 363.52 | 128.13 |
| 20 | 287.00 | 31,579.11 | 367.71 | 129.65 |
| 40 | 289.53 | 32,100.98 | 374.05 | 131.51 |
| 60 | 291.31 | 32,506.63 | 377.16 | 132.97 |
| **Double Coal and Energy Prices:** | | | | | |
| 0<sup>c</sup> | 285.30 | 31,144.13 | 363.52 | 128.13 |
| 20 | 287.01 | 31,568.23 | 367.62 | 129.64 |
| 40 | 289.53 | 32,100.98 | 374.05 | 131.96 |
| 60 | 291.67 | 32,502.96 | 376.54 | 133.06 |
| **Sulfur Constraint:** | | | | | |
| 0<sup>c</sup> | 285.30 | 31,144.13 | 363.52 | 128.13 |
| 20 | 287.01 | 31,568.23 | 367.62 | 129.64 |
| 40 | 289.53 | 32,100.98 | 374.05 | 131.96 |
| 60 | 291.67 | 32,502.96 | 376.54 | 133.02 |

<sup>a</sup>Note: Energy use in the Soil Constrained scenario did not significantly vary from the Base so it is not reported.

<sup>b</sup>Includes gasoline converted to diesel.

<sup>c</sup>Percentage BTU replacement of crop residue for coal.
Table 27. Energy used in crop production and crop residue production, gross crop sales, and the ratio of Energy per dollar of output.

<table>
<thead>
<tr>
<th>Scenario(^a)</th>
<th>Energy Used</th>
<th>Gross Crop Sales</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(trillion BTU's)</td>
<td>(million dollars)</td>
<td>(BTU's per dollar)</td>
</tr>
<tr>
<td><strong>Base:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0(^b)</td>
<td>89.93</td>
<td>3,461.5</td>
<td>25.98</td>
</tr>
<tr>
<td>20</td>
<td>90.72</td>
<td>3,467.3</td>
<td>26.16</td>
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<td>91.68</td>
<td>3,475.1</td>
<td>26.60</td>
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<tr>
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<td>92.67</td>
<td>3,483.3</td>
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<td><strong>Double Energy Prices:</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>0(^b)</td>
<td>85.25</td>
<td>3,398.2</td>
<td>25.09</td>
</tr>
<tr>
<td>20</td>
<td>86.09</td>
<td>3,404.6</td>
<td>25.29</td>
</tr>
<tr>
<td>40</td>
<td>87.17</td>
<td>3,383.8</td>
<td>25.76</td>
</tr>
<tr>
<td>60</td>
<td>87.98</td>
<td>3,381.7</td>
<td>26.02</td>
</tr>
<tr>
<td><strong>Double Coal and Energy Prices:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0(^b)</td>
<td>85.25</td>
<td>3,398.2</td>
<td>25.09</td>
</tr>
<tr>
<td>20</td>
<td>86.09</td>
<td>3,404.6</td>
<td>25.29</td>
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<tr>
<td>40</td>
<td>87.17</td>
<td>3,383.8</td>
<td>25.76</td>
</tr>
<tr>
<td>60</td>
<td>87.98</td>
<td>3,381.7</td>
<td>26.02</td>
</tr>
<tr>
<td><strong>Sulfur Constraint:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0(^b)</td>
<td>85.25</td>
<td>3,398.2</td>
<td>25.09</td>
</tr>
<tr>
<td>20</td>
<td>86.09</td>
<td>3,404.6</td>
<td>25.29</td>
</tr>
<tr>
<td>40</td>
<td>87.17</td>
<td>3,383.8</td>
<td>25.76</td>
</tr>
<tr>
<td>60</td>
<td>87.98</td>
<td>3,381.7</td>
<td>26.02</td>
</tr>
</tbody>
</table>

\(^a\)Note: Energy use in the Soil Constrained scenario did not significantly vary from the Base so it is not reported.

\(^b\)Percentage BTU replacement of crop residue for coal.
Energy use in production of residues

There is little change among the scenarios in energy use (Table 28). Only in the 20 percent crop residue demand solution does the amount of energy use decrease as energy prices increase. Energy use per ton of residues supplied increases as the quantity of residues increase (from approximately 1,141 to 1,528 BTU's per ton in the Base and 950 to 1,550 BTU's per ton in the increased energy prices scenarios for 20 and 60 percent, respectively).

Since this study assumes that residues are supplying approximately 13 MMBTU's per ton burned, the energy balance if favorable with the maximum ratio of energy supplied to energy used is 13.71 and the minimum being 8.36 at 20 and 60 percent in the Double Energy Price scenario.

Nitrogen

Nitrogen use decreases between 8.5 to 9 percent at all levels of crop residue use as energy price increases (Table 29). There is virtually no change between the Base and Soil Constrained scenarios in nitrogen use.

The harvesting of crop residues requires approximately, 10, 20, and 30 thousand tons of additional nitrogen to be applied to replace the nitrogen lost from the residue. In addition, as the level of residues demanded increases, more nitrogen is used in crop production due to the change in cropping patterns previously mentioned. For instance, as the level of residue demanded increases, corn production (a nitrogen demanding crop) increases while soybean production (a nitrogen supplying crop) decreases somewhat.
Table 28. Energy use for nutrient replacing, harvesting, transporting, and processing crop residues by scenario

<table>
<thead>
<tr>
<th>Scenarioa</th>
<th>Diesel (million gallons)</th>
<th>Natural Gas (million cu. ft)</th>
<th>Electricity (million kwh)</th>
<th>Total (trillion MMBTU's per BTU's)</th>
<th>Ratio (per ton of residues)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Run:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>6.131</td>
<td>538.85</td>
<td>39.66</td>
<td>1.642</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>16.58</td>
<td>1,080.96</td>
<td>82.59</td>
<td>3.428</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>31.17</td>
<td>1,585.88</td>
<td>117.49</td>
<td>6.389</td>
</tr>
<tr>
<td>Double Energy Prices:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>1</td>
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<tr>
<td></td>
<td>20</td>
<td>4.77</td>
<td>546.88</td>
<td>41.42</td>
<td>1.369</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>16.65</td>
<td>1,095.06</td>
<td>82.00</td>
<td>3.732</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>31.93</td>
<td>1,582.7</td>
<td>119.70</td>
<td>6.449</td>
</tr>
<tr>
<td>Sulfur Constrained:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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<td>0</td>
<td>1</td>
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<tr>
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<td>20</td>
<td>4.73</td>
<td>547.99</td>
<td>41.34</td>
<td>1.364</td>
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<tr>
<td></td>
<td>40</td>
<td>16.65</td>
<td>1,095.06</td>
<td>82.00</td>
<td>3.732</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>31.58</td>
<td>1,599.55</td>
<td>120.48</td>
<td>6.470</td>
</tr>
</tbody>
</table>

*aNote: Energy use in the Soil Constrained scenario did not significantly vary from the Base so it is not reported.

*bPercentage BTU replacement of crop residue for coal.
Table 29. Nitrogen use by scenario

<table>
<thead>
<tr>
<th>Alternative Run</th>
<th>Nitrogen Used for Crop Production</th>
<th>Additional Nitrogen for Replacement</th>
<th>Total Nitrogen Used (1000 tons)</th>
</tr>
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<tbody>
<tr>
<td><strong>Base Run:</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>0b</td>
<td>665.727</td>
<td>0</td>
<td>665.727</td>
</tr>
<tr>
<td>20</td>
<td>673.497</td>
<td>10.076</td>
<td>683.573</td>
</tr>
<tr>
<td>40</td>
<td>683.022</td>
<td>20.136</td>
<td>703.158</td>
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<tr>
<td>60</td>
<td>690.540</td>
<td>29.852</td>
<td>720.394</td>
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<td><strong>Soil Constrained:</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>0b</td>
<td>665.727</td>
<td>0</td>
<td>665.727</td>
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<tr>
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<td>673.088</td>
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<td>683.164</td>
</tr>
<tr>
<td>40</td>
<td>681.941</td>
<td>20.138</td>
<td>702.077</td>
</tr>
<tr>
<td>60</td>
<td>688.898</td>
<td>29.851</td>
<td>718.750</td>
</tr>
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<td><strong>Double Energy Prices:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0b</td>
<td>605.690</td>
<td>0</td>
<td>605.690</td>
</tr>
<tr>
<td>20</td>
<td>614.025</td>
<td>10.174</td>
<td>624.199</td>
</tr>
<tr>
<td>40</td>
<td>624.450</td>
<td>20.397</td>
<td>644.847</td>
</tr>
<tr>
<td>60</td>
<td>632.033</td>
<td>29.852</td>
<td>661.885</td>
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<td></td>
</tr>
<tr>
<td>0b</td>
<td>605.690</td>
<td>0</td>
<td>605.690</td>
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<tr>
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<td>614.017</td>
<td>10.207</td>
<td>624.224</td>
</tr>
<tr>
<td>40</td>
<td>624.450</td>
<td>20.397</td>
<td>644.847</td>
</tr>
<tr>
<td>60</td>
<td>632.319</td>
<td>29.823</td>
<td>662.142</td>
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<td></td>
</tr>
<tr>
<td>0b</td>
<td>605.69</td>
<td>0</td>
<td>605.690</td>
</tr>
<tr>
<td>20</td>
<td>614.017</td>
<td>10.206</td>
<td>624.224</td>
</tr>
<tr>
<td>40</td>
<td>624.450</td>
<td>20.397</td>
<td>644.847</td>
</tr>
<tr>
<td>60</td>
<td>632.319</td>
<td>29.823</td>
<td>662.142</td>
</tr>
</tbody>
</table>

a Additional nitrogen for replacing the nitrogen incorporated within the crop residues.

b Percentage BTU replacement of crop residue for coal.
Agricultural Production Cost and Net Income

Several components must be examined before net income is derived. As previously mentioned, the objective function includes not only the costs and returns attributed to agricultural activities but also the at-the-mine, transportation, handling costs of coal used by Iowa's power plants, and the transportation and processing costs of crop residues. When these components are added to the objective function, net income to the crop and crop residue producing portion of the agriculture sector is derived. Net income, then, is the monetary return to the farmers. It does not reflect any cost for land, management, or the risk aspects of agriculture. Production costs then are equal to gross sales minus net income (Tables 30, 31).

When comparing the Soil Constrained to the Base scenario, net income and production costs show no or very little change. However, when energy prices are doubled, net income decreases almost 14 percent with production costs decreasing between 4 to 6 percent. When examining the Base scenario, the results indicate that by supplying crop residue, farmers lost 1.36, 2.81, and 4.17 percent at the 20, 40, and 60 percent levels as compared to when no residues are demanded by the power plants. This percentage loss increases only slightly in the Increased Energy Prices scenarios.

¹Farmers are not being compensated for supplying the residues. In actual practice they would have to see a return of this amount for residue supplies.
## Table 30. Derivation of net income by scenario for Iowa's crop producing agricultural sector

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Objective function&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Coal Cost&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Transportating and Processing Costs of Crop Residues</th>
<th>Net Income</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1,215.14</td>
<td>99.70</td>
<td>0</td>
<td>1,314.84</td>
</tr>
<tr>
<td>20</td>
<td>1,208.34</td>
<td>79.00</td>
<td>9.52</td>
<td>1,296.86</td>
</tr>
<tr>
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<td>1,212.71</td>
<td>58.51</td>
<td>16.58</td>
<td>1,277.80</td>
</tr>
<tr>
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<td>1,202.04</td>
<td>38.08</td>
<td>19.89</td>
<td>1,260.01</td>
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<td><strong>Soil Constrained:</strong></td>
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<td></td>
</tr>
<tr>
<td>0&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1,215.14</td>
<td>99.70</td>
<td>0</td>
<td>1,314.84</td>
</tr>
<tr>
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<td>1,208.31</td>
<td>79.00</td>
<td>9.52</td>
<td>1,296.86</td>
</tr>
<tr>
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<td>1,202.58</td>
<td>58.51</td>
<td>16.58</td>
<td>1,277.67</td>
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<tr>
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<td>1,201.38</td>
<td>38.08</td>
<td>19.89</td>
<td>1,259.35</td>
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<td></td>
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<tr>
<td>0&lt;sup&gt;c&lt;/sup&gt;</td>
<td>974.55</td>
<td>156.80</td>
<td>0</td>
<td>1,131.35</td>
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<tr>
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<td>972.73</td>
<td>124.70</td>
<td>11.60</td>
<td>1,109.03</td>
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<tr>
<td>40</td>
<td>971.01</td>
<td>92.73</td>
<td>22.87</td>
<td>1,086.61</td>
</tr>
<tr>
<td>60</td>
<td>974.27</td>
<td>61.28</td>
<td>31.19</td>
<td>1,066.74</td>
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<td><strong>Double Coal and Energy Prices:</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>0&lt;sup&gt;c&lt;/sup&gt;</td>
<td>930.78</td>
<td>200.68</td>
<td>0</td>
<td>1,131.46</td>
</tr>
<tr>
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<td>157.18</td>
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<td>1,108.81</td>
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<tr>
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<td>117.48</td>
<td>22.87</td>
<td>1,086.73</td>
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<tr>
<td>60</td>
<td>960.38</td>
<td>72.73</td>
<td>31.19</td>
<td>1,064.30</td>
</tr>
<tr>
<td><strong>Sulfur Constrained:</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0&lt;sup&gt;c&lt;/sup&gt;</td>
<td>878.31</td>
<td>253.15</td>
<td>0</td>
<td>1,131.46</td>
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<td>20</td>
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<td>163.45</td>
<td>11.60</td>
<td>1,100.54</td>
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<td>941.60</td>
<td>124.19</td>
<td>22.87</td>
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<td>60</td>
<td>957.72</td>
<td>77.73</td>
<td>31.19</td>
<td>1,066.64</td>
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</table>

<sup>a</sup>The maximized objective function consists of agricultural sale less costs incurred due to production of costs less the coal cost less the costs attributed directly to crop residue production.

<sup>b</sup>Includes the estimated cost of transporting and handling coal as well as the at-the-mine costs.

<sup>c</sup>Percentage replacement of crop residue for coal.
Table 31. Derivation of production costs in the crop producing portion of the agricultural sector

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Gross Sales (million dollars)</th>
<th>Net Income (million dollars)</th>
<th>Total Production Costs (million dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0^a</td>
<td>3,461.5</td>
<td>1,314.8</td>
<td>2,146.7</td>
</tr>
<tr>
<td>20</td>
<td>3,467.3</td>
<td>1,296.9</td>
<td>2,170.4</td>
</tr>
<tr>
<td>40</td>
<td>3,475.1</td>
<td>1,277.8</td>
<td>2,197.3</td>
</tr>
<tr>
<td>60</td>
<td>3,483.3</td>
<td>1,260.0</td>
<td>2,283.3</td>
</tr>
<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>0^a</td>
<td>3,461.5</td>
<td>1,314.8</td>
<td>2,146.7</td>
</tr>
<tr>
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<td>3,466.8</td>
<td>1,296.9</td>
<td>2,169.9</td>
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<tr>
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<td>2,196.1</td>
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<tr>
<td>60</td>
<td>3,439.4</td>
<td>1,259.4</td>
<td>2,180.0</td>
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<td><strong>Double Energy Price Scenarios^b:</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>0^a</td>
<td>3,398.2</td>
<td>1,131.4</td>
<td>2,266.8</td>
</tr>
<tr>
<td>20</td>
<td>3,404.6</td>
<td>1,109.0</td>
<td>2,295.6</td>
</tr>
<tr>
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<td>3,383.8</td>
<td>1,086.6</td>
<td>2,297.2</td>
</tr>
<tr>
<td>60</td>
<td>3,381.7</td>
<td>1,066.7</td>
<td>2,315.0</td>
</tr>
</tbody>
</table>

^a Percentage replacement of crop residue for coal.

^b Since there is no change in the gross sales or net income portion of the results of the Doubled Energy Prices, Double Coal and Energy Prices, and Sulfur Constrained scenarios, only one set of results is reported.
Economic feasibility of crop residues

The costs of crop residues include both direct\(^1\) and indirect\(^2\) costs (Table 32). These costs, when compared to the costs of coal, indicate whether residue use is feasible.

On a BTU basis alone, the use of crop residues becomes economically feasible only when coal and other energy prices are doubled. Even at this point, the feasibility of residues is marginal (Table 33). If the benefit of the sulfur contribution is credited, however, the Doubled Coal and Energy Price scenario indicates crop residues are indeed feasible with a net benefit of $0.29 and $0.54 per MMBTU for the 20 and 60 percent residue levels, respectively (Table 34). Even when coal prices only double at-the-mine and the energy prices also double, the use of residues are feasible when residues are used to replace 60 percent of the coal.

\(^1\)Direct costs are defined as those costs attributed to harvesting, transporting and processing the residues plus the agronomic costs of nutrient replacement.

\(^2\)Indirect costs are those costs that result from cropping pattern shifts.
Table 32. Costs of crop residues by scenario

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Payment to Farmers</th>
<th>Additional Costs to Power Plant</th>
<th>Total Cost (dollars per ton)</th>
<th>(dollars per MMBTU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>9.69</td>
<td>5.16</td>
<td>14.85</td>
<td>1.14</td>
</tr>
<tr>
<td>40</td>
<td>9.93</td>
<td>4.59</td>
<td>14.52</td>
<td>1.12</td>
</tr>
<tr>
<td>60</td>
<td>8.52</td>
<td>3.22</td>
<td>11.74</td>
<td>0.90</td>
</tr>
<tr>
<td>Soil loss:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>9.70</td>
<td>5.16</td>
<td>14.86</td>
<td>1.14</td>
</tr>
<tr>
<td>40</td>
<td>9.96</td>
<td>4.59</td>
<td>14.55</td>
<td>1.12</td>
</tr>
<tr>
<td>60</td>
<td>8.64</td>
<td>3.22</td>
<td>11.86</td>
<td>0.91</td>
</tr>
<tr>
<td>Other scenarios:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>11.86</td>
<td>6.28</td>
<td>18.14</td>
<td>1.40</td>
</tr>
<tr>
<td>40</td>
<td>11.90</td>
<td>6.33</td>
<td>18.23</td>
<td>1.40</td>
</tr>
<tr>
<td>60</td>
<td>9.84</td>
<td>5.06</td>
<td>14.95</td>
<td>1.15</td>
</tr>
</tbody>
</table>

\(^a\) percentage of crop residue demand.

\(^b\) Since there is no change in the gross sales or net income portion of the results of the Doubled Energy Prices, Double Coal and Energy Prices, and Sulfur Constrained scenarios, only one set of results is reported.
Table 33. Economic feasibility of crop residues when evaluated on a BTU basis alone

<table>
<thead>
<tr>
<th>Type of Fuel by Scenario</th>
<th>Percentage BTU Replacement of Residue for Coal at:</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Base:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>0.84</td>
<td>0.83</td>
<td>0.81</td>
</tr>
<tr>
<td>Crop Residue</td>
<td>1.14</td>
<td>1.12</td>
<td>0.90</td>
</tr>
<tr>
<td>Difference&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-0.30</td>
<td>-0.29</td>
<td>-0.09</td>
</tr>
<tr>
<td>Soil Constrained:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>0.84</td>
<td>0.83</td>
<td>0.81</td>
</tr>
<tr>
<td>Crop Residue</td>
<td>1.14</td>
<td>1.12</td>
<td>0.91</td>
</tr>
<tr>
<td>Difference&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-0.30</td>
<td>-0.29</td>
<td>-0.10</td>
</tr>
<tr>
<td>Double Energy Prices:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>1.30</td>
<td>1.30</td>
<td>1.28</td>
</tr>
<tr>
<td>Crop Residue</td>
<td>1.40</td>
<td>1.40</td>
<td>1.15</td>
</tr>
<tr>
<td>Difference&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-0.10</td>
<td>-0.10</td>
<td>+0.13</td>
</tr>
<tr>
<td>Double Coal and Energy Prices:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>1.65</td>
<td>1.65</td>
<td>1.58</td>
</tr>
<tr>
<td>Crop Residue</td>
<td>1.40</td>
<td>1.40</td>
<td>1.15</td>
</tr>
<tr>
<td>Difference&lt;sup&gt;a&lt;/sup&gt;</td>
<td>+0.25</td>
<td>+0.25</td>
<td>+0.43</td>
</tr>
<tr>
<td>Sulfur Constrained:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>1.76</td>
<td>1.71</td>
<td>1.63</td>
</tr>
<tr>
<td>Crop Residue</td>
<td>1.40</td>
<td>1.40</td>
<td>1.15</td>
</tr>
<tr>
<td>Difference&lt;sup&gt;a&lt;/sup&gt;</td>
<td>+0.36</td>
<td>+0.31</td>
<td>+0.48</td>
</tr>
</tbody>
</table>

<sup>a</sup>Negative quantities indicate lower costs for coal while positive figures show lower costs for residues.
Table 34. Comparison of coal costs with the most of residue by scenario in dollars per MMBTU

<table>
<thead>
<tr>
<th>Type of Fuel by Scenario</th>
<th>Percentage Replacement of Residue of Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td><strong>Base:</strong></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>0.85</td>
</tr>
<tr>
<td>Crop Residue</td>
<td>1.14</td>
</tr>
<tr>
<td>Difference b</td>
<td>-0.29</td>
</tr>
<tr>
<td><strong>Soil Constrained:</strong></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>0.85</td>
</tr>
<tr>
<td>Crop Residue</td>
<td>1.14</td>
</tr>
<tr>
<td>Difference b</td>
<td>-0.29</td>
</tr>
<tr>
<td><strong>Double Energy Prices:</strong></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>1.31</td>
</tr>
<tr>
<td>Crop Residue</td>
<td>1.40</td>
</tr>
<tr>
<td>Difference b</td>
<td>-0.09</td>
</tr>
<tr>
<td><strong>Double Coal and Energy Prices:</strong></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>1.69</td>
</tr>
<tr>
<td>Crop Residue</td>
<td>1.40</td>
</tr>
<tr>
<td>Difference b</td>
<td>0.29</td>
</tr>
<tr>
<td><strong>Sulfur Constrained:</strong></td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>2.12</td>
</tr>
<tr>
<td>Crop Residue</td>
<td>1.40</td>
</tr>
<tr>
<td>Difference b</td>
<td>0.72</td>
</tr>
</tbody>
</table>

*Cost of coal at the 0 percent crop residue use in each scenario.

bNegative quantities indicate lower costs for coal, while positive figures show lower costs for residue.
V. SUMMARY AND CONCLUSIONS

Summary

Energy production from renewable resources is currently under intensive discussion and examination. Today, fossil fuels provide all but 4 percent of the energy consumed in the United States. Exxon Corporation [Annonymous, 1978] and the Project Independence Report [Alich and Inman, 1976], however, suggest that synthetics, solar, and other energy forms be the base for a rapid rate of expansion. This report examines an energy form in this area.

The primary past and present purpose of U.S. agriculture has been to provide food and fiber to consumers. In addition to providing food and fiber, a secondary purpose of U.S. agriculture may be to provide energy. Significant amounts of energy from U.S. agriculture may be derived from energy crops, agricultural by-products, crop residues, and animal wastes. In present day vernacular, these forms are commonly known as biomass.

This study examines the economic feasibility in Iowa of directly burning crop residues in electrical generating facilities. The purpose of using crop residues is two-fold: first, crop residue is a renewable resource unlike fossil fuels, and secondly, crop residue is virtually sulfur free. Therefore, mixing crop residue with coal could allow plants to meet the increasingly stringent environmental constraints.
This report examines the economic feasibility of using crop residues in existing Iowa power plants under five different scenarios -- the Base Run, Soil Constrained, Doubled Energy Prices, Double Coal and Energy Prices, and Sulfur Constrained. Under each of these options, crop residues are demanded by the power plant at steps of 0, 20, 40, and 60 percent of the levels of coal use in 1975 using a linear programming model.

The use of crop residues effects crop production, energy consumed, nitrogen demanded, agricultural production cost, and net income. The impacts of utilizing crop residues on Iowa's agricultural sector are first examined, then the economic viability of using crop residues are determined by examining the costs and benefits of residue use in comparison to coal use.

**Impacts on Iowa's Agricultural Sector**

The total value of endogenous crops sold exceeds three billion dollars in all scenarios examined. With both Increased Energy Prices and Sulfur Constrained, as the percentage of crop residues increased to from 0 to 60 percent, the gross value of crops produced decreases from 1.78 to 2.92 percent, respectively (Table 2). Thus, using crop residues causes a shift in most cases to a lower valued crop at 1970-1975 average prices. For the most part, this shift is because of a shift from soybean production to corn production, a higher residue-yielding crop.

Total energy does not change significantly among options. When residues are utilized by power utility plants, however, the quantity of energy used in supplying the fuel is less than the quantity saved in replacement of coal.
Nitrogen use decreases between 8.5 to 9 percent at all levels of crop residue use as energy prices increase. The harvesting of residues results in additional nitrogen requirements of 10, 20, and 30 thousand tons to replace the nitrogen lost in the residue removed. In addition, more nitrogen is used in crop production, corresponding to the change in cropping patterns previously mentioned. More nitrogen intensive rotations are required as residues demanded increases.

Net income, the monetary return to Iowa farmers, does not reflect any cost for land, management, or the risk aspects of agriculture. When examining the Base scenario, the results indicate that by supplying crop residues a decrease in net income of 1.36, 2.81 and 4.17 percent occurs at the 20, 40, and 60 percent levels of residue use in the Base run.¹

As energy price increase and sulfur levels are further restricted, the decrease in net income is much less. This loss in net income is primarily due to the agronomic and harvestings costs borne by farmers, and costs are increased due to the shifting crop patterns. The Soil Constrained scenario shows little change from the Base, with a net cost to farmers of an additional $.12 per ton of residue supplied at the 60 percent residue demand level. Thus, the cost due to the production of a less profitable but higher residue yielding crop is

¹Farmers are not being compensated for supplying the residues. Although the costs of residues do incorporate a labor cost and a return on capital used, in actual practice farmers would require a return of this amount for providing the residues. Net income, the monetary return to Iowa farmers, does not reflect any cost for land, management, or the risk aspects of agriculture.
included in the total cost of crop residue. Indirect costs of additional soil loss occurring because residue is removed from the land are only incorporated in the Soil Constrained alternative, however.

Conclusion

The costs of crop residues include both direct and indirect costs. The direct costs are those attributed to harvesting, transporting, and processing the residues plus the agronomic costs of nutrient replacement. The indirect costs include the costs incurred due to cropping pattern shifts caused when residues are supplied by farmers. Other costs of crop residues such as organic matter maintenance and decreased productivity over the long run, benefits of reduced pesticides, and reduced fall plowing are not incorporated within the scope of this study. These components would affect the direct and indirect costs of crop residue. The Soil Loss Constraint scenario indicated that if soil erosion is maintained at the base level, it would cost the farmer an additional $0.12 per ton of residue produced at the 60 percent replacement level. At other levels, 20 and 40 percent, the cost of the soil constraint is about $0.01 per ton of residue. This is due in part to a shift in management practices so that yields would be maintained in the long run.

The power plant would have to pay farmers from $8.52 per ton for use of residues at the 60 percent level in Base run to $11.90 per ton for the 40 percent residue use level in the Sulfur Constrained scenario. Total cost per million BTU's ranges from $0.98 to $1.40 in 1975 dollars.
On a BTU basis alone, the use of crop residues becomes economically feasible when coal and other energy prices are doubled. Even at this point, the feasibility of residues is marginal. If the benefit of the sulfur contribution is credited, however, the Doubled Coal and Energy Price scenario indicates crop residues are indeed feasible with a new benefit of $0.29 and $0.54 per MMBTU for the 20 and 60 percent residue levels, respectively. Even when coal prices only double at-the-mine and other energy prices also double, the use of residues are feasible when residues are used to replace 60 percent of the coal.

The proportion of costs incurred by farmers and power plant operators are illustrated in Figure 7 for the Base scenario. These results are consistent over all the alternatives, although the percentages differ slightly because of increased energy costs. Figure 7 shows the farm share of increases cost as the percentage of residue used increases. This increase is primarily because of the fixed costs inherent in the power plant's processing facility. It should be remembered, however, that power plants have large capital investments in the processing facilities.

The above analysis does not account for risk costs. Also, previously mentioned, additional benefits received by farmers from residue removal, such as reduced fall plowing and reduced need for pesticides and herbicides, are not included in the analysis. These benefits could result in lower payments by power plants to farmers, than are otherwise indicated.
Figure 7. Proportion of crop residue costs incurred by farm and power plant operators in the Base run
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Crop Reporting Board
Division of Fuels Data


Division of Fuels Data and Division of Coal


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APPENDIX A: SULFUR OXIDE POLLUTION

When coal is burned, a major pollutant, sulfur oxide, is produced. This is one of the foremost problems in electrical generation by coal-fired power plants. The purpose of this appendix is threefold: to describe the sulfur pollution standards that presently exist, to discuss various technologies that can be used to meet these standards and to make cost estimates of the three technologies incorporated in this study.

No one challenges the fact that the presence of sulfur dioxide ($SO_2$) and other sulfur compounds in the air is toxic. However, there is not wide agreement on the relationship between the concentrations of $SO_2$ in the ambient air and the effect on human health. Table A.1 summarizes the levels of $SO_2$ and sulfates that have been identified

<table>
<thead>
<tr>
<th>Response</th>
<th>$SO_2$ Concentration</th>
<th>Sulfate Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Death</td>
<td>500-1,000$^a$</td>
<td>N.A.</td>
</tr>
<tr>
<td>Illness (acute, chronic)</td>
<td>80-275$^a$</td>
<td>7-14$^a$</td>
</tr>
<tr>
<td>Functional changes</td>
<td>90-120$^b$</td>
<td>9-11$^a$</td>
</tr>
<tr>
<td>preceding disease</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Changes of uncertain</td>
<td>500-1,000$^c$</td>
<td>250$^c$</td>
</tr>
<tr>
<td>significance</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$24-hour average.

$^b$Annual average

$^c$Experimental studies.

SOURCE: [Elliott, 1974].
with specific physiological responses. In addition, some types of crops such as alfalfa, barley, and wheat are damaged by concentrations of \( \text{SO}_2 \) as low as 250-750 \( \mu g/m^3 \). Prolonged exposure will cause corrosion to metal, clothing, paints, and materials.

In 1970, Congress amended the Clean Air Act by establishing strict requirements and a time table for improved air quality. The amendments require the Environmental Protection Agency (EPA) to formulate primary (related to health) and secondary (related to welfare) ambient air quality standards. The states were required to develop and implement EPA approved plans for limiting pollutants to achieve the EPA's primary standards by 1975. In addition, the states must meet the EPA's secondary standards within a reasonable time thereafter.

The ambient air quality standards currently promulgated by the EPA are shown in Table A.2. The standards give the maximum amount of \( \text{SO}_2 \) present in the atmosphere at all points where people may reasonably be exposed to the pollutants. These standards cannot be exceeded more than once a year at any point.

Table A.2. National ambient air quality standards

<table>
<thead>
<tr>
<th>Standard</th>
<th>Primary (Health)</th>
<th>Secondary (Welfare)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>micrograms per cubic meter</td>
<td></td>
</tr>
<tr>
<td>Annual mean</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Maximum 24 hour concentration</td>
<td>365</td>
<td></td>
</tr>
<tr>
<td>Maximum 3 hour concentration</td>
<td></td>
<td>1,300</td>
</tr>
</tbody>
</table>

SOURCE: [Anonymous, 1973].
By the end of 1972 all states had prepared and submitted their plans to the EPA. To meet ambient air quality standards for $\text{SO}_2$, the states established limitations on the amounts that can be discharged into the atmosphere by major polluters. Power plants were include as sources requiring control because they emit roughly 60 percent of the $\text{SO}_2$ presently discharged into the atmosphere.

To control pollution from power plants the states established standards in terms of pounds of $\text{SO}_2$ per MMBTU of heat input. Formulating the regulation in terms of the amount of $\text{SO}_2$ per MMBTU of heat input makes the measurement of sulfur emissions manageable. Heating values and the percentage sulfur by weight of various fuels are readily obtained. As 90-100 percent of the sulfur in the fuel is converted into $\text{SO}_2$, the weight of $\text{SO}_2$ emissions per MMBTU of heat input can be determined.

From the molecular weights of sulfur (S) and oxygen ($\text{O}_2$), one pound of sulfur will combine with a pound of $\text{O}_2$ to produce two pounds of $\text{SO}_2$. Assuming 100 percent conversion, a coal with 6 percent sulfur content has 120 pounds of sulfur per ton of coal. When burned this will produce 240 pounds of $\text{SO}_2$ per ton of coal input. Assuming 24 MMBUT's per ton of coal, 10 pounds of $\text{SO}_2$ is produced per MMBTU. An equation used to express this mathematical example is:

$$\text{SE} = \frac{2S}{H} + C$$

where SE is the sulfur emissions expressed in pounds per MMBTU; $S$ is the amount of sulfur in pounds per ton of coal; $H$ is the heat input value of coal in MMBTU per ton; and $C$ is the percentage conversion.
In practice, ambient air quality depends upon SO\textsubscript{2} emissions from a great many sources as well as power plants. Large concentrations of automobiles and buildings may necessitate lower emission levels in metropolitan areas to achieve the EPA ambient air quality standards.

The EPA and Iowa Department of Environmental Quality (DEQ) recognize that there are considerable economies of scale in controlling SO\textsubscript{2}. The agencies also seek to recognize the burden that growth of the power industry places on the environment as well as the problems of modifying existing units. Consequently uniform standards are not imposed upon power plants within the state.

Iowa has, in agreement with the EPA, established stricter standards for newer, larger, power plants located in areas having high amounts of SO\textsubscript{2} pollution from other sources. The standards are less stringent for smaller, older, power plants in rural areas. In addition, the EPA and some local communities have established stricter standards in some areas than those proposed by the state. The restrictions on power plants are those shown in Tables A.3 and A.4.

The standards given in Tables A.3 and A.4 have been derived in an attempt to ensure that the state satisfies the EPA ambient air quality standards without imposing an undue burden on specific individuals. The standards may change from time to time but for the most part should not change greatly in the foreseeable future.

Estimated Allocation of Sulfur Control Methods

It is estimated that there will be an increasing reliance on coal conversion processes with the next decade (Figure A.1). Not until 1980
<table>
<thead>
<tr>
<th>Facility Type of Location</th>
<th>Allowed Emission (lb. ( \text{SO}_2 / 10^6 \text{BTU} ))</th>
<th>Standard set by DEQ County</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polk and Linn counties</td>
<td>5.0</td>
<td>X</td>
</tr>
<tr>
<td>Existing facilities of &lt; 500 MM BTU/hr.</td>
<td>12.0</td>
<td>X</td>
</tr>
<tr>
<td>in other counties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nine proposed exceptions: (Also see Table 4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dubuque, Jackson, Clinton, Scott, Muscatine, Louis, Des Moines, Lee, Black Hawk and Linn</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New boilers of &lt; 250 MM BTU/hr.</td>
<td>6.0</td>
<td>X</td>
</tr>
<tr>
<td>New boilers of ≥ 250 MM BTU/hr.</td>
<td>1.2</td>
<td>X</td>
</tr>
<tr>
<td>Existing facilities of ≥ 500 MM BTU/hr.</td>
<td>8.0</td>
<td>X</td>
</tr>
<tr>
<td>in all counties</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**SOURCE:** Distributed at Iowa Department of Environmental Quality public information meeting, July 14, 1977.
Table A.4. EPA proposed emission limits where different from Iowa regulations

<table>
<thead>
<tr>
<th>County</th>
<th>Facility</th>
<th>State Limit</th>
<th>Facility Emissions*</th>
<th>Proposed EPA Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(lb./10^6 BTU)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Black Hawk</td>
<td>John Deere, Waterloo</td>
<td>6</td>
<td>2.8</td>
<td>5.8</td>
</tr>
<tr>
<td>Cerro Gordo</td>
<td>Lehigh Portland Cement Mason City</td>
<td>6</td>
<td>2.2</td>
<td>1.7</td>
</tr>
<tr>
<td>Dubuque</td>
<td>John Deere, Dubuque</td>
<td>6</td>
<td>4.6</td>
<td>4.9</td>
</tr>
<tr>
<td>Johnson</td>
<td>University of Iowa, Iowa City</td>
<td>8</td>
<td>6.3</td>
<td>7.4</td>
</tr>
<tr>
<td>Linn</td>
<td>Iowa Electric Light and Power Company, 6th Street Station, Cedar Rapids</td>
<td>6**</td>
<td>4.4</td>
<td>5.2</td>
</tr>
<tr>
<td>Monroe</td>
<td>Iowa Southern Utilities Company, Bridgeport Power Plant, Eddyville</td>
<td>8</td>
<td>5.2</td>
<td>4.3</td>
</tr>
<tr>
<td>Muscatine</td>
<td>Grain Processing Company, Muscatine</td>
<td>6</td>
<td>5.2</td>
<td>5.6</td>
</tr>
<tr>
<td>Polk</td>
<td>Iowa Power and Light Des Moines Power Plant Des Moines</td>
<td>8**</td>
<td>5.2</td>
<td>6.2</td>
</tr>
<tr>
<td>Woodbury</td>
<td>Iowa Public Service Company George Neal Station Sioux City</td>
<td>8</td>
<td>1.0</td>
<td>7.2</td>
</tr>
</tbody>
</table>

* Based on 1975 Emissions Inventory submitted to DEQ.
** Local program regulation of 5 lb./10^6 BTU in effect.

SOURCE: Distributed at Iowa Department of Environmental Quality public information meeting, July 14, 1977.
Figure A.1. Estimated allocation of control methods for $\text{SO}_2$ from coal to the year 1985

Key
1. Naturally low sulfur
2. Uncontrolled high sulfur
3. Solvent refined
4. Stack gas cleaned
5. Converted to oil
6. Converted to gas

SOURCE: [Elliott, 1974]
is coal converted into oil or gas expected: by 1985, it is estimated that over 15 percent of the coal mined will be converted to gas, and even a larger percentage converted to oil. It might be noted that no uncontrolled high sulfur coal will be used in 1985 [Elliott, 1974].

Sulfur Oxide Removal

With the environmental standards on sulfur emissions in effect, there presently exists only two options available to the power plant. The power plant companies can use low-sulfur coal or remove the sulfur. When high-sulfur coal is burned, sulfur emissions can be controlled through four different means. These include:

1. removal of sulfur before burning;
2. capture of sulfur dioxide (SO₂) in boiler;
3. removal of SO₂ emissions before leaving the stack; or by
4. control of emissions after leaving stack.

Sulfur is present in raw coal in amounts ranging from trace quantities to 8 percent or more. This sulfur in coal exists in three forms: pyritic, organic, and sulfate with sulfate sulfur amounts being insignificant (<.1%). Both pyritic and organic sulfur are considered nonremovable impurities unless the coal itself is refined. Only pyritic can be removed by mechanical means.

The most promising method, still being developed, seems to be the removal of sulfur from the stack gases. However, there is much disagreement among investigators on the economic feasibility of this method.

Figure A.2 gives a summary of the options available to the power plant. No control (option one) has been the traditional approach to
Figure A.2. Sulfur emission management alternatives
sulfur emission management but has been disallowed by Congress. Controlling emissions leaving the stack (option six) is presently used; however, in the future this option will not be an alternative to sulfur emissions management. Capturing $SO_2$ in the boiler (option four) is not considered practical for existing boilers.

Using coal naturally low in sulfur

Coal is heterogeneous combination of inorganic and organic materials. Because of the heterogeneousness of coal, coal characteristics such as sulfur content and BTU value vary between mines and even within the mines themselves. In this study, values found by Levins, Boehlje, Otte, and Libbin [1976] are assumed (Table 5).

In 1975, Iowa used 6,741 thousand net tons of coal of which 5,560 thousand net tons were used in electric utilities. This coal originates from ten areas. A major portion (92.2 percent) of the coal used by electric utilities originates from five major regions including Illinois, Iowa, Montana, West Kentucky, and Wyoming-Idaho (Table 5) [Division of Fuels Data, 1976].

Sulfur removal before burning

Sulfur is present in raw coal in three forms: pyritic, organic, and sulfated with sulfate sulfur amounts being insignificant (< 0.1%). Organic sulfur is chemically bound to the carbon, hydrogen, and oxygen components of coal. These bonds cannot be broken through mechanical means.

Since coal beneficication (sometimes referred to as coal washing) is a mechanical means of removing sulfur from coal before it is burned,
Table A.5. Estimated characteristics and cost of coal consumed by Iowa's utilities

<table>
<thead>
<tr>
<th>Coal Origin</th>
<th>Quantity of Coal Used in 1975(^a)</th>
<th>Average Heating Value(^b)</th>
<th>Sulfur Dioxide Remissions(^b)</th>
<th>Average 1975 Cost(^{c,d})</th>
<th>Average 1975 Cost(^d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illinois</td>
<td>2,290</td>
<td>11,405(^e)</td>
<td>7.69(^e)</td>
<td>15.64</td>
<td>0.642</td>
</tr>
<tr>
<td>Iowa</td>
<td>620</td>
<td>11,746</td>
<td>7.1</td>
<td>11.08</td>
<td>0.472</td>
</tr>
<tr>
<td>Montana</td>
<td>285</td>
<td>8,416</td>
<td>0.96</td>
<td>5.06</td>
<td>0.301</td>
</tr>
<tr>
<td>West Kentucky</td>
<td>64</td>
<td>12,513</td>
<td>7.4</td>
<td>12.6</td>
<td>0.486</td>
</tr>
<tr>
<td>Wyoming</td>
<td>1,870</td>
<td>9,400</td>
<td>1.1</td>
<td>6.74</td>
<td>0.359</td>
</tr>
</tbody>
</table>

\(^a\)Source: [Division of Fuels Data, 1976].

\(^b\)Source: [Levins, R.A., M.D. Boehlje, J.A. Otte, and J.D. Libbin, 1976].

\(^c\)Source: [Division of Fuels Data and Division of Coal, 1977].

\(^d\)At the mine. Does not include transportation.

\(^e\)A weighted average of two coal types.
beneficiation of coal cannot remove organic sulfur. This places an upper limit to the amount of sulfur that can be removed.

Proposed coal beneficiation processing plants have up to three mechanical methods of cleaning coal. These methods include the dense media method (float and sink method), the jig cleaning process, and the froth flotation process.

The dense media method is primarily designed for the larger pieces of coal (1.5 x 0.375 inches) left after being crushed [Grieve, Chu, and Fisher, 1976]. The large chunks of coal are immersed in a liquid having a known specific gravity. Any particle having a higher specific gravity than the liquid media will sink and those particles with a lower one will float. Thus, if the fluid's specific gravity is between that of coal and refuse, separation will occur. Because of this process, it is often referred to as the float and sink method.

The jig cleaning process is designed to clean medium to fine coal particles (0.375 x 0.0 inches). In this process, the coal rests on a cleaning screen and is cleaned by an upward stream of water. The flow of water is changed in direction, leaving the mixture in a state of easy movement between particles. Light materials are then swept away from the mixture [Snyder and Fisher, unpublished].

Fine coal particles can be cleaned by a froth flotation method. Incoming particles are mixed with water, air and reagent solution. This mixture is vibrated so that a froth forms on the surface. This froth is made up of tiny bubbles which attach to coal making the coal buoyant. The refuse remains in the solution. This process can remove
up to 50 percent of the ash and 40 percent of the sulfur but is still in the experimental stage [Snyder and Fisher, unpublished]. The coal output of this process is too fine for use in traveling grate boilers.

Several problems exist in the coal benefication process. First, the cleaned coal normally has a higher moisture content than raw coal. Therefore, it takes more heat to drive the moisture away before the coal ignites. (This problem is not as severe as might be expected, as the BTU content of beneficiated coal has increased about 12 percent per ton.) Secondly, processing problems arise as the temperature passes the freezing point because water is an important ingredient in the benefication process. This problem can be overcome by insulating portions of the plant, using a mixture of other liquids with a lower freezing point and water, or by shutting the plant down. Once minus 15 degrees centigrade is reached for a prolonged time period, it is difficult to overcome this freezing problem.1

Coal conversion

This process involves the conversion of high-sulfur coal to oil or gas, removing much of the sulfur in the process. With advances in technology and increasing energy prices, this process will become increasingly attractive making utilization of high-sulfur coal feasible. While no commercial operation currently exists, there are numerous pilot plants in operation.

1Personal interview with Richard Grieves, Energy and Mineral Resources Research Institute, Iowa State University, Ames, Iowa.
Two of the most significant coal conversion technologies include solvent refining and coal gasification. In the solvent refining process, pulverized coal is refined yielding a liquified product having a sulfur content of 0.6 percent and a heat content of approximately 16,000 BTU's per con. This occurs regardless of the coal feedstock quality. Coal gasification involves reacting coal, steam, and oxygen under heat and pressure. A synthetic product is formed which has the characteristics of a low BTU gas [Elliott, 1974]. The coal conversion processes, based on current estimates, remain more costly than other methods of sulfur removal. Therefore, in this analysis, conversion of coal to other types of energy is not considered.

**Sulfur oxide captured within the boiler--fluidized-bed combustion**

The fluidized-bed combination method involves capturing $SO_2$ within the boiler immediately following the combustion of high-sulfur coal. This process involves intimate contact between limestone, coal, and the combustion gases in a fluidized-bed boiler. This is achieved by employing a cushion of air to suspend crushed limestone particles and burning coal. The suspension promotes a reaction of $SO_2$ with the calcined limestone sorbent. Sulfate and ash are formed and then continuously removed from the boiler [Elliott, 1974].

**Removing $SO_2$ from combustion products before discharge**

The conversion process and the removal of $SO_2$ from stack gases (tail-end removal or scrubbing) can be accomplished in many ways.
Classification of these processes depends on whether the end product after $SO_2$ removal is recovered or thrown away. In the throw away process, the by-product is either deposited in a nearby pond or landfill or trucked to remote disposal sites. The recovery process yields a usable product such as sulfur, sulfuric acid, or fertilizer-based compounds [Elliott, 1974].

Another method of classifying tail-end sulfur removal systems depends on the type of system used. Stack gases can be cleaned of sulfur by the use of either wet or dry scrubber systems. In the dry system, there is no need for reheating in order to raise the temperature making the use of dispersion of the gas possible. Therefore, the dry system appears more advantageous but the wet system is more common.

There numerous variations of types of scrubbing systems under consideration. For the purpose of this study, three types are considered more closely because of data and time restrictions. The processes considered include a wet limestone process, a magnesia slurry variation, and a clear liquor variation.

There are three main components in a limestone scrubbing system: the scrubber, the reaction tank, and the settling pond. The scrubber promotes intimate mixing of the flue gas with limestone-water-mixture. The limestone reacts with the sulfur in the reaction tank to form calcium sulfite and calcium sulfate. These are removed from the scrubber and settled out in a settling pond [Elliott, 1974].
The magnesia slurry process uses magnesium oxide (MgO) to absorb SO₂. This produces magnesium sulfite (MgSO₃) by oxidation. The SO₂ is then recovered and the MgO is recycled.

The final process considered is the clear liquor variation. In this process, the stack gas is scrubbed to simultaneously remove the SO₂ and absorb particulates with an acidic solution of magnesium sulfites. Sulfite crystals are removed from the slurry and converted to trihydrates which are dried and calcined.

Tall stack diluting

Tall stacks are also presently being used. Their sole purpose is to emit the sulfur over a larger area before the SOₓ affects health. In essence, the amount of SO₂ emitted is not reduced, but rather it is dispersed over a wide area to satisfy the ambient air quality standards. This method relies primarily on local wind currents. Therefore, if weather conditions are such that the SO₂ is not dispersed, either a power cutback is necessary or secondary measures for SO₂ reduction need to be used.

Sulfur Oxide Removal Costs

Two SO₂ removal methods are considered in this analysis of naturally low sulfur coal, and coal benefication.¹ The estimated costs of each of these methods are then used to determine the sulfur credit for

¹Scrubbing costs are not incorporated in the study as comparison of these costs with coal mixing and coal benefication indicated that they would not come into the LP solution.
crop residues. Coal blending is a plant specific technology and one of the major factors in determining costs in plant size. Coal benefication is assumed to be mine specific and the cleaned coal is treated as another coal type with the costs of coal benefication added on to the coal price. In many cases, coal cleaning is not sufficient in attaining the sulfur dioxide standards. In this case, additional blending is assumed.

**Coal blending costs**

The costs of blending coal to remove sulfur depends on the additional cost per MMBTU of the low sulfur coal required to meet the sulfur regulation. This additional cost can be determined through a series of basic equations. Assuming that only two coals are available for plant use and that coal number two is low in sulfur, then the sulfur content of the coal mix is

\[ S_m = R S_1 + (1-R) S_2 \]  

(A.1)

where:

- \( S_m \) is the sulfur oxide emissions of the coal mix;
- \( R \) is the proportion of coal one use; and
- \( S_i \) is the amount of sulfur oxide emitted by coal.

The amount of BTU's per pound of coal mix is determined by

\[ BTU_m = R BTU_1 + (1-R) BTU_2 \]  

(A.2)

where:

- \( BTU_m \) is the heat value of the coal mix expressed in BTU's per pound; and
- \( BTU_i \) is the heat value of coal i.
By dividing equation (1) by equation (2) the amount of emissions of \( \text{SO}_2 \) per MMBTU (E) (Equation 3) is determined. Unless E is less than or equal to the environmental standard, adjustment of R is required. To find the coal mix needed to satisfy this restriction, R is determined by substituting equations (1) and (2) into (3) and solving for R, we find that

\[
R_s = \frac{S_2 \times 10^6 - E_A \text{BTU}_2}{E_A (\text{BTU}_1 - \text{BTU}_2) + (S_2 - S_1) \times 10^6}
\]  

(A.4)

where:

- \( E_A \) is the maximum emissions allowed;
- \( R_s \) is the proportion of coal one that can be burned and still meet the environmental standards; and all other variables are previously defined.

The price of the coal mix can be

\[
P_m = R_3 P_1 + (1 - R_3) P_2
\]  

(A.5)

where:

- \( P_m \) is the price of the coal mix in dollars per MMBTU; and
- \( R_s \) is the proportion of coal one that can be used and still meet the environmental restrictions; and
- \( P_i \) in the price of coal i in dollars per MMBTU.
Then by subtracting equation (5) from $P_1$, the opportunity cost ($OC$) of this method of sulfur removal is determined

$$OC = P_1 - P_m$$  \hspace{1cm} (A.6)

where:

$OC$ is the estimated opportunity cost in dollars per MMBTU.

In the model this is done directly as the linear program chooses the least cost coal mix available and still meet the sulfur constraint.

### Table A.6 Estimated fixed benefications costs by coal type, 1975

<table>
<thead>
<tr>
<th>Coal Origin</th>
<th>Percent Weight Recovery</th>
<th>Coal Output Quantity $^a$</th>
<th>Total Fixed Costs $^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illinois</td>
<td>82.4</td>
<td>692,160</td>
<td>0.978</td>
</tr>
<tr>
<td>Iowa</td>
<td>71.5</td>
<td>600,600</td>
<td>1.127</td>
</tr>
<tr>
<td>West Kentucky</td>
<td>81.8</td>
<td>687,120</td>
<td>0.985</td>
</tr>
</tbody>
</table>

$^a$ Derived by multiplying annual coal input by the percent weight recovery.

$^b$ Derived by dividing annual fixed costs by the amount of coal output.

### Coal beneficitation costs

Two plant sizes are examined with capacities of 70 and 250 ton per hour coal input rates. Economics of scale dictate that the 250 ton per hour plant is more typical of the size that would be economically feasible.
in Iowa. Because of these economies of scales, the processing plant would be located at the mine rather than at the electric generating site. Therefore, a single cost per MMBTUs is determined for cleaning coal. This cost, incurred by a power plant using beneficated coal, is a function of the amount of "clean" coal used.

In examining the costs, both fixed and variable costs are estimated. Fixed costs for a 250 ton per hour coal benefication plant are estimated to be $676,857 per year. In converting annual fixed costs to a per ton basis, it is assumed that the annual raw coal input is 840,000 tons when the plant is operating on two seven hour per day shifts, five days a week, 48 weeks per year. Fixed costs are derived in Table A.6.

Variable costs of a plant this size include utilities; lime and magnetite supplies; the front end loader's fuel, lubricants, etc.; repairs and maintenance; and the labor (Table A.7). Total costs then vary on type of coal assumed. The range of total costs is $1.93 per ton for Illinois coal to $2.15 per ton for Iowa coal.

The amount of sulfur reduction occurring varies depending on the amount of pyritiz sulfur in the coal. However, if Illinois, Iowa, and Western Kentucky coals are beneficated, they can meet a 6 pound per MMBTU standard (Table A.8).
Table A.7. Estimated variable costs of a coal benefication plant, 1975

<table>
<thead>
<tr>
<th>Variable Cost Item&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Coal Origin</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Illinois</td>
<td>Iowa</td>
<td>West Kentucky</td>
<td></td>
</tr>
<tr>
<td>Utilities</td>
<td>.078</td>
<td>0.090</td>
<td>0.078</td>
<td></td>
</tr>
<tr>
<td>Supplies:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limestone</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>Magnetite</td>
<td>0.012</td>
<td>0.012</td>
<td>0.011</td>
<td></td>
</tr>
<tr>
<td>Front End Loader</td>
<td>0.050</td>
<td>0.057</td>
<td>0.050</td>
<td></td>
</tr>
<tr>
<td>Repairs &amp; Maintenance</td>
<td>0.182</td>
<td>0.210</td>
<td>0.183</td>
<td></td>
</tr>
<tr>
<td>Labor Including</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fringe Benefits</td>
<td>0.130</td>
<td>0.150</td>
<td>0.131</td>
<td></td>
</tr>
<tr>
<td>Profit</td>
<td>0.500</td>
<td>0.500</td>
<td>0.500</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.954</td>
<td>1.021</td>
<td>0.955</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>Based on data from a 250-tons-per-hour feed capacity plant provided by Chuck Eldridge, Iowa State University.

Table A.8. Estimated washability data for Illinois, Iowa, and West Kentucky coal.

<table>
<thead>
<tr>
<th>Coal Origin</th>
<th>Processed at a Specific Gravity of.</th>
<th>Heat Value After Processing</th>
<th>Sulfur Oxide Emissions of Cleaned Coal</th>
<th>Percent Weight Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illinois</td>
<td>1.60</td>
<td>12,723&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>82.4&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Iowa</td>
<td>1.40</td>
<td>12,735</td>
<td>5.2</td>
<td>71.5</td>
</tr>
<tr>
<td>West Kentucky</td>
<td>1.40</td>
<td>13,313</td>
<td>4.3</td>
<td>81.8</td>
</tr>
</tbody>
</table>

<sup>a</sup>Weighted average of two coal qualities

SOURCE: [Levins, Boehlje, Otte, and Libbin, 1976].
APPENDIX B: CALCULATION OF COMMERCIAL NITROGEN COEFFICIENTS

Information used in deriving commercial nitrogen coefficients include 1974 acres harvested and tons of fertilizer applied by producing area and the 1974 state quantities of commercial nitrogen, phosphorous, and potassium applied by crop. This information is then used in a series of equations to determine average quantities of nitrogen, phosphorous, and potassium applied in pounds per acre by crop. These average quantities were then adjusted for land class and rotation.

Initially, five ratios are determined. Average state and producing area fertilizer ratios are derived by dividing the quantity of fertilizer applied for a given crop by the total harvested acres.

\[ \text{SRATIO}_j = \frac{\text{SFERT}_j \times 2000}{\text{SACRE}_j} \]  
\[ \text{PARATIO}_{ij} = \frac{\text{FERT}_{ij} \times 2000}{\text{ACRE}_{ij}} \]  

where:

- \( \text{SRATIO}_j \) is the average state fertilizer ration for crop \( j \) (pounds per acre);
- \( \text{SFERT}_j \) is the quantity of fertilizer applied in 1974 on crop \( j \) (tons);
- \( \text{SACRE}_j \) is the quantity of land on which fertilizer was applied in 1974 on crop \( j \) (acres);
- \( \text{PARATIO}_{ij} \) is the average fertilizer applied for crop \( j \) in PA \( i \) (pounds per acre);
FERT$_{ij}$ is the quantity of fertilizer applied in 1974 on crop $j$ in PA $i$ (tons); and
ACRE$_{ij}$ is the quantity of land on which fertilizer was applied on crop $j$ in PA $i$ (acres).

A weight (TRATIO) derived for a given PA by dividing the PARATIO$_{ij}$ by SRATIO$_{ij}$. Thus a weight for each PA can be derived. The 1974 state per acre average for nitrogen, phosphorous, and potassium by crop acre then determined. These averages are then weighted by the TRATIO.

The information required for this procedure is taken from the Bureau of Census [1977] and the Economic Research Service [1976] (Tables B.1 and B.2)

Table B.1. The quantity of acres harvested and fertilizer applied for corn by producing area

<table>
<thead>
<tr>
<th>Producing Area</th>
<th>Quantity of Land with Commercial Fertilizer Applied (acres)</th>
<th>Quantity of Fertilizer Applied (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,170,175</td>
<td>157,343</td>
</tr>
<tr>
<td>2</td>
<td>1,324,038</td>
<td>233,442</td>
</tr>
<tr>
<td>3</td>
<td>1,164,281</td>
<td>219,567</td>
</tr>
<tr>
<td>4</td>
<td>1,047,786</td>
<td>175,216</td>
</tr>
<tr>
<td>5</td>
<td>804,477</td>
<td>120,096</td>
</tr>
<tr>
<td>6</td>
<td>715,930</td>
<td>114,880</td>
</tr>
<tr>
<td>7</td>
<td>1,025,952</td>
<td>176,171</td>
</tr>
<tr>
<td>8</td>
<td>1,576,017</td>
<td>268,982</td>
</tr>
<tr>
<td>9</td>
<td>429,313</td>
<td>67,791</td>
</tr>
<tr>
<td>10</td>
<td>682,589</td>
<td>95,602</td>
</tr>
<tr>
<td>11</td>
<td>337,290</td>
<td>51,991</td>
</tr>
<tr>
<td>12</td>
<td>680,242</td>
<td>100,283</td>
</tr>
<tr>
<td>State Total</td>
<td>10,958,090</td>
<td>1,779,384</td>
</tr>
</tbody>
</table>

Table B.2. Quantity of nitrogen, phosphorous, and potassium applied and total acres harvested by crop in Iowa, 1974

<table>
<thead>
<tr>
<th>Crop</th>
<th>Quantity of Land Harvested (thousand acres)</th>
<th>Quantity of Fertilizer Applied by Type (thousand pounds)</th>
<th>Nitrogen</th>
<th>Phosphorous($P_2O_5$)</th>
<th>Potassium($K_2O$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>.11,850</td>
<td>1,203,011</td>
<td>589,708</td>
<td>517,779</td>
<td></td>
</tr>
<tr>
<td>Corn Silage</td>
<td>855</td>
<td>86,864</td>
<td>41,511</td>
<td>34,286</td>
<td></td>
</tr>
<tr>
<td>Alfalfa</td>
<td>1,720</td>
<td>4,947</td>
<td>51,772</td>
<td>52,623</td>
<td></td>
</tr>
<tr>
<td>Other Hay</td>
<td>540</td>
<td>11,340</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Oats</td>
<td>1,900</td>
<td>8,713</td>
<td>17,465</td>
<td>12,042</td>
<td></td>
</tr>
<tr>
<td>Sorghum</td>
<td>19</td>
<td>1,721</td>
<td>705</td>
<td>536</td>
<td></td>
</tr>
<tr>
<td>Soybeans</td>
<td>7,200</td>
<td>7,200</td>
<td>45,465</td>
<td>52,783</td>
<td></td>
</tr>
<tr>
<td>Wheat</td>
<td>44</td>
<td>2,151</td>
<td>1,262</td>
<td>503</td>
<td></td>
</tr>
</tbody>
</table>

**SOURCE:** [Economic Research Service, 1976].

Using the Tables B.1 and B.2, these estimated quantities of nitrogen, phosphorous, and potassium can be determined for corn.

Following the procedure outlined above, we find that

\[
SRAITO_{\text{corn}} = \frac{1,779,384 \times 2000}{10,958,090} = 324.76 \quad \text{(B.3)}
\]

\[
PARATIO_{1,\text{corn}} = \frac{157,343 \times 2000}{1,170,175} = 268.92 \quad \text{(B.4)}
\]

\[
TRATIO_{1,\text{corn}} = \frac{PARATIO}{SRAITO} = \frac{268.92}{324.76} = 0.828 \quad \text{(B.5)}
\]

Thus, the weight for corn in PA 1 is 0.828 and is used to determine the quantities of nitrogen (n), phosphate ($P_2O_5$), and potassium ($K_2O$) for PA one as follows:
\[ N_{\text{corn}} = \frac{1,203,011}{11,850} \times 0.828 \quad \text{(B.6)} \]
\[ = 84.06 \]
\[ P_{2O_5}^{\text{corn}} = \frac{589,708}{11,850} \times 0.828 \quad \text{(B.7)} \]
\[ = 41.20 \]
\[ K_{2O}^{\text{corn}} = \frac{517,779}{11,850} \times 0.828 \quad \text{(B.8)} \]
\[ = 36.18 \]
Means used to derive energy requirements to produce one pound of fertilizer nutrient N, P, P₂O₅, K and K₂O are found in Dvoskin, Heady, and English [1978]. The coefficients used in this study are found in Table C.1.

Table C.1. Energy requirements for production of one pound of fertilizer nutrient N, P, P₂O₅, K, and K₂O

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Natural Gas</th>
<th>Electricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>24.321</td>
<td>.065</td>
</tr>
<tr>
<td>P</td>
<td>1.429</td>
<td>.257</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>3.274</td>
<td>.588</td>
</tr>
<tr>
<td>K</td>
<td>1.162</td>
<td>.180</td>
</tr>
<tr>
<td>K₂O</td>
<td>1.400</td>
<td>.217</td>
</tr>
</tbody>
</table>

Source: [Dvoskin, Heady, and English, 1978]
Erosion control can be accomplished by manipulating several factors including the vegetative cover, slope length, surface sealing, and strength of cohesion. Vegetative cover has the greatest possibilities for manipulation (Shrader, 1975). Therefore, removal of crop residue and soil erosion control are inversely related.

Means of varying vegetative cover include:

1. Rotation that includes at least one year in close growing vegetation;
2. Strip-cropping and terracing;
3. Contouring;
4. Benching; and
5. Contour ridging.

Crop residue removal will increase soil erosion if present practices do not change. Buchele (1975) found that when examining conventional, till plant, and no-till ridges average concentration of soil in runoff water was 73,826, 22,829, and 6,526 parts per million (PPM) respectively in 1973. In 1974, conventional and till plant were approximately equal at 48,000 PPM and ridge had 10,927. Also, he found that approximately 2,600 pounds of crop residues are needed in the field to promote the water infiltration rate and resist wind and water erosion.
To estimate total soil erosion, the Universal Soil Loss Equation (D.1) is applied [Wischmeier and Smith, 1965].

\[ A = R \times K \times L \times S \times C \times P \]  

where:

- \( A \) is the amount of soil lost;
- \( R \) is the runoff and rainfall erosivity index;
- \( K \) is the soil erodibility factor;
- \( LS \) is the dimensionless topographic factor referring to percentage slope and length;
- \( C \) is the cover and management factor; and
- \( P \) is the factor for supporting practices.
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