A Technology
Assessment of
Solar Energy Systems

**Environmental and Economic Evaluation
of Energy Recovery from
Agricultural and Forestry Residues**

MASTER

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A Technology Assessment of Solar Energy Systems

Environmental and Economic Evaluation of Energy Recovery from Agricultural and Forestry Residues

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FORWARD

The U. S. Department of Energy, Office of Environment, Office of Environmental Assessments, is conducting a project entitled Technology Assessment of Solar Energy (TASE) Systems, to evaluate the range of potential environmental, health, and socioeconomic consequences of rapid, large-scale commercialization of solar technologies. The goal of this project is to identify and analyze both the positive and negative effects of solar technology deployment. The project will provide a basis for avoiding potential problems and for grasping opportunities during the transition to solar energy in the U. S.

Massive solar development will force major increases in the use of those raw materials needed to make solar system components. Along with this increased resource consumption and production will come associated pollution. In addition, rapid solar energy development may mean significant secondary or unplanned changes in institutions and lifestyles as the nation moves toward greater use of solar energy systems. The TASE project is designed to provide a quantitative analysis of the direct and indirect effects of solar energy use. In so doing, it will help define an environmentally acceptable solar future.

This report is an element of the TASE Solar Technology Characterization Series. We would like to express our appreciation to Terry Surles of the Argonne National Laboratory for his efforts in preparing this document.

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EXECUTIVE SUMMARY

Agricultural and forestry residues have been converted to energy for centuries. The technologies employed range from straightforward approaches such as combustion to produce heat to more involved approaches such as pyrolysis of the residues to produce medium-Btu synthetic gas, charcoal, and oil. Thus there is no one technology that can be characterized as the best or most promising for conversion of agricultural and forestry residues into energy. Selection of the appropriate conversion method depends on several factors, e.g., the chemical composition of the residue, the quantity present, the immediate need for energy near the site of production, and the economics of the process. Therefore, to accurately assess the potential of agricultural and forestry residues as energy resources, an array of current conversion options should be addressed.

Four conversion methods and five residues are examined in this report, which describes six model systems: hydrolysis of corn residues, pyrolysis of corn residues, combustion of cotton-ginning residues, pyrolysis of wheat residues, fermentation of molasses (i.e., sugar processing waste), and combustion of pulp and papermill wastes. Estimates of material and energy flows for those systems are given per 10^{12} Btu of recovered energy.

Regional effects are incorporated by addressing the regionalized production of the residues. A national scope cannot be provided for every residue considered because of the biological and physical constraints of crop production (e.g., cotton does not grow well in Illinois). Thus, regionalization of the model systems to the primary production region for the crop from which the residue is obtained has been undertaken. The associated environmental consequences of residue utilization are then assessed for the production region. In addition, the environmental impacts of operating the model systems are examined by quantifying the residuals generated and the land, water, and material requirements per 10^{12} Btu of energy generated.

On the basis of estimates found in the literature, capital, operating, and maintenance cost estimates are given for the model systems. These data are also computed on the basis of 10^{12} Btu of energy recovered. The cost, residual, material, land, and water data were then organized into a format acceptable for input into the SEAS data management program.

The study indicates that the most serious environmental impacts arise from residue removal rather than from conversion. Therefore, future development of the technology lies in the development of cropping systems capable of residue removal as much as in the development of improved conversion processes. This conclusion is important for the future development of agricultural and silvicultural residues as biomass energy resources.

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1 COMBUSTION OF COTTON GIN RESIDUES

ABSTRACT

This section contains an analysis of capital and environmental costs of energy recovery from cotton-ginning residues through direct combustion. The analysis concentrates on data from Arkansas, Mississippi, and Texas, which are representative of the country's major cotton-producing areas. A model system for seed-cotton drying based on current designs is used to evaluate the conversion technology. Results of the analysis indicate that use of cotton-ginning residues for drying cotton lint would conserve significant quantities of natural gas and other fuels now used but that excess removal of residues can have a deleterious effect on the soil. Maintaining favorable chemical and structural properties of the soil over several crop years could be more costly, in terms of energy required for fertilizer, than the amount of energy in the residues.

1.1 INTRODUCTION

1.1.1 General System Description

This section concerns the direct combustion of cotton-ginning residues to produce process heat for drying the cotton lint at the ginning facility. Use of these residues for process heat would not only solve a solid waste disposal problem (i.e., the ginning residue) but would also conserve significant quantities of natural gas and other fuels now being used to dry cotton lint. This study provides an accounting of the material and energy flows for incineration of these residues, estimates of the associated capital and operating costs, and quantification of the residuals produced during conversion of the residues.

Before harvesting, cotton fields are sprayed with either desiccants or defoliant, such as pentachlorophenol, calcium cyanamide, sodium chlorate - borate mixtures, magnesium chlorate, aminotriazole, and tributyl-phosphorotrithionite, to open the cotton bolls for harvesting. Defoliation is preferred over desiccation because there is less debris and less green foliage to stain the cotton. However, defoliation is a more critical operation, and premature defoliation may cause adverse qualitative and quantitative changes in the lint and seed.¹ Thus desiccation is the more practical and more frequently used method. Cotton is mechanically harvested by two types of machines, picker-harvesters (also called spindle pickers) and stripper-harvesters. Stripper-harvesters are so named because they remove not only cotton bolls but excessive amounts of field residue as well. The quantity of cotton residue arriving at the gin depends on the machine used for harvesting and the chemical harvest aid. The desiccant/stripper-harvesting approach sends the most field residue to the gin, whereas the defoliant/picker-harvesting approach provides the least amount of residue. A defoliant/stripper harvest would most likely contain more residue than a desiccant/picker harvest. Availability of residue for conversion at the gin varies with local harvesting approaches.

1.1.2 Resource Distribution

The two major foci of cotton production in the United States are the southwest region and the south-central region, with greater acreage devoted to cotton production in the latter (see Fig. 1.1). For example, a three-state area in the south-central region (Arkansas, Mississippi, and Texas) accounted for 64% (approximately 7 million acres) of the land harvested for cotton in 1976 and 50% (5.3 million bales) of 1976 cotton production.³ Only 13% of the 1976 cotton acreage was in Arizona and California, but these two states generated 32% of the 1976 cotton crop. Thus cotton production is more widespread in the south but more productive in the west.

Because of such regional variability the analysis concentrates on cotton production in Arkansas, Mississippi, and Texas. Approximately 1.6 million tons of cotton gin residue were generated by these three states in 1976 (Table 1.1). This residue accounted for 50% of the total cotton gin residues generated in the United States. These figures were calculated from lint yield using a ratio of 1:1.24, lint:cotton gin residue (assuming stripper-harvesting), on a dry weight basis.⁴ Stripper-harvesting leaves approximately 0.75 ton of cotton residue per acre in the field.^{5,6} Total removal of all residue would increase the total residue production for the three states by 5.2 million tons but would greatly increase soil erosion.

These three cotton-producing states contain very productive soils, so they are ideal for evaluating the effects of crop removal on soil and environment. Although the environmental impacts of residue removal from the field are a concomitant of processing it, cotton ginning residue should be considered a field residue rather than a process residue because of the variation in harvesting options, the degree of processing, the scale of the industry, and the composition of the residue.

Table 1.1. Cotton Lint and Gin Residue Production and Energy Value of Residues

Location	Lint ^a (lb/acre)	Gin Residue ^b (lb/acre)	1976 Harvested Acreage (10 ³ acres)	Estimated Ginning Residues (10 ³ tons)	Estimated Residue Heating Value ^c (10 ¹² Btu)
Texas	353	441.4	4,500	984.8	13.8
Mississippi	376	466.2	1,470	342.7	4.8
Arkansas	392	486.1	950	230.9	3.2
Three-State Total	-	-	6,920	1,566.7	21.9
U.S.	464	575.4	10,869.1	3,127.0	43.7

^aData for 1976.³

^bRatio of 1:1.24, (lint:cotton gin residue) was used.⁴ Assumes stripper-harvested.

^cBased on 6,985 Btu/lb (13.97 x 10⁶ Btu/ton).⁴

Fig. 1.1 Cotton Harvested, 1969

1.2 DESCRIPTION OF MODEL SYSTEM

1.2.1 System Description

Cotton produced in the U.S. is ginned at plants located throughout the cotton growing areas. Ginning gives rise to three distinct products: lint (cotton fibers), cottonseed, and ginning residues, which consist of leaves, sticks, stems, hulls, soil, and motes.^{4,7} Two of the products, lint and cottonseed, are marketable; the ginning residues are usually disposed of as wastes. Residue production per bale typically ranges between 98 lb for picker-harvested mid-south cotton and 750 lb for Texas stripper-collected cotton.⁸

The seed cotton must be dried at the plant before it can be ginned. The two primary energy sources used in cotton lint drying are natural gas and propane, and drying one bale typically requires 430,000 Btu,⁹ though the energy requirements for drying vary greatly with environmental conditions and drier design.¹⁰

Designs of systems for recovering gin residues and incinerating them to provide energy for drying have been reported recently by several authors.¹¹⁻¹⁴ The heat exchange efficiencies range from a low of approximately 10% to a high of approximately 40%. Researchers at the U.S. Cotton Ginning Research Laboratory have developed a system with 30% heat-exchanger efficiency.¹² This system provided sufficient heat recovery for processing rates of 6 to 30 bales per hour, which spans production capacities for most cotton gins in the U.S. Thus self-sufficiency at 30% heat recovery can be expected for most ginning operations.

The dry-basis fuel values of cotton gin residues per bale are given in Table 1.2. The fuel values are typical of mid-south spindle-picked and Texas stripper-harvested residues. The per-pound fuel values for the two

Table 1.2. Type and Quantity of Ginning Wastes and Their Fuel Values Obtained from Mississippi Delta Spindle-Picked Cotton and Texas High Plains Stripper-Harvested Cotton per 500 Pounds of Lint Ginned

Type of Waste	Spindle-Picked			Stripper-Harvested		
	Quantity ^a (lb)	Moisture Content ^a (%)	Fuel Value ^b (Btu)	Quantity ^a (lb)	Moisture Content ^a (%)	Fuel Value ^b (Btu)
Leaf	21	12	144,800	100	11	696,700
Sticks, Stems, and Hulls	35	16	231,000	570	12	4,111,400
Motes and Lint-Cleaner Waste	42	11	289,900	30	10	209,500
All types	98	-	675,700	700	-	5,017,600

^aEstimated from various laboratory observations.

^bRounded to nearest hundred.

Source: ref. 8.

harvesting systems are within 5% of each other (mid-south fuel value 6,895 Btu/lb; Texas fuel value 7,168 Btu/lb), and the mean fuel value (7,032 Btu/lb) can be used as representative. From these data it does not appear that the gin residue from spindle-picking systems will meet the average 430,000 Btu/bale required for drying seed cotton (30% of 657,700 Btu/bale is 207,710 Btu). But gin residues from stripper harvest systems will provide more heat than the amount necessary for drying. A recent study of seed cotton drying in Arkansas indicates an average fuel consumption of 175,000 Btu/bale with a range of 71,000 to 380,000 Btu/bale, whereas a similar study on a California dryer found fuel consumption to range from 329,000 to 406,000 Btu/bale.¹⁵ Thus it is very difficult to estimate fuel requirements for drying, but current research indicates that gin residue will on the average be more than sufficient for seed cotton drying. Typical ratios of cotton gin residue to lint reported by various authors are given in Table 1.3. For this study stripper-harvested cotton arrives at the gin with an average residue/lint ratio of 1.25.

1.2.2 Equipment

The model system proposed for seed cotton drying is simple and consists of three unit operations: separation, combustion, and heat transfer. This system does not have a gas scrubber on the incinerator, so a worst-case residual estimate can be provided and the most economical design can be used to evaluate the conversion technology. Thus only two major equipment requirements exist for the system: an incinerator with feeder and heat recovery unit.

1.2.3 Energy and Material Flows

The operating material and energy flows for the system are shown in Fig. 1.2 and Table 1.4. The plant and processing capacities are typical of the industry; the residue production level (750 lb per 500-lb bale stripper-harvested cotton) was selected so that sufficient residue for combustion will be realized.

Table 1.3. Dry Weight Relationship Between
Cotton Gin Residue and Lint

Harvesting Approach	Residue/Lint Ratio	Source
Picker (spindle)	0.30	Moore and McCaskill, ¹⁶ Pendleton, ¹⁷ McCaskill and Wesley ¹²
Stripper	1.00	Larson et al. ¹⁸
Stripper	1.24	Griffin ⁴
Stripper	1.50	Moore and McCaskill, ¹⁶ Pendleton, ¹² McCaskill and Wesley ¹²
Stripper	1.25	Cotton Residue Model

Fig. 1.2. Flow of Energy and Material in the Cotton Residue Combustion System

Table 1.4. Material and Energy Flows for
Cotton Residue Combustion System

System Variable	Material Flow	Energy Flow
Plant Capacity	20,000 Bales/Year ^a	-
Processing Rate	20 Bales/Hour	430,000 Btu/Bale (drying requirement)
Residue Feed Rate ^b	15,000 lb/Hour	7,032 Btu/lb (heat value)
Heat Exchange Efficiency		30%

^aAssuming 1,000 hr/yr operation.

^bCorresponding to 750 lb of residue per bale of stripper-harvested cotton.

In summary, the model system considered here is of an average size for the industry, assuming seed cotton has been stripper-harvested and that no environmental control technology has been used during conversion.

1.3 ENVIRONMENTAL DATA

1.3.1 General Soil Effects

Total removal of residues from cotton, corn, and wheat crops has the same ultimate effect on the soil although the rate will vary because of crop root system, plant physiology, climatic conditions, and soil properties. Soil destruction begins with the first harvest of residue because the soil is completely exposed to water and wind. Brady¹⁹ reports that Wischmeier and Mannering found that removing residues increased runoff from 0.52 inches to 0.98 inches on 678 plot-years of corn. When residues are removed, the raindrop effect destroys surface soil structure, causing puddling, decreased water infiltration, soil compaction, reduced porosity, and a loss of organic matter. In wheat and cotton growing areas, wind takes over after the soil has dried. The wind sorts the surface material, blowing away the fines and leaving only the semisterile skeletal matter.²⁰

Organic matter acts as a binding agent to develop and maintain soil structure, by maintaining good tilth, increasing infiltration, maintaining soil porosity, and acting as a counter force against soil compaction.^{19,21} Organic matter also serves as a storehouse for nutrients, increases cation and anion exchange capacity, and chelates micronutrients, protecting plants from potentially toxic concentrations.^{19,21-23} In high-organic-matter soils this material releases approximately 40-80 lb/acre of nitrogen for crops per year.^{22,23} Removal of all residues from fields where corn was grown continuously during a period of 18 years resulted in a 15,000 lb/acre decrease in organic matter.²²

Not all residues need to be returned to the soil to maintain organic carbon content. Larson and others¹⁸ found that by using conservational tillage (e.g., chisel plow), 1% to 57% of the corn area in selected land resource areas of Minnesota and Iowa could have all the residues removed without losing more than 4 tons of soil per acre per year. However, these are only calculated data; the amount of residues that can be safely removed from an area depends on the soil, climatic conditions, and especially management practices such as type of tillage and fertility programs.¹⁸

The adverse effect of removing cotton residues on the chemical properties of soil can be partially overcome by increased fertilizer application. Data discussed in this report concern only the first year that crop residues are removed. In the second crop year, fertilizer application must be increased to replace that portion of the nutrients removed by the grain, residue, and erosion. Maintaining favorable chemical properties over a period of several crop years could be more costly in terms of energy for fertilizer than the amount of energy in the residues. Unfortunately, the adverse impact on the physical properties of the soil can only be slowed down with higher fertilizer rates. It takes the continual passing of crop residues through the soil and being transformed into organic matter to stop the deterioration of soil physical properties.^{21,23}

1.3.2 Some Aspects of Cotton Residue Removal

Table 1.5 shows the inputs needed for cotton production in West Texas, and Table 1.6 shows the nutrients removed with each cotton crop. The harvesting of cotton leaves 0.75 ton of residue in the field per acre and removes 0.25 ton/acre of residue that will become cotton gin wastes.^{4,5} Even with application of nitrogen, phosphorus, and potassium in fertilizer programs, total removal of all cotton residue will adversely affect the soil. Repeated removal of calcium, magnesium, sulfur, and micronutrients will result in a decrease in the supplies of these elements in the soil, and chemical fertilizers will be needed to replace them.

Wind and water erosion are extremely important hazards in the areas where cotton is grown. No specific data were discovered on cotton yield reduction because of wind erosion, but Lyles²⁰ found annual reductions in wheat of 0.17-2.52 bushels/acre and annual reductions in grain sorghum of 0.22-2.69 bushels/acre in West Texas. Thus the environmental impact associated with crop residue removal is a serious constraint to utilization of this biomass resource.

1.3.3 Operating Residuals

During the combustion of cotton residues at a gin, there are three major environmental problems: boiler ash and slag, air emissions, and waste heat. Cotton residue contains on the average 12% noncombustible material.¹⁵ This amounts to 240 lb of solid waste (ash) per ton of residue burned.

Air pollution from the process has been estimated from emissions data for the burning or incineration of similar organic materials. Table 1.7 gives some representative air emission values for the combustion of various

Table 1.5. Inputs Needed to Obtain a Cotton Yield of 1,500 Pounds per Acre of Lint and Seed

	Input per Acre	Input per Ton of Residue Removed
Nutrients		
Nitrogen (lb)	82.0	328
Phosphorus (lb)	13.4	53.6
Potassium (lb)	21.0	84
Seeds (lb)	25.0	100
Pesticides (lb)	11.1	44.4
Gasoline (gal)	8.4	33.6
Diesel Fuel (gal)	15.9	63.6
L.P. Gas (gal)	2.2	8.8

Data sources: refs. 5,24,25.

Table 1.6 Nutrients and Mineral Matter Removed by Cotton Crop^a

Element	Lint and Seed		Residue	
	Lb per Acre	Lb per Ton	Lb per Acre	Lb per Ton
Nitrogen	40.1	40.1	34.8	34.8
Phosphorus	8.9	8.9	4.5	4.5
Potassium	12.5	12.5	29.4	29.4
Calcium	1.8	1.8	27.7	27.7
Magnesium	3.6	3.6	8.0	8.0
Sulfur	1.8	1.8	-	-
Copper	0.06	0.06	-	-
Manganese	0.11	0.11	-	-
Zinc	0.32	0.32	-	-
Mineral Matter	-	-	84.0	84.0

Data sources: refs. 21,26,27.

^aAn assumption was made that a linear relationship existed between crop yield and nutrient uptake; therefore data were adjusted for a yield of 1,500 pounds/acre.

biomass sources. Regarding air quality, it should be noted that since defoliants or desiccants are applied close to harvest, these chemicals may also be present in the stack gases. However, it is not now possible to quantify the amounts of such chemicals emitted.

Waste heat results from the operation both because of inefficient heat transfer and also because of excess residue that is disposed of by incineration. Approximately 13×10^6 Btu of heat are lost into the air per ton of residue incinerated. Much of this heat could be utilized by developing an alternative system such as the one proposed by Lalor and Smith.²⁹ They describe an 800-kW power plant in which both heat for drying and electricity for ginning would be supplied. The total estimated cost for the system is \$545,000, which includes an incinerator (\$125,000), a waste heat boiler (\$40,000), a turbine generator (\$85,000), miscellaneous equipment (\$85,000), and building, foundations and installation (\$210,000).

The operating residuals generated by cotton gin residue combustion have been tabulated per 10^{12} Btu, in Table 1.8.

1.4 ECONOMIC DATA

1.4.1 Capital Costs

The incineration system for combustion of cotton gin residues and generation of process heat requires two material components: a multiple-chamber incinerator with a gas pilot and a heat recovery unit. On the basis of a processing rate of 20 bales per hour (8.6×10^6 Btu/hr), 1,000 hr per year operation, and a 30% heat recovery efficiency, approximately 2 tons per hour of cotton gin residue (14.1×10^6 Btu/ton) will have to be incinerated.

Table 1.7. Air Emissions From Combustion of Biomass and Related Materials

Source	Pounds per Ton of Material Burned				
	Particulates	SO _x	NO _x	CO	HC
Wood Waste Combustion ^a	30	1.5	10	2-60	2-70
Agricultural Residues, ^b Open Burning	5-18	-	1-2	20-70	2.1-10
Municipal Refuse, Multiple Chamber ^a	30	2.5	3	35	1.5
Cotton Gin Residue, Estimated	21	2	4	37	3.9

^aSource: ref 28.

^bSource: ref 29.

Table 1.8 Residuals Data for Combustion of Cotton Residues

Residual	Gross Residual per 10 ¹² Btu Input	Gross Residual per 10 ¹² Btu End-Use Energy
Particulates	744	9,150
SO ₂	69	850
NO _x	142	1,750
CO	1,313	16,150
Hydrocarbons, Toxic Hydrocarbons	138	1,700
Slag, ash	8,720	104,640

The cost of a 1,200-lb/hr incinerator with feeder was \$50,000 in 1977.³¹ Using a cost-scaling approach known as the "six-tenths factor" method,³² the increased cost for the larger unit (4,000 lb/hr) was calculated as follows:

$$L = S \times (C_L/C_S)^{0.6}$$

where:

L = cost of the larger unit
 S = cost of the smaller unit
 C_L = capacity of the larger unit
 C_S = capacity of the smaller unit

Therefore $\$50,000 \times (4,000/1,200)^{0.6} = \$50,000 \times 2.059 = \$102,967$. The cost of a heat recovery unit is 100% the cost of the incinerator. Labor on the 1,200 lb/hr unit was 4% of the total cost, and overhead and profit came to 10%.³⁰ It is assumed that these costs would be proportionally the same for the larger unit. The capital cost data are summarized in Tables 1.9 and 1.10. The total estimated capital cost for this system in 1972 dollars is \$158,093.

1.4.2 Operating and Maintenance Costs

Annual operating and maintenance costs (in 1978 dollars) have been computed as follows for the incineration and drying system:

• Labor cooperation and maintenance (0.1 hr/bale at \$10/hr)	\$20,000
• Supervision (20% of labor)	4,000
• Overhead (60% of labor plus supervision)	14,000
• Parts (\$1,000/year)	<u>1,000</u>
• Total	\$39,000

Operating and maintenance costs, in 1972 dollars, would be \$26,263.

Table 1.9: Capital Costs for Model System for Model System for
Combustion of Cotton Gin Residues for Process Heat

Component (Industrial Sector)	Cost in 1978 Dollars
Incinerator with Feeder (Plumbing and Heating Equipment)	95,760
Heat Recovery Unit (Plumbing and Heating Equipment)	95,760
Transportation	14,414
Labor for Installation (634 hr at \$13/hr)	8,242
Overhead and Profit	20,593
All Components	234,769

Table 1.10. Capital Expenditures and Materials Summary for Model System for
Combustion of Cotton Gin Residues for Process Heat

	1978 Dollars	Deflator	1972 Dollars
Total Capital Cost	234,769	1.485	158,093
Materials	191,519	1.485	128,969
Transportation	14,414	1.485	9,707
Construction Labor	8,242	1.485	5,550
Profit and Overhead	20,593	1.485	13,867
Annual System 10^{12} Btu Output		8.6×10^{-3}	
Total Capital Cost/ 10^{12} Annual Btu		18.383×10^6	
Number of Years to Construct Facility		1	
Expected Life of Facility (yr)		20	
Man Years to Construct Facility		0.317	
Man Years/ 10^{12} Btu Annual Output		36.9	
Estimated Land Use		0	

1.5 SUMMARY OF FINDINGS

On the basis of 10^{12} Btu of energy output by the system, the material, energy, residual, and cost inputs and outputs for the system are summarized in Table 1.11. It would require 116 such systems to substitute for 10^{12} Btu of natural gas or other appropriate fuel.

Table 1.11. Cotton Gin Residue Combustion Input/Output Summary

System Variables	Inputs (per 10^{12} Btu)	Outputs (per 10^{12} Btu)
<u>Size</u>	<u>Fuel</u>	<u>Air Pollutants</u>
Processing capacity -- 20,000 bales per year	2.326×10^6 bales will require 10^{12} Btu for drying and 116 gins	Particulates: 9.15×10^3 tons SO _x : 0.85×10^3 tons NO _x : 1.75×10^3 tons CO: 16.15×10^3 tons Hydrocarbons: 1.7×10^3 tons
Annual fuel requirement -- average of 430,000 Btu/bale or 8.6×10^9 Btu per year at capacity	0.872×10^6 tons of cotton residue (stripper-harvested) will be at mill (heating value 14.1×10^6 Btu/ton)	<u>Water Pollutants</u> None
<u>Description</u>		<u>Solid Waste</u>
Cotton residue incinerator with a natural gas - fired burner for start-up or auxiliary heating coupled with a heat exchanger for drying seed cotton	Total energy content of cotton residue 12.3×10^{12} Btu Energy required for drying (30% efficiency) 3.689×10^{12} Btu	Boiler ash/slag: 104,640 tons
<u>Components</u>	<u>Water</u> None	<u>Energy</u> Effective process heat: 10^{12} Btu (replaces natural gas)
Incinerator		Wasted process heat: 11.3×10^{12} Btu (from excess residue burned to reduce solid wastes)
Gas burner	<u>Land</u>	
Heat exchanger (30% efficiency)	No additional requirements	
Fan	conversion system anticipated	
Exhaust air scrubber (optional)		
Cyclone separator (should already be at plant)	<u>Costs</u>	
	Capital: \$18.38 million	
<u>Major Environmental Problems</u>	Operation and maintenance: \$3.08 million	
Boiler ash/slag disposal		
Air emissions	Credits: \$2.91 million	
Waste heat		

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2 COGENERATION FROM BLACK LIQUOR AND BARK AND WOOD RESIDUES

ABSTRACT

This section evaluates capital costs and environmental residuals of energy recovery from black liquor and bark and wood residues through direct combustion to generate heat, steam, and electricity. A large integrated Kraft-process pulp and paper mill is used in the analysis to represent the most common type of U.S. mill, and data are presented on construction and operation of the mill and on the energy involved in the conversion processes. Use of black liquor and bark and wood residues for generating energy is an economically and environmentally sound practice for mills in the U.S. producing pulp and paper, but it is noted that removal of residues from logging areas depletes the soil. The model system requires 4 acres for processing and storage and will dispose of wastes from a paper mill consuming 54 acres of mature trees per year of operation.

2.1 INTRODUCTION

2.1.1 General System Description

Forestry and wood manufacturing residues have been used for energy generation since old times, and several technologies have been employed to produce fuel forms from this waste material.

Cogeneration from bark and wood wastes has been proved to be a profitable technology for energy generation and safe disposal of wood manufacturing wastes. The vast amount of residues (black liquor and bark and wood refuse) yielded by the pulp and paper industries is burned by these companies to cogenerate steam, heat, and electricity. During combustion a considerable amount of residuals is released into the air, water streams, and soil. Besides polluting the environment, these residuals represent losses of capital and energy. Since pulp and paper mills demand great amounts of energy in the form of heat and electricity and also generate huge tonnages of residuals, this study is addressed to the environmental residual and capital cost evaluation of energy recovery from cogeneration with black liquor bark and wood residues.

Conversion of bark and wood residues to energy by combustion is examined here, and a model system is described for material estimates and energy flow purposes. A national scope is provided for the residues considered and the associated environmental consequences of residue utilization. Energy operating this system is given in 10^{12} Btu, and the environmental impacts of operating this model system are examined by quantifying the residuals generated, land required, water needed, and material utilized in terms of 10^{12} Btu of energy produced.

Capital operating and maintenance cost estimates are given for the model system on the basis of information found in the literature and obtained from personal communication. The data on costs, residuals, materials, and

land and water requirements have been organized into the format required for the SEAS (Strategic Environmental Assessment System) computer program.

2.1.2 Resource Characteristics

In the manufacture of pulp and paper, several fuels are used, including fossil fuels (oil, coal, and natural gas), residues from bark and wood, and spent liquor solids. The pulp and paper industry is, in fact, the fourth largest consumer of fuels and electricity in the United States.¹ In 1970 the industry consumed 1.5 Quads of energy, and in 1975 it used 1.896 Quads.²

In the past, residues were either dumped or burned, but most of today's mills burn their residues for the cogeneration of process steam and electricity. In 1975 the pulp and paper industry consumed 0.830 Quads of self-generated and waste fuels,² and in 1976 the industry generated and used a total of 0.98 Quads (0.124 Quads of bark, 0.791 Quads of spent liquor, and 0.069 Quads of hogged fuel -- a mixture of bark, sawdust, scraps, and slabs of wood).³

Large mills are usually integrated, producing both pulp and paper, whereas smaller ones are frequently nonintegrated, producing either one or the other. Most of the paper produced in the U.S. is manufactured by integrated mills processing wood cellulose as main raw material.² Over ten different pulping processes are employed by the paper-making industry, but most of the pulp and paper produced today have been processed through the Kraft method.

The major unit operations in a pulp or paper mill are: (a) preparation (barking, chipping); (b) pulping (chemical, chemical/mechanical, mechanical); (c) heat and chemical recovery; (d) washing and bleaching; (e) stock preparation; and (f) paper and board manufacture (sheet formation, mechanical water removal and drying).¹ The main energy-consuming operations are (b), (c), (d), and (f), and the main pollution sources are (b), (c), and (d).¹

2.2 DESCRIPTION OF MODEL SYSTEM

2.2.1 Technology Involved

The Kraft process, which, as mentioned previously, is the pulping process most prevalent in the United States, is used as the basis for our model forestry-residue conversion system (see Fig. 2.1 for a schematic of the process). In the Kraft process, wood chips are cooked for 2 to 4 hours in an alkaline solution of sodium sulfate and sodium sulfite under high temperatures and pressures (350°F, 100 psig) in order to separate the cellulose fibers from the lignin and other materials.^{2,4} The spent cooking liquor, known as black liquor, contains the lignin and the chemicals used in the process. The liquor passes through a recovery system, and most of the chemicals are obtained and reused; the remaining lignin plus other combustible materials are solidified (55-65% solids) by drying. Thereafter the solidified liquor is conveyed to the furnaces/boilers and combusted to generate heat, steam, or electricity.

Fig. 2.1. The Kraft Process

If 10,000 lb of weak black liquor (16.5% solids) enters the recovery system, then about 987 lb of dissolved lignin can be burned in the furnace, 14,300 lb of steam and 2,281 lb of CO_2 are generated, and 1,925 lb of water vapor and 6,494 lb of N_2 are released.⁶ Also during this combustion, 8,473 lb of air and 6,359 lb of water are introduced into the furnace boiler.⁶ The black liquor generated from the Kraft process in producing one bone-dry (BD) ton of pulp has been found to contain 2,334 lb of lignin, 257 lb of Na_2CO_3 , 697 lb of NaOH , 439 lb of Na_2S , and 12,425 lb of water.⁴

It has been estimated that production of a one BD ton of Kraft pulp by the batch digester process requires 325 kWh of electric energy and 8,500 lb of steam at about 80 psig (equivalent to 10.67×10^6 Btu) and that one ton of spent liquor solids burned in the recovery furnace releases 13.2×10^6 Btu.²

Arthur D. Little¹ has computed the following data concerning the production of one air-dry (AD) (10% moisture content) ton of Kraft pulp (= 1,800 BD lb): the power boiler uses 312 BD lb of bark residues plus 90 BD lb of wood chip residues and 3.9×10^6 Btu of fossil fuels to produce 3,800 lb of steam (800 lb from bark and wood chips and 3,000 lb from fossil fuels). In the same mill and for one AD ton of pulp, 15,800 lb of steam (12,000 lb from the chemical recovery system and 3,800 lb from the boiler) in a back-pressure turbine generate 720 kWh of electricity, of which 580 kWh are used and 140 kWh are credited.

In the direct combustion of black liquor, wood, and bark wastes, various types of wood burners are used: the Dutch oven, the fuel cell, the spreader-stoker, the inclined grate, and the fluidized bed. A Dutch oven with a flat grate is used in small and old operations: here the fuel is dumped through the furnace roof and burned in a cone-shaped pile on the grate.⁷ In larger operations other types of furnaces and boilers are used. Fuel cell boilers are mostly used in the drying kilns of small companies and produce up to 30,000 lb/hr of steam (25 psig). The spreader-stoker system with traveling or vibrating grates is common in newly constructed plants and can be used either by small plants (25,000 lb/hr steam rate) or by larger ones (500,000 lb/hr steam rate). The inclined-grate furnace is like that used for incineration of municipal solid wastes. The fluidized-bed heat recovery system can burn wood residues containing up to 55% moisture. Because of the high moisture content of the bark and wood residues, the various burning processes have to spend energy to evaporate the water. Commonly, in these furnaces an auxiliary fossil fuel is also used to maintain the flame and to provide steam.

The moisture content of wood residues is the main factor that determines their economic suitability as combustion feedstocks. On the average, wood containing 50% moisture requires close to 13% of its total heat value to evaporate the water. Therefore, in order to be combusted, very moist wood material has to be dried first, and such drying requires additional use of fuel.⁸ Bark residue has two main disadvantages as a fuel: an effective heating value of only about 4,000 Btu per pound because of a 50% moisture content (dry bark's heating value is about 9,000 Btu/lb), and a lack of homogeneity (because of species, season, moisture, dirt content, etc.).⁹ Large quantities of air are required for complete combustion of bark residue.

Hogged wood fuel has an average heating value of 3,850 Btu/lb at 50% moisture and possesses characteristics similar to bark residue. The heating value of solidified black liquor (50% moisture) is about 6,700 Btu/lb.²

The model selected for this study is that of an integrated mill using the Kraft process, in which black liquor and bark and wood are combusted for heat, process steam, and generation of electricity. This model represents an average U.S. pulp and paper mill. The requisite unit processes for energy generation from black liquor and bark and wood residues in the model mill are depicted in Fig. 2.2. The main operations required for residue utilization are generation of bark and wood residues, black liquor generation, drying, storage, and finally combustion.

The solidified black liquor is burned in the recovery furnace to supply heat for making high-pressure steam.¹⁰ The high-pressure steam is used to generate electricity and low-pressure process steam. The combustible gases (300°F) released from the furnace supply heat to the evaporator.

2.2.2 Energy and Material Flows

The material and energy flows for operation of the model system are summarized in Table 2.1, and the data give typical operating flows that could be found in an average Kraft process pulp and paper mill in the United States.

In this model mill, in addition to bark and wood residues and black liquor, fossil fuels are used to generate additional steam and electricity as follows:

Additional steam (0.1×10^{12} Btu/mill implies 0.5×10^6 Btu/BD ton of pulp)

(a) from gas: $(0.35 \times 10^6 \text{ Btu/BD ton of pulp}) \times 200,000 \text{ BD}$
 $= 0.07 \times 10^{12} \text{ Btu/yr}$

(b) from oil: $(0.15 \times 10^6 \text{ Btu/BD ton of pulp}) \times 200,000 \text{ BD}$
 $= 0.03 \times 10^{12} \text{ Btu/yr}$

Additional electricity (188×10^9 Btu/mill $\times 0.3$ by gas implies
 $(0.28 \times 10^6 \text{ Btu/BD ton of pulp})$ implies 0.56×10^{12} Btu/yr/mill

2.3 ENVIRONMENTAL DATA

2.3.1 Environmental Consequences of Residue Utilization

It has been estimated that annual U.S. production of forestry residues amounts to $3.5 \times 10^9 \text{ ft}^3$ from unused and precommercial thinning.⁸ In 1970, forest residues were estimated to be approximately 49 percent of logging wastes, 37 percent of standing biomass, and 14 percent of mill by-products.¹¹

Lumber, plywood, pulp, and allied industries reprocess part of the wood residues into pulp and paper, composition board, and fuels. More than

Fig. 2.2. Model Cogeneration System for Bark and Wood Residues

Table 2.1. Material and Energy Flows for Energy Recovery from Model Residue-Conversion System

System Variable	Material Flow	Energy Flow
Plant Capacity	200,000 BD tons pulp/yr	830 kWh electricity and 20,186 ^a lb of steam (80 psig) or 20.83 x 10 ⁶ Btu per BD of pulp [0.5 x 10 ⁶ kWh and 12.2 x 10 ⁶ lb steam (80 psig) per day]
Processing Rate	606 BD tons pulp/day ^b	
Residue Production Rate	360 BD lb bark residue/BD tons of pulp 80 BD lb wood chip residue/BD tons of pulp 2.75 tons (55% solids) black liquor/BD tons of pulp	18 x 10 ⁶ Btu/BD tons of residue 17 x 10 ⁶ Btu/BD tons of residue 9.9 x 10 ⁶ Btu/ton of residue
Steam Generation (68% efficiency)		3.9 x 10 ¹² Btu steam (116 x 10 ⁶ kWh electricity) ^c

^aOne pound of steam at 80 psig and 312°F saturation temperature is equivalent to 891.7 Btu; therefore 18 x 10⁶ Btu of steam is equivalent to 20,186 lb of steam.

^b330 days operation/year (=90% of the year); 24 hr/day.

^c116 x 10⁶ kWh electricity is generated by the power boilers and turbines utilizing 30.8% of steam produced. Conversion efficiency of steam to electricity is 33%.

30% of the raw material used in the pulp and paper industry in the U.S. originates from wood wastes.⁸

Especially in large plants, disposal of wood residues may become a problem; therefore the use of residues for generating energy is environmentally and economically sound. The most common method for converting wood residues to energy forms is their direct combustion for generating heat, steam, and electricity.

One acre of U.S. forest produces, on the average, close to 6 BD tons of bark and wood residues per year (equivalent to 102 x 10⁶ Btu of heating value).¹³ Use of these residues for energy generation releases residuals that pollute the air and water streams. An additional and serious environmental consequence of residue utilization is destruction of the physiochemical balance of the soil.

It is estimated^{11,12} that fertilizer inputs in pounds for the production of one BD ton of bark and wood residues (1b per acre annually x 15 year rotation divided by 6 BD ton of residues) are as follows:

Nitrogen (15 lb/acre-year)	37.5 lb
Phosphorus (3 lb/acre-year)	7.5 lb
Potassium (11 lb/acre-year)	27.5 lb
Calcium (10 lb /acre-year)	25.0 lb

The element content of one BD ton of bark and wood residues in (percent and pounds) is:

Carbon (53.3%)	1070 lb
Hydrogen (5.8%)	116 lb
Oxygen (39.2%)	784 lb
Nitrogen (0.2%)	4 lb
Phosphorus (0.01%)	0.2 lb
Potassium (0.12%)	2.4 lb
Sulfur (0.01%)	0.2 lb
Misc. Elements (1.36%)	23.2 lb

Removal of residues from the logging area (and from the forest generally) results in depleting the soil of organic matter and inorganic nutrients. Assuming that 6 BD tons of residues are removed from one acre of forest land, a considerable amount of nutrients is removed too: 24 lb of nitrogen, 6,420 lb of carbon, 1.2 lb of phosphorus, 14.4 lb of potassium, and 1.2 lb of sulfur. Erosion, destruction of the balance of soil microcosmos, unmatched carbon/nitrogen ratio, and decrease of the soil fertility, porosity, and moisture are several concomitant environmental impacts of withdrawal of forest residues from the site of their production.

2.3.2 Land Requirements

Land requirements for the model system are estimated to be (a) 4 acres for storage and combustion of residues and (b) 54 forest acres of 30-yr-old trees per year of operation. After harvesting and processing in the pulp/paper mill, these trees generate 36×10^3 BD tons of bark residue and 8×10^3 BD tons of wood residue for the 200×10^3 BD tons of pulp produced in one year by the model system (that is, 18 such acres per 10^{12} Btu unit input). Therefore, over 15 years, $15 \times 54 = 810$ forest acres would be required. Note that this much land is required for the pulp/paper mill feedstock independent of waste processing; the waste-conversion system per se requires only 4 acres.

2.3.3 Water Requirements

No water is required during combustion of residues. During processing of pulp and paper and generation of bark and wood residues and black liquor, the paper mill requires an estimated amount of water close to 5×10^9 gallons (25×10^3 gallons/BD ton of paper produced).

2.3.4 Operating Residuals

There are two major environmental problems with this conversion approach: air emissions and solid residuals. Major air pollutants are particulates ($3,145$ tons/ 10^{12} Btu), SO_x (105 tons/ 10^{12} Btu), NO_x (0.699 ton/ 10^{12} Btu), CO ($2,097$ tons/ 10^{12} Btu), and hydrocarbons (2.446 tons/ 10^{12} Btu).

Boiler ash and slag are produced at a rate of $2,097$ tons/ 10^{12} Btu. Total solids suspended in the water released have been calculated to be close

to 25 tons/ 10^{12} Btu, and the biological oxygen demand (BOD)₅ is estimated to be about 4 tons/ 10^{12} Btu.

The residuals data have been tabulated for the SEAS model and are found in Table 2.2. These calculations of operating residuals are based on the following assumptions.⁶

- Annual amount of particulates emitted by the furnaces consuming bark and wood residues and black liquor: 273 tons per mill. Output equivalent per Quad, 3.145×10^6 tons.
- Annual amount of sulfur oxides (SO₂) released from the furnaces burning bark and wood residues and black liquor: 0.54 tons per mill. Output per Quad, 0.105×10^6 tons.
- Annual amount of carbon monoxide released from the combustion of bark and wood residues and black liquor: 266 tons per mill. Output per Quad, 2.097×10^6 tons.
- Annual amount of hydrocarbons released from the combustion of bark and wood residues and black liquor: 136 tons per mill. Output per Quad, 2.446×10^6 tons.
- Annual amount of solid wastes (ash and slag) generated by the furnaces: 1,480 tons per mill. Output per Quad, 2.097×10^6 tons.
- Water pollutants from combustion of bark and wood residues and black liquor in pulp and paper mills are assumed negligible. Water use per BD ton of pulp produced, 16.7 tons, and per BD ton of paper produced, 104.3 tons. Waste water released after pulp/paper processing and residue generation contains 10.8 lb total suspended solids plus 1.5 lb of BOD₅ per ton of waste water.

Table 2.2. Residuals Data for Combustion/
Cogeneration from Bark and
Wood Residues

Residual	Gross Residuals per 10^{12} Btu End-Use Energy (Tons)
Particulates	3,145
SO ₂	105
NO _x	699
CO	2,097
Hydrocarbons, Toxic Hydrocarbons	2,446
Ash and Slag	2,097
Total Suspended Solids	25
BOD ₅	4

Table 2.3. Construction Costs of Model System for
Combustion/Cogeneration from Black
Liquor and Bark and Wood Residues

Component	Cost in 1977 Dollars
Boilers and Equipment (3)	6,750,000
Materials for Installation of Boilers	1,800,000
Turbine-Generator	1,700,000
Materials for Installation of Turbine- Generator	300,000
Residue Handling and Preparation Machinery	400,000
Environmental Systems	1,200,000
Engineering	1,500,000
Labor for Construction and Installation (250 x 10 ³ man-hours, \$13/hr)	3,250,000
Operation and Maintenance (14.6 x 10 ³ man- hours, \$13/hr)	190,000
All Components	17,090,000

Table 2.4. Capital Expenditures, Materials Requirements, and
Energy Summary for Combustion/Cogeneration from Black
Liquor and Bark and Wood Residues per 10¹² Btu

	1977 Dollars	Deflator	1972 Dollars
Total Capital Cost	20,210,000	1.43	14,200,000
Materials	12,150,000	1.43	8,500,000
Construction Labor	3,250,000	1.43	2,300,000
Profit and Overhead	3,120,000	1.43	2,200,000
Engineering, etc.	1,690,000	1.43	1,200,000
Annual System 10 ¹² Btu Output			3.9
Total Capital Cost/10 ¹² Annual Btu			5,180,000
Number of Years to Construct Facility			3
Expected Life of Facility (yr)			15+
Man Years to Construct Facility			125
Man Years/10 ¹² Btu Annual Output			32
Estimated Land Use (acres)			4 ^a

^aFor plant site; model system consumes 54 acres of mature trees per year of operation.

- Air emissions from combustion of one ton of wood waste are estimated to be 30 lb of particulates, 1.5 lb of SO_x , 10 lb of NO_x , 2 to 60 lb of CO, and 2 to 70 lb of hydrocarbons.

2.4 ECONOMIC DATA

2.4.1 Capital Costs

Production, harvesting, transportation, and delivery to the furnaces of one BD ton of bark and wood residues are estimated to cost \$23.30 (\$1.34/ 10^6 Btu). To arrive at this figure, the following estimates of materials, energy, labor, and capital inputs were assumed (on the basis of references 8,11-14):

- Two "green" tons of bark and wood residues (50% average moisture content) are equivalent to one BD ton. It is also assumed that one dry pound of residues is equivalent to 8,500 Btu of heating value; therefore one BD ton of residues generates 17×10^6 Btu.
- One acre of U.S. forest produces close to 6 BD tons of bark and wood residues.
- Forest management cost in dollars per BD ton of bark and wood residues is \$15.00 (\$6.00 per acre annually times 15-year rotation of 6 BD tons)
- Fertilizer inputs in pounds and dollars for the production of one BD ton of bark and wood residues (pounds and dollars per acre annually x 15-year rotation divided by 6 BD tons of residues):
 - Nitrogen (15 lb/acre-year) 37.5 lb costing \$1.88 (\$105/ton)
 - Phosphorus (3 lb/acre-year) 7.5 lb costing \$0.43 (\$95/ton)
 - Potassium (11 lb/acre-year) 27.5 lb costing \$1.00 (\$70/ton)
 - Calcium (10 lb/acre-year) 25 lb costing \$0.60 (\$20/ton)
- Pest control cost in dollars per BD ton of bark and wood residues, \$0.20.
- Harvesting cost in dollars per BD ton of bark and wood residues, \$1.20.
- Transportation cost (from the harvesting site to the mill) in dollars per BD ton of bark and wood residues, \$3.00.

In order to estimate the inputs and outputs of the model pulp and paper mill, the assumptions listed above were taken into consideration together with

records from Arthur D. Little,¹ Sittig,^{2,7} Hall et al.,⁴ Cheremisinoff and Morresi,⁸ Reding and Shepherd,¹⁰ Inman et al.,¹² Grantham et al.,¹⁵ Blake and Salo,¹⁶ Gordian Associates,¹⁷ and U.S. EPA⁶ yielding the following data:

- Number of integrated wood pulp and paper mills (Kraft pulping process), 175; annual wood pulp and paper production in BD tons per mill, 200,000.
- Annual wood input in BD tons per mill, 400,000; heating value of one BD ton of wood, 17×10^6 Btu; annual wood (bark not included) residue generation in BD ton per mill (2% of 400,000 BD tons), 8,000.
- Annual generation of bark in BD tons per mill (12% of 400,000 BD tons), 36,000; heating value of one BD ton of bark residue, 18×10^6 Btu.
- Annual sawdust input in BD ton per mill, 120,000; heating value of one BD ton of sawdust, 17.5×10^6 Btu.
- Annual generation of black liquor in tons (55% solids content) per mill, 550,000; combustible content (lignin, carbohydrates, etc.) of black liquor in tons (45% moisture) per mill, 500,000; heating value of the combustible content of a ton (45% water content) of black liquor (1 BD ton releases 13.2×10^6 Btu), 9.9×10^6 Btu ($3/4$ of 13.2×10^6 Btu).
- Annual combustion of wood (including sawdust) residues in BD tons per mill to generate heat, steam, and electricity, 8,000; annual combustion of generated bark in BD tons per mill, 36,000; annual combustion of black liquor in tons (45% water content) per mill, 500,000.
- Furnace/boiler efficiency in steam production per mill, 68%
- Efficiency of conversion of steam to electricity, 33%.
- Annual steam production by the furnaces/boilers combusting bark and wood residues and black liquor in heat equivalent per mill, 3.9×10^{12} Btu; [$(8,000 \text{ BD tons of wood} \times 17 \times 10^6 \text{ Btu}) + (36,000 \text{ BD tons bark} \times 18 \times 10^6 \text{ Btu}) + (500,000 \text{ BD tons black liquor} \times 9.9 \times 10^6 \text{ Btu}) \times 0.68 \text{ efficiency} = 3.9 \times 10^{12} \text{ Btu}$]. Steam is produced by burning black liquor (86%) and bark and wood residues (14%).
- Annual electricity generation by the power boilers/turbines using steam produced by the combustion of wastes in heat equivalent per mill, 396×10^9 Btu (116×10^6 kWh; 1 kWh = 3,413 Btu).
- Annual consumption of steam (produced by burning mill residues and fossil fuels) for heating and process purposes in heat equivalents per mill (3.5×10^{12} Btu from mill wastes + 0.1×10^{12} Btu from fossil fuels), 3.6×10^{12} Btu.

- Annual consumption of electricity in heat equivalents per mill, 566×10^9 Btu (166×10^6 kWh). Power is generated by gas-oil and steam turbines (30% and 70%, respectively).

The capital cost estimates for our model plant are based on data from a survey performed by the North Central Forest Experiment Station, St. Paul, Minnesota.¹⁸ The cost includes expenditures for new boilers, structures, auxiliary plant and turbine plant systems, residue handling and preparation systems, and environmental systems.

The plant uses one power boiler burning bark and wood residues and two main recovery boilers burning the organic matter of black liquor. The energy liberated is used to generate process steam and electricity. In addition a turbogenerator unit is employed.

The basic parts of a boiler are the boiler, grate, dust collector, stack, and supporting frame. In addition, there are auxiliary structures and equipment, as well as equipment for handling sludge and ash. It is estimated that a boiler of 150,000 pounds of steam per hour (pph) capacity (consuming bark and wood) costs \$2,250,000 ($\$15/\text{pph} \times 150,000 \text{ pph} = \$2,250,000$). The installation cost for the boiler is estimated to be close to one-fourth of the cost of the boiler, that is, \$600,000. This boiler is designed to generate process steam at 600 psig. Therefore the cost of three such boilers installed is \$8,550,000 (1977 dollar value).

The turbogenerator costs \$1,700,000 plus \$300,000 for installation. In addition to boilers and tubogenerator, the environmental control systems operating in the model system cost \$1,200,000 (1977 dollar value).

Material and cost estimations are presented in Table 2.3 and capital cost requirements are given in 1977 dollar values. Table 2.4 summarizes capital expenditures and materials requirements for the model system per 10^{12} Btu.

2.4.2 Operating and Maintenance Costs

It has been estimated that 14.6×10^3 man-hours are needed for operation and maintenance of the furnaces/boilers of the model system. Capital cost of operation and maintenance is estimated at \$190,000 (14.6×10^3 man-hours at \$13/hr).

2.5 SUMMARY OF FINDINGS

Table 2.5 summarizes the estimates relevant to the pulp and paper mill residues combusted for generation of steam, heat, and electricity. The numerical data are estimated nationwide averages, and the calculated costs are expressed in 1977 dollars. Estimated energy is given in Btu heat equivalents, and the weights are given in short tons.

Tabulated costs and energy-balance estimations reveal the magnitude of gains and losses depending on whether the residuals liberated during the manufacturing process are recycled.

Table 2.5. Energy Generation from Black Liquor and Bark and Wood Residues

Size	Input (per 10^{12} Btu)	Output (per 10^{12} Btu)
Plant produces 200,000 BD tons of pulp per year.	<u>Fuel</u>	<u>Air Pollutants</u>
Residues generated annually: 36,000 BD tons of bark residue, 8,000 BD tons of wood residue, 302,000 BD tons of black liquor	11.9 x 10^3 BD tons of bark residue, 2.6 x 10^3 BD tons of wood residue, 100.1 x 10^3 BD tons of black liquor	Particulates: 3.145 x 10^3 tons SO ₂ : 0.105 x 10^3 tons NO _x : 0.699 x 10^3 tons CO: 2.097 x 10^3 tons Hydrocarbons: 2.446 x 10^3 tons
<u>Description</u>	<u>Water</u>	<u>Water Pollutants</u>
Steam is produced by burning bark and wood (14%) and black liquor (86%) (both pulp and paper plant residues) and using gas and oil	No water required during combustion of residues	Negligible from the combustion of bark, wood, and black liquor residues
Power generation is conducted by gas and steam turbines (30% and 70%, respectively)	During processing of pulp and paper and generation of residues, 1,128 x 10^3 gallons of H ₂ O will be used (25 x 10^3 gallons of H ₂ O per BD ton of paper produced)	Wastewater released after pulp/paper processing and generation of residues contains 50.5 x 10^3 lb total susp. solids plus 7.02 x 10^3 lb BOD ₅
<u>Components</u>	<u>Land</u>	<u>Solid Waste</u>
Power boiler furnace	4 acres for storage and combustion of residues	Boilers ash and slag: 2.097 x 10^3 tons
Recovery boiler furnaces	(810 forest acres to generate the above residues, plant used for 15 years)	<u>Energy</u>
Turbogenerator	<u>Costs (1977 Dollar Value)</u>	Electricity: 0.102 x 10^{12} Btu
<u>Major Environmental Problems</u>	Capital: \$5,180,000	In steam for pulp and paper processes: 0.898 x 10^{12} Btu
Air emissions	Operation and Maintenance: \$190,000	
Solid residuals disposed		
Waste water		

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3 HYDROLYSIS OF CORN RESIDUES TO OBTAIN FURFURAL

ABSTRACT

In this section the extraction of furfural from corn residues by acid digestion and subsequent distillation is analyzed in terms of capital and environmental costs. The analysis is based on use of a model furfural plant capable of producing over 44,000 tons of furfural per year; such a plant would be approximately four times larger than required for economically viable production. Production of furfural from corn residues is economically sound and would make it possible to substitute furfural for certain refined petroleum products, and the energy generated by the model system could be doubled by marketing its by-products (acetic acid, methanol, and methyl acetate). However, removal of all corn residues rapidly depletes the soil, and expensive nutrient programs would be required to maintain soil productivity.

3.1 INTRODUCTION

3.1.1 General Systems Description

Furfural is an aldehyde with the $-CHO$ group in the position and is obtained from pentosan-containing agricultural residues. It was identified in 1832, and its production was commercialized by Quaker Oats in 1922.¹ Table 3.1 lists the pentosan content and furfural yield that can be expected from various agricultural residues.

Furfural is the most industrially important furan, a class of heterocyclic compounds characterized by a double saturated ring of four carbons and one oxygen atom.⁵ It serves as a chemical intermediate for the production of furfuryl alcohol, tetrahydrofurfuryl alcohol, furan, tetrahydrofuran, and polytetramethylene ether glycol, and as a precursor of pyrrole, pyrrolidine, pyridine, piperidine, lycine methylfuran, and many other compounds with important applications.¹ Furfural is also used as a selective solvent in the refining of lubricating oils to increase their stability during processing,⁶ as an extractive distillation medium in the manufacture of butadiene from petroleum,⁷ as a decolorizing agent for wood resin, and as a resin former.⁸ Furfural may also have other industrial uses that are currently being served by petroleum-derived chemicals.

The focus of this section is the production of furfural from corn residues (corn cobs and corn stalks). Furfural is included in this study of biomass energy resources because it is an organic compound that spares petroleum-derived industrial chemicals: if furfural were not derived from biomass, it or its analog would most likely come from petroleum.

3.1.2 Resource Distribution

If corn residues are used to produce furfural, the regional applications should be located in the Corn Belt. The distribution of acreage planted to corn in the U.S. is presented in Fig. 3.1. A three-state area

Fig. 3.1. Corn Harvested, 1969

Table 3.1. Pentosan Content and Furfural Yield
for Selected Agricultural Residues

Agricultural Residue	Pentosan Content ^a (% dry basis)	Furfural Recovery ^b (% dry basis)
Corn cobs ^c	19	12.9
Bagasse	15	9.6
Oat Hulls	20	12.3
Rice Hulls	12	6.3
Corn stalks ^c	17	6.5-9.5
Cottonseed Hulls	18	10.2

^aHitchcock and Duffey.²

^bPaturall.³

^cLipinsky et al.⁴

in the Midwest (Illinois, Iowa, and Indiana) accounts for approximately 50% of the corn produced in the U.S. Average corn yields ranged from 2.7 to 3.08 tons/acre in 1976,¹⁰ and average residue yields were estimated at between 2.89 and 3.3 tons/acre. Residue yields were calculated from grain yields using a ratio of 1:1.07, grain:residue, on a dry weight basis.¹¹⁻¹⁴ Using this ratio, it is estimated that in 1976 over 90 million tons of corn residues were generated in the above three midwestern states (see Table 3.2).

Since this area contains some of the world's most productive soils, it is ideal for evaluating the effects of total crop removal on the soil and the environment. Corn in this area is grown continuously or in a corn-soybean rotation. The yield per acre and the acreage in corn have steadily increased in recent years.¹⁰ This trend will probably continue, but climatic and economic fluctuations must be taken into account. If corn and other crop residues are to be a viable biomass energy alternative in the Corn Belt, consideration must be given to the consequences of crop residue removal on soil quality in order to maintain land productivity.

3.2 DESCRIPTION OF MODEL SYSTEM

3.2.1 System Description

Extraction of furfural from corn residues involves acid digestion under steam pressure followed by a series of distillations to separate and purify the furfural and other by-products of the hydrolysis. The flow diagram for furfural production (Fig. 3.2) illustrates the unit operations and processes required for furfural production. This flow diagram was constructed from descriptions of the process provided by several authors^{1,3,4,15-17} and serves as the basis for assessing the material and energy flows required for furfural production in our model system.

The process begins with milling of corn residue (25% cob, 75% stalk materials) into fine particles while the hydrolysis water is mixed (1 part

Fig. 3.2. Process Flow Diagram for Production of Furfural from Corn Residues

Table 3.2. Corn - Grain, and Residue Production, and Energy Value of Residues: Three Midwestern States and U.S., 1976

Location	Grain ^a (bushels/acre)	Grain (tons/acre)	Residue ^b (tons/acre)	Total Harvested Acreage ^a (10 ³ acres)	Total Residue (10 ⁶ tons)	Total Energy Value ^c (10 ¹² Btu)
Illinois	107.0	3.00	3.21	11,690	37.5	413.5
Indiana	110.0	3.08	3.30	6,300	20.8	229.3
Iowa	90.0	2.70	2.89	12,750	36.8	405.8
Three-State Total	-	-	-	30,740	95.1	1,048.6
U.S. Total	87.4	2.45	2.62	71,085	186.2	2,053.0

^aData from ref. 10.

^bRatio of 1:1.07 (grain:residue) was used.¹⁴

^cBased on 5,513 Btu/lb (11.026 x 10⁶ Btu/ton).⁴

concentrated H₂SO₄ plus 9 parts H₂O). The two streams are then mixed to yield a liquid/solid ratio of approximately 0.25.¹⁷ Hydrolysis takes place in a rotary digester, and steam (50 to 100 psi,) is passed through the mixture for 6 to 12 hours depending on the pressure of the stream.^{3,16} The material remaining after complete digestion is separated into solid and liquid fractions by a screw press.

The solid residue is granular and composed principally of modified cellulose, lignin and resins, and ash, with 2-3% acid measured as sulfuric.¹⁸ A more detailed chemical description of the solid residue is given in Table 3.3. On leaving the press the residue has a moisture content of 35% and a heating value of 4,174 Btu/lb⁴ and accounts for 70% of the initial weight of the raw material.³ The liquid fraction contains the dissolved carbohydrates and spent acid. Given that 70% of the initial weight of the raw materials is in the solid residue and that the furfural extracted accounts for approximately 8-10% of the input material, one can estimate that 20-22% of the raw material is dissolved in the water from the screw press. Both these by-products may have value: the solid residue can be burned in the boilers to produce steam or it can be sold as animal feed,¹⁸ and Lipinsky et al.⁴ have postulated that the liquid fraction could be fermented into ethanol. In this model it is assumed that the solid residue will be burned to produce steam and that the liquid fraction is a waste stream.

The steam that has passed through the acid digester contains 4-6% furfural.¹⁶ The furfural is recovered from the vapor by passing it through a distillation column. The vapors leaving the column are 20-25% furfural, and water leaving the bottom of the distilling column usually contains 0.02-0.05% furfural by weight.¹ The overhead is then condensed, and a furfural layer and a water layer are separated by decanting. Furfural leaving the decanter contains 5.8% water,¹ and the water leaving the decanter contains about 10% furfural.¹⁶ The furfural layer is then passed through a dehydration column which employs vacuum distillation and requires 0.25 lb steam per pound of furfural vaporized.¹ The resultant furfural has a purity of 99.5%.¹⁶ The overhead from the dehydration column is then recovered by condensation and recycled through the decanter.

Table 3.3. Chemical Composition of Solid Residue
By-Product from Furfural Production

Chemical Fraction	% (dry basis)
2% Caustic Soda Extract	22
Alcohol-Soluble	21
Acetone Extract	20
Ether-Extractable	4
Cellulose	38
Residue from Saccharification (lignin and resins)	42
pH	3 - 15
Protein (N x 6.25)	2.9 - 4.2
Crude Fat	2.5 - 4.2
Crude Fiber	45 - 58
Ash	2.8 - 15
Nitrogen-Free Extract	38 - 46
Carbon	50 - 53
Hydrogen	5.1 - 5.3
Nitrogen	0.7 - 0.9
Oxygen	36 - 38
Sulfur	1.2 - 1.7

Source: ref. 18.

The water layer in the decanter yields highly volatile by-products, namely, methyl alcohol, methyl acetate, and acetic acid. The production of methyl alcohol and methyl acetate equals roughly one-sixteenth of furfural production at the plant, while that of acetic acid equals the production of furfural.⁴ These compounds are recovered by passing the water layer through a stripping column and recovering the compound by condensing the overhead. The material remaining in the column is then recycled through the system, beginning with the original distillation of the furfural vapor coming from the digesters.

3.2.2 Material Requirements

The material flows proposed for the model furfural production system are given in Table 3.4. The model system proposed has approximately four times the minimum economically viable capacity for furfural production in the U.S.¹⁷ The capacity of this plant is over 44,000 tons of furfural per year, which is roughly equivalent to 50% of U.S. production.

3.3 ENVIRONMENTAL DATA

3.3.1 General Soil Effects

Total removal of residues from corn, wheat, and cotton fields has the same ultimate effect on the soil although the rate will vary because of dif-

Table 3.4. Material and Energy Flows for Model Furfural Production System

System Variable	Material Flow
Plant Capacity	44,550 tons/yr furfural 524,040 tons/yr corn stover
Processing Rate	135 tons/day furfural 1,588 tons/day corn stover
Utilities	40,000 lb steam/ton furfural 11,000 ft ³ H ₂ O/ton furfural 250 kWh/ton furfural
Acid Digestion	50 lb conc. H ₂ SO ₄ /ton Residue
By-Product Recovery	8.4 tons methyl alcohol/day 8.4 tons methyl acetate/day 135 tons acetic acid/day 1,112 tons solid residue/day

Data estimated from refs. 3,4,16.

ferences in crop root systems, plant physiology, climatic conditions, and soil properties. Soil destruction begins with the first harvest of residue because the soil is completely exposed to water and wind. Brady¹⁹ reports that Wischmeir and Mannering found that removing residues increased runoff from 0.52 inch to 0.98 inch on 678 plot-years of corn. When residues are removed, the raindrop effect destroys surface soil structure, causing puddling, decreased water infiltration, soil compaction, reduced porosity, and a loss of organic matter. In wheat and cotton growing areas, wind takes over after the soil has dried. Wind sorts the surface material, blowing away the fines and leaving only the semisterile skeletal matter.²⁰

Organic matter acts as a binding agent to develop and maintain soil structure, by maintaining good tilth, increasing infiltration, maintaining soil porosity, and acting as a counter force against soil compaction.^{19,21} Organic matter serves as a storehouse for nutrients, increases cation and anion exchange capacity, and chelates micronutrients, protecting plants from potentially toxic concentrations.^{19,21-23} Organic matter in high organic-matter soils releases 40-80 lb/acre of nitrogen for crop uses.^{22,23} Removal of all residues from fields where corn was grown continuously during a period of 18 years resulted in a 15,000-lb/acre decrease in organic matter.²²

Not all residues need to be returned to the soil to maintain organic carbon content. Larson and others²⁴ found that by using conservation tillage (e.g., chisel plow) 1% to 57% of the corn area in selected land resource areas of Minnesota and Iowa could have all the residues removed without losing more than 4 tons of soil per acre per year. However, these are only calculated data; the amount of residues that can be safely removed from an area depends on the soil, climatic conditions, and especially management practices such as type of tillage and fertility program.²⁴

The adverse effect of removing corn residues on the chemical properties of soil can be partially overcome by increased fertilizer application. Data presented in this report are only for the first year that crop residues are removed. The second year, fertilizer rates must be increased to replace that portion of the nutrients removed by the grain, residue, and erosion. Maintaining favorable chemical properties over a period of several crop years could be more costly in terms of energy required for fertilizer than the amount of energy in the residue. Unfortunately, the adverse impact on the physical properties of the soil can only be slowed down with higher fertilizer rates. It takes the continual passing of crop residues through the soil and being transformed into organic matter to stop the deterioration of soil physical properties.^{21,23}

3.3.2 Some Aspects of Corn Residue Removal

Table 3.5 shows the inputs needed to obtain a yield of 107 bushels/acre of corn. Data taken from Pimentel et al.²⁵ were adjusted to reflect the increased yield. Assumption that a linear relationship exists between expected yield and fertilizer rates²⁸ made calculation of the nutrient data possible.

The amount of fertilizer nitrogen applied to the soil for corn production is based on maximum economic return.²⁸ Other nutrients (phosphorus and potassium) are added on the basis of soil tests that indicate the amount of nutrient needed for maintenance of optimum crop yield plus a build-up factor that provides for fixation of these nutrients by soils that are low in these elements. Calcium and magnesium are seldom required for Illinois soils.

Table 3.5. Inputs per Year Needed to Obtain a Corn Yield of 107 Bushels of Grain and 3.21 Tons of Residue per Acre under Continuous Cropping System in Illinois

Input	Amount per Acre	Amount per Ton of Residue
Nutrients (lb)		
Nitrogen	148	46.1
Phosphorus	41	12.8
Potassium	79	24.6
Calcium	634 ^a	197.8
Magnesium	1	0.33
Seed (lb)	19	5.9
Active Ingredients in		
Pesticides (lb)	3	0.93
Gasoline (gal)	22	6.9

Data sources: refs. 10,25-28.

^aYearly rate assuming that soils are limed every 4th year.

These soils are rich in basic cations; however, the advent of continuous corn production with high application of nitrogen fertilizer made the addition of agricultural lime necessary to maintain a pH of 6.5 in the surface soil horizon.

Table 3.6 shows the approximate amounts of nutrients removed in the grain and residue. When only the grain is removed, the fertilizer added to produce this crop (Table 3.5) is adequate to maintain the productivity of the soil; however, the loss of nutrients by erosion (Table 3.7) eliminates most of the build-up fertilizer applied. Also the material eroded away usually contains a high proportion of nutrients that are readily available to plants. In some experiments the material eroded away contained five times more organic matter and nitrogen than the original soil.¹⁹

Data in Tables 3.6 and 3.7 show that nutrient losses greatly increase because erosion increases and that nutrients in crop residues are also lost when these residues are completely removed. Nitrogen losses are 1.6-2 times greater than the amount applied, and phosphorus losses are 1.2-1.6 times greater than the amount applied. Potassium losses are 10.6-16.7 times greater than the amount applied, and magnesium losses are 130-200 times greater. Calcium losses are high because of erosion, but the total calcium loss is not greater than the amount applied. No sulfur is applied unless a deficiency is noted; however, at the rate of removal indicated in Tables 3.6 and 3.7 it will not take many growing seasons for sulfur deficiencies to appear in corn plants. Trace elements are not normally added to the soil as fertilizer, but sprayed on the growing plants when deficiency symptoms become evident. Some soils already exhibit deficiencies in sulfur and some of the trace elements;²⁸ therefore a management system in which corn is grown in monoculture and the

Table 3.6. Nutrients and Mineral Matter Removed by Corn Crop^a

	Grain		Residue	
	Pounds per Acre	Pounds per Ton of Grain	Pounds per Acre	Pounds per Ton of Residue
Nitrogen	96	32.0	71.3	22.2
Phosphorus	16.6	5.5	11.4	3.6
Potassium	23.6	7.9	85.8	26.8
Calcium	11.4	3.8	19.6	6.1
Magnesium	14.0	4.7	12.1	3.8
Sulfur	10.2	3.4	7.0	2.2
Copper	0.04	0.013	0.04	0.012
Manganese	0.06	0.020	1.07	0.334
Zinc	0.11	0.037	0.21	0.066
Mineral Matter	-	-	371.9	116.0

Data sources: refs. 21,29,30.

^aThe assumption was made that a linear relationship exists between crop yield and nutrient uptake; therefore the data were adjusted for a yield of 107 bushels/acre.

Table 3.7. Nutrients Lost by Soil Erosion under Continuous Corn Production with Two Residue-Management Techniques^a

Nutrient Loss Measurement	Nutrient					
	N	P	K	Ca	Mg	S
RESIDUES REMOVED						
Pounds Lost/Yr	79-132	22-36	726-1,210	264-440	104-174	20-34
Pounds Lost/Ton of Residues	25-41	7-11	226-377	82-137	33-54	6-11
RESIDUES RETURNED						
Pounds Lost /Acre	66	18	605	220	87	17
Pounds Lost/Ton of Residues	21	6	189	69	27	5
Pounds Lost/Ton of Grain	22	6	202	73	29	6

Data sources: refs. 19,24.

^aData can vary between 120% and 200% increase in soil and nutrient loss.

For this study we used a range of nutrient loss because the exact increase depends on many factors (e.g., soil type, tillage method, slope).

total crop is removed will only increase the number of acres that must have these nutrients supplied by fertilizers. There are additional losses of nutrients, particularly nitrogen, by the leaching process. Nutrients move down through the soil out of the root zone and are no longer available to corn plants.

Table 3.8 lists the nutrients that must be returned to the soil to maintain productivity. These data are given both per ton of residue removed and per 10^{12} Btu output.

3.3.3 Operating Residuals

The two major environmental problems resulting from furfural production are water and air contamination by organics and sulfuric acid. Solid residue is also generated in the process, but this has potential as a fuel or feed and should not be considered a pollutant.

Lacking a published estimate for hydrocarbon and acid losses into the atmosphere during the process, it was assumed that 1% of the total hydrocarbons produced (furfural, methanol, methyl acetate, and acetic acid), or 1,011.6 tons per 10^{12} Btu generated, are lost to the atmosphere. The 1% assumption was also made for sulfuric acid losses, calculated at 140 tons per 10^{12} Btu.

The major water pollutant is the carbohydrate dissolved in the liquid after digestion; it was estimated that the carbohydrate in the waste pro-

cess equals 12% of the input residue and has a biological oxygen demand of 0.4 lb/lb carbohydrate (similar to flucose). This results in a BOD of 26,880 tons per 10^{12} Btu. The water pollution from sulfuric acid was assumed to be equal to 20% of the input acid, or 2,800 tons per 10^{12} Btu. A summary of these residuals is shown in Table 3.9.

3.3.4 Land Requirements

It is estimated that 300 acres per plant site (320.6 acres per 10^{12} Btu) will be required for the plant. Additional land to supply the residue (approximately 0.25 acre/ton residue) will also be needed.

3.3.5 Water Requirements

The two main water demands for hydrolysis are for process water (3,000 gallons/ton furfural) and cooling water (13,000 gallons/ton furfural). Plant operation requires 814,323,000 gallons of water per 10^{12} Btu.

Table 3.8. Nutrient Replacement Required when Corn Residue is Removed for Furfural Production

Nutrient	Replacement per Ton of Residue (20% Moisture) (tons))	Replacement per 10^{12} Btu (tons)
Nitrogen	0.0185	10,360
Phosphorus	0.0051	2,856
Potassium	0.0099	5,544
Calcium	0.079	44,240
Magnesium	0.00013	72.8

Table 3.9. Residuals Data for Hydrolysis of Corn Residues

Residual Category	Gross Residual per 10^{12} Btu End-Use Energy (Tons)
Hydrocarbons, Toxic Hydrocarbons	1,011.6
Other Gases, Sulfur	140
Biological Oxygen Demand	26,880
Sulfuric Acid	2,800

3.4 ECONOMIC DATA

3.4.1 Capital Costs

A bottom-up approach was used for estimating the capital costs and material inputs of the furfural production plant. A list of process equipment was developed from the process flow diagram; estimates of costs for each piece were determined by using published cost data for similar equipment³¹ and modifying where we felt necessary.

Once the process equipment costs were determined, other direct and indirect costs were calculated from the process equipment estimate. Table 3.10 gives a breakdown of capital costs for a typical multiprocess chemical plant. These estimates are within the ranges incurred during chemical plant construction.³² Using Table 4.1, other costs were inferred on the basis of the process cost estimate. These results are found in Tables 3.11 and 3.12. The total capital cost for the system was estimated at \$28,685,384 (1972 dollars).

3.4.2 Operating Costs

Operating costs for the facility were taken from estimates for a furfural plant of equivalent size that used bagasse in place of corn residues.³¹ The operating cost breakdown is given in Table 3.13. An additional factor is the cost of the residue, which is estimated at \$20/ton field-dried and delivered (1977 dollars).

Credits can be obtained from selling or using the following by-products: solid residue (\$1.00/10⁶ Btu), acetic acid (\$2,000/ton), methyl alcohol (\$2,000/ton), and methyl acetate (\$14,000/ton).

Table 3.10. Anticipated Distribution of Capital Costs for a Multiprocess Plant

Cost Component	Percent of Total Costs
Site and Preparation	1.5
Buildings and Auxiliaries	10.0
Construction Labor	6.5
Process Material (includes concrete substructures, piping and ductwork, electrical, insulation, process structural, instrumentation, paint)	13.0
Process Material Labor	8.0
Process Equipment	32.5
Process Equipment Labor	3.0
Home Office Expense (including overhead)	15.5
Field Office Expense (including overhead)	10.0

Table 3.11. Capital Costs for Model System for
Hydrolysis of Corn Residues

Component (Industrial Sector)	Cost in 1977 dollars
Process Equipment	
High Volatile Column (Other Fabricated Metal Products)	186,000
High Volatile Column Condenser (Plumbing and Heating Equipment)	18,600
High Volatile Column Vent Condenser (Plumbing and Heating Equipment)	55,800
High Volatile Column Reboiler (Metal Plate (Boilers))	279,000
Furfural Storage Tanks, 1 X 10 ⁶ Gal (2) (Other Structural Metal Products)	279,000
Acetic Acid Storage Tank, 20,000 Gal (Other Structural Metal Products)	65,100
Methanol Storage Tank, 20,000 Gal (Other Structural Metal Products)	65,100
Methyl Acetate Storage Tank, 20,000 Gal (Other Structural Metal Products)	65,100
Residue Mills (2) (Spec. Industrial Machinery)	111,600
Sulfuric Acid Make-up Tanks, 25,000 Gal (2) (Other Fabricated Metal Products)	167,400
Rotary Acid Digester, 50,000 Gal (4) (Other Fabricated Metal Products)	5,580,000
Digester Surge Tank, 50,000 Gal (Other Fabricated Metal Products)	139,500
Screw Presses, 2,000 Tons/Day (4) (Spec. Industrial Machinery)	744,000
Steam Boiler (Metal Plate, Boiler Shop)	651,000
Stripping Column, 15-20 Plate (Other Fabricated Metal Products)	279,000
Stripping Column Condenser (Plumbing and Heating Equipment)	232,500
Stripping Column Vent Condenser (Plumbing and Heating Equipment)	55,800
Stripping Column Reboiler (Metal Plate, Boiler Shop)	837,000
Furfural Decanter (Other Fabricated Metal Products)	279,000
Dehydrating Column (Other Fabricated Metal Products)	465,000
Dehydrating Column Vent Condenser (Plumbing and Heating Equipment)	162,750
Dehydrating Column Reboiler (Metal Plate, Boiler Shop)	530,100
Materials	
Process Materials	4,508,640
Buildings and Auxiliaries	3,467,970
Transportation	1,447,040
Site and Preparation	559,000
Construction Labor (220,363 hr at \$11/hr)	2,424,000
Process Materials Labor (271,181 hr at \$11/hr)	2,983,000
Process Equipment Labor (101,727 hr at \$11/hr)	1,119,000
Home Office Expense	5,780,000
Field Office Expense	3,729,000
All Components	37,266,000

Table 3.12. Capital Expenditures and Materials Requirements for Model System for Hydrolysis of Corn Residues per 10^{12} Btu Output

	1977 Dollars	Deflator	1972 Dollars
Total Capital Cost	37,266,000	1.28	29,114,063
Materials	19,224,960	1.28	15,019,500
Transportation	1,447,040	1.28	1,130,500
Construction Labor	6,526,000	1.28	5,098,438
Profit & Overhead	10,068,000	1.28	7,865,625
Annual System 10^{12} Btu Output			0.936
Total Capital Cost/ 10^{12} Annual Btu			\$31,104,768
Number of Years to Construct Facility			3
Expected Life of Facility (years)			20+
Man-Years to Construct Facility			296.6
Man-Years/ 10^{12} Btu Annual Output			316.9
Estimated Land Use (acres)			300 ^a

^aFor plant site. Additional land also needed to supply residue (approximately 0.25 acre/ton residue).

Table 3.13. Estimated Annual Operating Costs for Furfural Facility

Cost Element	Millions of 1976 Dollars
Sulfuric Acid	0.175
Utilities	7.833
Labor, 10 men per shift	0.710
Supervision, 20% of labor	0.142
Maintenance Materials	2.016
Maintenance Labor	1.120
Maintenance Supervision	0.224
Payroll Burden	0.659
Supplies, 20% of maintenance materials	0.403
Indirect Costs	1.846
Taxes, Insurance	1.120
Total	16.248

Source: ref. 31.

3.5 SUMMARY OF FINDINGS

The material, energy, residual, and cost inputs and outputs for this system have been calculated on the basis of 10^{12} Btu of output energy in the form of furfural. These results are summarized in Table 3.14. This system produces 0.94×10^{12} Btu of chemical energy that could substitute for refined petroleum products.

However, this process has the potential to double its energy generation by marketing its by-products (acetic acid, methanol, and methyl acetate). The water pollution load could be reduced if the spent acid and carbohydrate waste were used for fermentation of ethanol.

The off-side impacts resulting from residue removal could be more severe than the impacts from the operating residuals. Table 3.8 depicts the additional nutrient requirements to offset the losses from residue removal. These additional inputs total 63,073 tons. Coupled with an estimated 20% increase in loss of nutrients from increased soil erosion, the impacts from corn residue utilization are greater for collection than for conversion.

Table 3.14. Input/Output Summary of Furfural Production by Hydrolysis of Corn Residues

SIZE: Plant designed to produce 135 tons/day of furfural & operate 330 stream days/yr; process uses 11.76 tons of corn residue (20% moisture) to produce 1 ton of furfural	INPUT (per 10¹² Btu): <u>Fuel</u> Residue requirement, 560,000 tons corn residue (11.76 tons corn residue [20% moisture] per ton furfural) Steam (100 psig), 952,380 tons Electricity, 11,904,750 kWh Process chemical, sulfuric acid, 14,000 tons/10 ¹² Btu Requires 1.0688 plants operating at full capacity per yr to produce 10 ¹² Btu <u>Water</u> Cooling water, 619 x 10 ⁶ gal (13,000 gal/ton furfural) Process water, 142.9 x 10 ⁶ gal (3,000 gal/ton furfural) <u>Land</u> 300 acres/plant site, 320.6 acres/10 ¹² Btu 140,000 acres of corn residue/10 ¹² Btu (0.25 acre/ton residue) Cost (1972 dollars): Capital costs, \$31,104,768 Operating & maintenance, \$11,360,000 Residue cost, \$7,832,000 Credits can be obtained for solid digester residue, methyl alcohol, acetic acid, and methyl acetate by-products	OUTPUT (per 10¹² Btu): <u>Air pollutants</u> Hydrocarbons, 1,011.6 tons (0.01 ton/ton furfural) H ₂ SO ₄ vapor, 140 tons (1% of total H ₂ SO ₄ input) <u>Water pollutants</u> BOD, 26,880 tons (4.8% of total residue input) H ₂ SO ₄ , 2,800 tons (20% of input) <u>Solid waste</u> Solid digester residue (35% moisture), 392,240 tons (3.27 x 10 ¹² Btu) (8.23 tons/ton furfural) (heating value of 4,174 Btu/lb) Can be sold as animal feed or used as boiler fuel <u>Energy</u> Furfural - 10 ¹² Btu Petroleum substitute, 47,619 tons furfural/10 ¹² Btu Methyl alcohol, 0.0622 tons/ton furfural (2,963 tons) Acetic acid, one ton/ton furfural (47,619 tons) Methyl acetate, 0.0622 tons/ton furfural (2,963 tons)
DESCRIPTION: Acid hydrolysis of corn stover frees pentose sugars in residue, from which furfural is stripped through a series of distillations		
COMPONENTS: Mixing tanks, digesters, screw press, steam boilers, stripping columns, distillation columns, condensers		
MAJOR ENVIRONMENTAL PROBLEMS: Hydrocarbon air pollutants, H ₂ SO ₄ , air and water pollutants, solid waste, organic water pollutants		

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4 CORN RESIDUE PYROLYSIS (GASIFICATION)

ABSTRACT

In this section capital and environmental costs are analyzed for energy recovery through pyrolysis of corn residues to produce a low-Btu fuel gas. The analysis is based on use of a gasification unit that would consume 1.17 tons/hr of corn residues to produce approximately 64,000 ft³ of gas with a heating value of 150 Btu/ft³. The model system is designed to be used on large farms, where it would probably be used to supply gas for grain dryers. Use of such systems is commercially sound, but removal of corn residues rapidly depletes the soil, and extensive soil management would be necessary to maintain soil productivity. Air pollution is the major environmental problem associated with pyrolysis.

4.1 INTRODUCTION

4.1.1 General System Description

Pyrolysis is the thermochemical alteration of organic matter in the absence of air. The first material pyrolyzed by man most likely was wood, and the end-use energy produced was charcoal, a cleaner-burning fuel. This simple approach to pyrolysis is still one of the most widely practiced biomass conversion strategies in the world. Brazil has an intensive national program to increase charcoal production, and today 40% of the energy needs of the Brazilian steel industry (approximately 2 million tons annually) are supplied by charcoal.¹

The principal products of pyrolysis are gas, a highly carbonized solid residue called char, and oil-like liquids with a high tar content. The proportions of char, oil, and gas produced depend on the chemical composition of the feed, its preparation, the reaction temperature and pressure, and the time the material stays in the reactor.²⁻⁵ Heat for pyrolysis may be externally applied to the biomass (true pyrolysis), or it may be produced by combustion of part of the biomass itself.

The modern method of charcoal production from wood is carried out in a steel retort. The wood is externally heated for 20-24 hr at 500-700°F near atmospheric pressure.^{6,7} The process is often referred to as destructive wood distillation because certain chemical products are produced in addition to charcoal. Distillation of one cord (4,000 lb) of wood yields 7,000-12,000 ft³ of condensable gas, 900-1,100 lb of charcoal, 200-300 gal of raw pyrolygneous acid, and 200 lb of acetate of lime.⁷

Liquefaction of biomaterials occurs at 400-700°F at pressures ranging from 1,000 psig to 4,000 psig.^{8,10} Table 4.1 gives the percent conversion of some agricultural and forestry residues to oil. A typical catalyst used in this process is sodium bicarbonate. This process can produce an oil very similar to No. 6 fuel oil.¹¹ The properties of the two oils are summarized in Table 4.2.

Table 4.1. Conversion of Various Cellulosic Wastes to Oil^a

Raw Material	Amount (gm)	Time at Reaction Temp. (hr)	Maximum Pressure (psig)	Conversion (%)	Oil Yield (%)	CO Used (gm/100 gm oil)
Cornstalks	50	1	1,760	95	42	21
Corncobs	100	1	2,400	95	38	9.7
Rice Hulls	50	1	1,600	97	40	25
Newsprint	50	0.5	1,640	88	40	21
Pine Bark	50	1	1,600	83	32	45

Source: ref. 11.

^a200 ml water, 10 gm NaHCO₃, 500 psig initial CO pressure, 250°C reaction temperatures.

Table 4.2. Properties of No. 6 Fuel Oil and a Typical Pyrolytic Oil

Property	No. 6 Fuel Oil ¹⁵	Pyrolytic Oil
Btu/lb	18,200	10,500
Specific gravity	0.98	1.30
Pounds per Gallon	8.18	10.85
Flash Point (°F)	150	133
Viscosity (SSU) at 190°F	340	3,150
Pumping Temperature (°F)	115	160
Atomization Temperature (°F)	220	240

Source: ref. 11.

Methane is the main gas component of pyrolysis if the reaction is carried out at high temperature and pressure (2,000°F, 1,000 psig), and production can be boosted by injecting water into the reactor.¹² The water reacts with the hot char to produce carbon monoxide and hydrogen, and methane generation then proceeds by the following routes:

Under even high pressure (up to 4,000 psig), methanol can be formed from the reaction of carbon dioxide and hydrogen gas.^{13,14} The use of various chemical catalysts also can affect the volume and composition of gas produced.^{15,16}

In this section, pyrolysis is examined for the production of a low-Btu fuel gas, often called producer gas, from corn residues under conditions of low pressure and relatively high temperature (about 1,600°F). The reaction is actually a two-stage process in which part of the biomass in the reactor is combusted, with a limited air supply, to raise the temperature in the gasifier unit above 1,600°F to pyrolyze the remaining biomass. Steam is often injected to react with the char to generate hydrogen and carbon monoxide gas.

The composition of the gas produced by such a gasifier unit and that of a true pyrolysis gas is given in Table 4.3. The large amounts of nitrogen present in gasifier gas are from the air burned to increase the temperature in the unit. It should also be noted that a gasifier converts eight to nine times more of the feedstock to gas than does pyrolysis.

Table 4.4 shows the char composition for different biomass feedstocks. The heating values of these pyrolytic chars range from 5,500 to 8,300 Btu/lb, similar to the heating values of many coals. The ash content reported in various chars from gasifiers is between 1% and 20%.^{17,18} Tars are often generated in gasifiers, but the tar content is usually less than 5%.

4.1.2 Resource Distribution

If corn residues are used to fire the gasifiers, the regional applications will presumably be located in the Corn Belt. The distribution of

Table 4.3. Characteristics of a True Pyrolytic Gas and Gasifier Gas

Characteristics	Pyrolytic Gas ^a (wt %)				Gasifier Gas ^b (Vol %)		
	Annual Waste	Rice Hulls	Grass Straw	Fir Bark	Cubed Cotton Gin Trash	Raw Cracked Walnut Shells	Broken Corncobs
Components							
H ₂	6.1	23.3	9.6	6.3	18.3	18.4	16.1
CO	21.9	28.5	53.9	14.7	16.4	20.1	18.7
CO ₂	55.9	40.8	26.9	64.7	11.6	8.7	9.8
CH ₄	6.1	3.5	3.8	10.5	—	—	—
C ₂ H ₂	0.5	0.8	0.8	1.0	—	—	—
C ₂ ⁺	1.8	0.8	2.8	1.2	—	—	—
THC	—	—	—	—	1.8	5.1	4.3
N ₂	—	—	—	—	51.4	47.3	50.9
O ₂	—	—	—	—	0.5	0.4	0.2
H ₂ S	7.8	2.4	2.2	1.7	—	—	—
Other Characteristics							
Btu/ft ³	226	214	349	222	118	159	141
Gas Yield (%)	10.8	12.1	5.2	8.2	88	91	93
Char Yield (%)	48.1	35.9	23.2	41.2	11	9	5

^aSource: ref. 11.

^bSource: ref. 17.

Table 4.4. Analysis of Pyrolytic Chars from Organic Solid Wastes

Characteristics	Animal Waste	Rice Hulls	Fir Bark	Grass Straw
Components (Wt %)				
Carbon	34.5	36.0	49.9	51.0
Hydrogen	2.2	2.6	4.0	3.7
Nitrogen	1.9	0.4	0.1	0.5
Sulfur	0.9	0.1	0.1	0.8
Oxygen	7.9	11.5	24.3	19.2
Ash	48.8	49.2	21.4	24.3
Btu/lb	5,450	6,100	8,260	8,300
Char Yield (%)	48.1	35.9	41.6	23.2

Source: ref. 11.

acreage planted to corn in the U.S. is presented in Fig. 4.1. A three-state area in the Midwest (Illinois, Iowa, and Indiana) accounts for approximately 50% of the corn production in the U.S.²⁰

Average corn yields range from 2.7 to 3.08 tons/acre in 1976, and average residue yields were estimated at between 2.89 and 3.3 tons/acre. Residue yields were calculated from grain yields using a ratio of 1:1.07, grain:residue, on a dry weight basis.²¹⁻²⁴ Using this ratio, it is estimated that in 1976 over 90 million tons of corn residues were generated in the above three midwestern states (see Table 4.5).

Since this area contains some of the world's most productive soils, it is ideal for evaluating the effects of total crop removal on the soil and the environment. Corn in this area is grown continuously or in rotation with soybeans. The yield per acre and the acreage in corn have steadily increased in recent years.²⁰ This trend will probably continue, but climatic and

Table 4.5. Corn -- Grain and Residue Production and Energy Value of Residues: Three Midwestern States and U.S., 1976

Location	Grain ^a (bushels/acre)	Grain (tons/acre)	Residue ^b (tons/acre)	Total Harvested Acreage (10 ³ acres)	Total Residue (10 ⁶ tons)	Total Energy Value ^c (10 ¹² Btu)
Illinois	107.0	3.00	3.21	11,690	37.5	413.5
Indiana	110.0	3.08	3.30	6,300	20.8	229.3
Iowa	90.0	2.70	2.89	12,750	36.8	405.8
Three State Total	--	--	--	30,740	95.1	1,048.6
U.S. Total	87.4	2.45	2.62	71,085	186.2	2,053.0

^aData from ref. 20.^bRatio of 1:1.07 (grain:residue) was used.²⁴^cBased on 5,513 Btu/lb (11.026 x 10⁶ Btu/ton).²⁵

Fig. 4.1. Corn Harvested, 1969

economic fluctuations must be taken into account. If corn and other crop residues are to be a viable biomass energy alternative in the Corn Belt, considerations must be given to the consequences of crop residue removal on soil quality in order to maintain land productivity.

4.2 DESCRIPTION OF MODEL SYSTEM

4.2.1 System Description and Equipment

The model system selected for this study is a an up-draft gasifier unit that operates at approximately 1,600°F and produces low-Btu gas and char. A similar commercial unit is in operation at Diamond/Sunsweet, Inc., Stockton, California.²⁶ The unit has a capacity of 28.6 tons per day and produces enough energy to sustain a steam production rate of 8,500 lb/hr (15 psig) at a fuel rate of one ton of mulled walnut shells per hour. A natural gas pilot flame is used. A laboratory-scale model similar to this unit has been built at the University of California at Davis.¹⁸ Several agricultural and forestry residues have been tested in the laboratory unit. The system's performance and energy inputs and the energy output for these feeds have been calculated (Tables 4.6 and 4.7). These data provide the basis for estimating the performance of our model commercial gasifier for different corn residues.

Table 4.6. Performance and Energy Inputs for Gasification of Agricultural and Forestry Residues

Gasification Characteristics	Corn Cobs	Tree Prunings	Walnut Shell
Fuel Consumption (lb/hr)	90	42	37
Percent Gasified	80	83	91
Char (%)	20	17	8
Condensate (%)	0	0	1
Pressure Differential, in.	30	25	17
Ash in Char (%)	4.5	17.2	6.3
Volatile and Combustible Matter in Refuse (%)	14.5	18.0	5.3
Fixed Carbon in Refuse (%)	81.0	64.8	88.4
Firebox Temp. (below choke, °F)	1,600	1,800	1,420
Sensible Heat in Air at Input Conditions (Btu)	1,438	690	303
Total Energy Input	654,298	301,200	270,421

Source: ref. 18.

Chopped cornfield residue would be the feedstock for the unit. Fifty-five percent of the input is gasified, and the principal by-product is a low-Btu gas (100-200 Btu/scf) with a char residue (30% of input energy) as a by-product. The remaining heat is not recovered. When corncobs are used the heating value of the dry fuel is approximately 7,254 Btu/lb. The mean heating value for dry corn residue (leaf, husk, cob, and stalk) is 7,268 Btu/lb.²¹

Table 4.7. Energy Outputs from Gasification of Agricultural and Forestry Residues

Energy Output Characteristics	Corn Cobs (Btu/hr)	Tree Prunings (Btu/hr)	Walnut Shells (Btu/hr)
Heat of Combustion of Solid Refuse	16,890	8,321	1,015
Volatile and Combustible Matter, Fixed Carbon	211,410	67,087	37,941
Sensible Heat in Char	6,588	2,613	1,083
Heat of Combustion of Anhydrous tar in Condensate	0	0	1,396
Latent and Sensible Heat of Water in Condensate	0	0	244
Radiant Heat	40,000	40,000	40,000
Total	274,897	118,021	81,679
Total Energy Output in Gas	379,401	183,179	188,742
Sensible and Latent Heat of Steam in Gas Stream	8,352	4,043	3,905
Sensible Heat in Dry Gas	9,882	4,660	4,622
Total	18,234	8,703	8,527
Net Energy Output in Gas	361,167	174,475	130,214
Conversion Efficiency (%)	55.2	57.9	66.6

Source: ref. 18.

The data presented for the laboratory gasifier with corncobs should be fairly close to the results for actual corn residue, but the fuel consumption rate will be somewhat higher (i.e., more moist corn residue will be required to realize the wet fuel heat potential). The increase in fuel consumption can be approximated by the following formula:

$$\text{Wet Fuel Consumption} = \frac{\text{Dry Fuel Consumption}}{1.0 - \text{Fraction of H}_2\text{O in Residue}}$$

It should be noted that a wetter fuel will also affect reactor efficiency.

4.2.2 Energy and Material Flows

The major material and energy flows for our model gasification system are given in Table 4.8. The model system is small, so it may be used on the farm near the site of production to reduce the cost of the corn residue fuel. Although the low-Btu gas could be used to operate machinery, such as irrigation pumps, the primary application for this unit probably would be to supply gas for grain dryers.

4.3 ENVIRONMENTAL DATA

4.3.1 General Soil Effects

Total removal of residues from corn, wheat, and cotton fields has the same ultimate effect on the soil although the rate will vary because of differences in crop root systems, plant physiology, climatic conditions, and soil properties. Soil destruction begins with the first harvest of residue because the soil is completely exposed to water and wind. Brady²⁷ reports

Table 4.8. Material and Energy Flows for Gasification^a of Corn Residues at 20% Moisture

System Variable	Material Flow	Energy Flow
Residue Utilization Rate	1.5 Tons (corn residue)/hr (20% H ₂ O)	17.4 x 10 ⁶ Btu/hr
Utilities	-	120 KWh/day
	-	10 gallons gasoline/day or natural gas equivalent
Production Efficiency	64,000 ft ³ (Gas/hr (150 Btu/ft ³)	9.6 x 10 ⁶ Btu/hr
	0.18 tons (Char)/hr (14,500 Btu/lb)	5.2 x 10 ⁶ Btu/hr

^aPlant Capacity: 24-hr/day, 330 stream days/yr.

that Wischmeir and Mannering found that removing residues increased runoff from 0.52 inch to 0.98 inch on 678 plot-years of corn. When residues are removed, the raindrop effect destroys surface soil structure, causing puddling, decreased water infiltration, soil compaction, reduced porosity, and a loss of organic matter. In wheat and cotton growing areas, wind takes over after the soil has dried. Wind sorts the surface material, blowing away the fines and leaving only the semisterile skeletal matter.²⁸

Organic matter acts as a binding agent to develop and maintain soil structure, by maintaining good tilth, increasing infiltration, maintaining soil porosity, and acting as a counter force against soil compaction.^{27,29} Organic matter also serves as a storehouse for nutrients, increases cation and anion exchange capacity, and chelates micronutrients, protecting the plant from potentially toxic concentrations.^{27,29-31} In high-organic-matter soils this material releases 40-80 lb/acre of nitrogen for crop uses.^{30,31} Removal of all residues from fields where continuous corn was grown during a period of 18 years resulted in a 15,000 lb/acre decrease in organic matter.³⁰

Not all residues need to be returned to the soil to maintain organic carbon content. Larson and others³² found that by using conservational tillage (e.g., chisel plow) 1% to 57% of the corn area in selected land resource areas of Minnesota and Iowa could have all the residues removed without losing more than 4 tons of soil per acre per year. However, these are only calculated data; the amount of residues that can be safely removed from an area depends on the soil, climatic conditions, and especially management practices such as type of tillage and fertility program.³²

The adverse effect of removing corn residues on the chemical properties of soil can be partially overcome by increased fertilizer application. Data presented in this report are only for the first year that crop residues are removed. In the second crop year, fertilizer rates must be increased to replace that portion of the nutrients removed with the grain, residue, and erosion. Maintaining favorable chemical properties over a period of several crop years could be more costly in terms of energy than the amount of energy in the residue. Unfortunately, the adverse impact on the physical properties of soil can only be slowed down with higher fertilizer rates. The continual passage of crop residues through the soil and their transformation into organic matter are needed to stop the deterioration of the physical properties of the soil.^{29,31}

4.3.2 Some Aspects of Corn Residue Removal

Table 4.9 shows the inputs needed to obtain a yield of 107 bushels/acre of corn. Data taken from Pimentel et al.³³ were adjusted to reflect the increased yield in our table. The assumption that a linear relationship exists between fertilizer rates³⁶ and yield made calculation of the nutrient data possible.

The amount of fertilizer nitrogen applied to the soil for corn production is based on maximum economic return.³⁶ Other nutrients (phosphorus and potassium) are added on the basis of soil tests that indicate the amount of nutrient needed for maintenance of optimum crop yield plus a build-up factor that provides for fixation of these nutrients by soils that are low in these elements. Calcium and magnesium are seldom required for Illinois soils.

These soils are rich in basic cations; however, the advent of continuous corn production with high rates of applied nitrogen fertilizer made the addition of agricultural lime necessary to maintain a pH of 6.5 in the surface soil horizon.

Table 4.10 shows the approximate amounts of nutrients removed in the grain and residue. When only the grain is removed, the fertilizer added to produce this crop (Table 4.9) is adequate to maintain the productivity of the soil; however, the loss of nutrients by erosion (Table 4.11) eliminates most of the build-up fertilizer applied. Also, the material eroded away usually contains a high proportion of nutrients that are readily available to plants; in some experiments the material eroded away contained five times more organic matter and nitrogen than the original soil.²⁷

Data in Tables 4.10 and 4.11 show that nutrient losses greatly increase because erosion increases and that nutrients in crop residues are also lost when these residues are completely removed. Nitrogen losses are 1.6 times greater than the amount applied, and phosphorus losses are 1.2-1.6 times greater than the amount applied. Potassium losses are 10.6-16.7 times greater than the amount applied, and magnesium losses are 130-200 times greater. Calcium losses are high because of erosion, but the total calcium loss is not greater than the amount applied. No sulfur is applied unless a deficiency is noted; however, at the rate of removal indicated in Tables 4.10 and 4.11 it will not take many growing seasons for sulfur deficiencies to appear in corn plants. Trace elements are not normally added to the soil as fertilizer, but sprayed on the growing plants when deficiency symptoms become evident. Some soils already exhibit deficiencies in sulfur and some of the trace elements;³⁶ therefore a management system in which corn is grown in monoculture and the total crop is removed will only increase the number of acres that must have these nutrients supplied by fertilizers. There are additional losses of nutrients, particularly nitrogen, by the

Table 4.9. Inputs per Year Needed to Obtain a Yield of 107 Bushels of Corn and 3.21 Tons of Residue per Acre under Continuous Cropping Systems in Illinois

Input	Amount per Acre	Amount per Ton of Residue
Nutrients (lb)		
Nitrogen	148	46.1
Phosphorus	41	12.8
Potassium	79	24.6
Calcium	634 ^a	197.8
Magnesium	1	0.33
Seed (lb)	19	5.9
Active Ingredients in Pesticides (lb)	3	0.93
Gasoline (gal)	22	6.9

Data sources: refs. 33-36.

^aYearly rate assuming that soils are limed every fourth year.

Table 4.10. Nutrients and Mineral Matter Removed by Corn Crop^a

Elements and Minerals	Grain		Residue	
	Pounds per Acre	Pounds per Ton of Grain	Pounds per Acre	Pounds per Ton of Residue
Nitrogen	96	32.0	71.3	22.2
Phosphorus	16.6	5.5	11.4	3.6
Potassium	23.6	7.9	85.8	26.8
Calcium	11.4	3.8	19.6	6.1
Magnesium	14.0	4.7	12.1	3.8
Sulfur	10.2	3.4	7.0	2.2
Copper	0.04	0.013	0.04	0.012
Manganese	0.06	0.020	1.07	0.334
Zinc	0.11	0.037	0.21	0.066
Mineral Matter	-	-	371.9	116.0

Data sources: refs. 29,37,38.

^aThe assumption was made that a linear relationship exists between crop yield and nutrient application; therefore the data were adjusted for a yield of 107 bushels/acre.

Table 4.11. Nutrients Lost by Soil Erosion under Continuous Corn Production with Two Residue-Management Techniques^a

Nutrient Loss Measurement	Nutrient					
	N	P	K	Ca	Mg	S
RESIDUES REMOVED						
Pounds Lost/Yr	79-132	22-36	726-1,210	264-440	104-174	20-34
Pounds Lost/Ton of Residues	25-41	7-11	226-377	82-137	33-54	6-11
RESIDUES RETURNED						
Pounds Lost/Acre	66	18	605	220	87	17
Pounds Lost/Ton of Residues	21	6	189	69	27	5
Pounds Lost/Ton of Grain	77	6	202	73	29	6

Data sources: refs. 27,32.

^aData can vary between 120% and 200% increase in soil and nutrient loss. For this study we used a range of nutrient loss because the exact increase depends on many factors (e.g., soil type, tillage method, slope).

leaching process. Nutrients move down through the soil out of the root zone and are no longer available to corn plants. Table 4.12 gives the nutrient replacement required by residue removal per ton of residue removed and per 10^{12} Btu generated by corn residue gasification.

4.3.3 Operating Residuals

The major environmental problem associated with pyrolysis is air pollution. The oil and char produced have been marketable in the past⁷ and may be considered by-products instead of pollutants. Although negligible amounts of oil and tar are expected to be generated during gasification of corn residue, a significant quantity of combustible solid waste is generated. It is estimated that 18,750 tons of char (heating value 29×10^6 Btu/ton) is produced per 10^{12} Btu output. This solid waste should have market value as a solid fuel.

There are three major air pollutants: NO_x , particulates, and hydrogen sulfides. In experiments on gasifier emissions using wood residues, Hodam and Williams¹⁷ measured emissions of 0.703 lb/hr of particulates and NO_x at 129 ppm. We have estimated these NO_x emissions to be about 1 lb/hr and assume that data for wood residues are applicable to corn residues. A review of pyrolysis by Nelson and Loehr³⁹ suggests that 25-30% of the sulfur goes into hydrogen sulfide, the third major air pollutant. Together with our data, this suggests that from one wet ton of corn residue (2.2 lb sulfur/ton) at 25% conversion of the sulfur to H_2S , 0.55 lb of sulfur or 0.59 lb of H_2S are emitted per ton of residue (20% moisture content). This amounts to 46.1 tons of H_2S per 10^{12} Btu of end-use energy. The H_2S from pyrolysis is mostly converted to SO_2 during combustion of the gas. In the same terms, about 36.6 tons of particulates and about 52.1 tons of NO_x are emitted per 10^{12} Btu of end-use energy.

4.3.4 Land Requirements

The amount of land required for the conversion facility is small -- 0.25 acre. However, the amount of land required for residue production is quite large, approximately 0.25 acre/ton.

Table 4.12. Nutrient Replacement Required when Corn Residue is Removed for Pyrolysis

Nutrient	Replacement per Ton of Residue (20% mois- ture) (tons/ton)	Replacement per 10^{12} Btu (tons/ 10^{12} Btu)
Nitrogen	0.0185	2,891
Phosphorus	0.0051	797
Potassium	0.0099	1,547
Calcium	0.079	12,344
Magnesium	0.00013	20

4.3.5 Water Requirements

No water requirements are anticipated for the gasification of corn residues.

4.4 ECONOMIC DATA

4.4.1 Capital Costs

The system described for the gasification of corn residue is quite simple: a gasifier unit, a materials handling unit, and the gasifier with piping and controls. The gasifier has a dry-fuel rating of 28.6 tons/day (330 stream days/yr). Tables 4.13 and 4.14 identify and summarize the capital costs of the system for major equipment purchases and per 10^{12} Btu output.

The total estimated capital cost for this system is \$112,042 (1972 dollars) per 10^{12} Btu of output.

4.4.2 Operating and Maintenance Costs

Labor cost as a percentage of process equipment cost is taken at 9%, and overhead and profit are 10% of the materials subtotal.

Annual labor (1977) and maintenance costs for this unit have been calculated by Goss²⁶ as follows:

- Annual labor (1,000 hr at \$10/hr) \$ 10,000
- Repairs and Maintenance (3% of new cost) \$ 4,800

To these expenses should be added:

- Supervision (20% of labor) \$ 2,000
- Overhead (60% of labor plus supervision) \$ 7,200
- Residue Cost (80% dry) (11,800 tons/yr at \$20/ton) \$237,600.

The residue cost is taken from the low estimate made by Lipinsky et al.²⁵ for field-dried chopped corn residue. The removal of this much residue would require 220 additional tons of nitrogen, 61 tons of phosphorus, and 117 tons of potassium. Lipinsky et al. considered the fertilizer value of the corn in their estimate although not necessarily in those quantities.

4.5 SUMMARY OF FINDINGS

The material, energy, residual, and cost inputs and outputs for this system have been calculated on the basis of 10^{12} Btu of energy output from the gasifier. These results are summarized in Table 4.15. It would require 13.2 systems to produce 10^{12} Btu.

Table 4.13. Construction Costs for a Gasification Unit

Component (Industrial Sector)	Cost in 1977 Dollars
Gasifier, 28.6 Tons/Day (Fabricated Metal Product)	79,794
Piping, Burner, and Controls (Plumbing and Heating Equipment)	37,200
Storage Bin, 12 Ft x 35 Ft (Fabricated Metal Product)	6,138
Conveyor Unit (Material Handling Machinery)	2,083
Labor, 932 Hr at \$13/Hr	12,116
Transportation	9,425
Overhead and Profit	13,464
Total	160,220

Table 4.14. Capital Costs of a Gasification Unit per 10^{12} Btu Output

	1977 Dollars	Deflator	1972 Dollars
Total Capital Cost	160,220	1.43	112,042
Materials	125,215	1.43	87,563
Transportation	9,425	1.43	6,593
Construction Labor	12,464	1.43	8,473
Profit and Overhead	13,464	1.43	9,415
Annual System 10^{12} Btu Output		0.07575	
Total Capital Cost/ 10^{12} Annual Btu	1,479,102		
Number of Years to Construct Facility		1	
Expected Life of Facility (years)		10	
Man Years to Construct Facility		0.466	
Man Years/ 10^{12} Btu Annual Output		6.15	
Estimated Land Use (acres)		0.25 ^a	

^aFor one plant site. Additional land also needed to supply residue (approximately 0.25 acre/ton residue).

Table 4.15. Input/Output Summary for Pyrolysis of Corn Residues

SIZE:

The system is designed to gasify 11,880 tons of residues/yr during 330 stream days of operation.

Annual fuel production average is 6.4×10^6 Btu gas/ton of residue or 7.6×10^{10} Btu/yr @ capacity.

DESCRIPTION:

Thermochemical conversion of corn residues occurs in a medium-sized gasification unit. Primary energy resource produced is a low-Btu gas for use in drying or machinery operation. An energy by-product is generated in char.

COMPONENTS:

Storage facility, gasifier and controls, and materials handling system.

MAJOR ENVIRONMENTAL

PROBLEMS:

Air emissions, soil nutrient depletion.

INPUT (per 10^{12} Btu):

Fuel

Residue requirement:
156,250 tons corn residue,
20% moisture content
(heating value = 11.6×10^6 Btu/ton)

Electricity: 521,000 kWh,

Gasoline: 43,421 gallons
(or natural gas equivalent)
Requires 13.2 gasifier
units operating at capacity to produce 10^{12} Btu

Water: None

Land:

0.25 acre/plant site, 3.3 acres/
 10^{12} Btu, 48,428 acres of corn
residue/ 10^{12} Btu (0.25 acre/ton
residue)

COST (1972 dollars):

Capital costs: \$1,479,102

Operation and maintenance:
\$2,398,000 (including
residue cost of \$20/ton)

OUTPUT (per 10^{12} Btu):

Air pollutants

Particulates: 36.6 tons
Hydrogen sulfide: 36.6 tons
NOx: 52.1 tons

Water pollutants

Negligible

Solid waste

Solid by-product has market
value and does not enter
environment as a pollutant

Energy

Low-Btu gas: 10^{12} Btu; can
replace natural gas or
petroleum fuel

Char by-product:
 0.54×10^{12} Btu combustible
carbonized material (18,750
tons), heating value =
 10^6 Btu/ton

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5 WHEAT RESIDUE PYROLYSIS (GASIFICATION)

ABSTRACT

This section analyzes capital and environmental costs of energy recovery through pyrolysis of wheat residue to produce a low-Btu fuel gas. The analysis is based on use of a model gasifier developed for corn residues. Used for gasification of wheat residue, the unit would consume 1.58 tons of residue per hour and would produce 73,846 ft³ of gas with a heating value of 130 Btu/ft³. The system is designed to be used on large farms, where it could be used to operate machinery such as irrigation pumps or grain dryers. Use of the system is commercially sound, but complete removal of wheat residues rapidly depletes the soil, and extensive soil management would be necessary to maintain soil productivity. Air pollution is the main environmental problem associated with pyrolysis.

5.1 INTRODUCTION

5.1.1 General System Description

Pyrolysis is the thermochemical alteration of organic matter in the absence of air. The first material pyrolyzed by man most likely was wood, and the end-use energy produced was charcoal, a cleaner-burning fuel. This simple approach to pyrolysis is still one of the most widely practiced biomass conversion strategies in the world. Brazil has an intensive national program to increase charcoal production, and today 40% of the energy needs of the Brazilian steel industry (approximately 2 million tons annually) are supplied by charcoal.¹

The principal products of pyrolysis are gas, a highly carbonized solid residue called char, and oil-like liquids with a high tar content. The proportions of char, oil, and gas produced depend on the chemical composition of the feed, its preparation, the reaction temperature and pressure, and the time the material stays in the reactor.²⁻⁵ Heat for pyrolysis may be externally applied to the biomass (true pyrolysis), or it may be produced by combustion of part of the biomass itself.

The modern method of charcoal production from wood is carried out in a steel retort. The wood is externally heated for 20-24 hr at 500-700°F near atmospheric pressure.^{6,7} The process is often referred to as destructive wood distillation because certain chemical products are produced in addition to charcoal. Distillation of one cord (4,000 lb) of wood yields 7,000-12,300 ft³ of condensable gas, 900-1,100 lb of charcoal, 200-300 gal of raw pyroligneous acid, and 200 lb of acetate of lime.⁷

Liquefaction of biomaterials occurs at 400-700°F at pressures ranging from 1,000 psig to 4,000 psig.⁸⁻¹⁰ Table 5.1 gives the percent conversion of some agricultural and forestry residues to oil. A typical catalyst used in this process is sodium bicarbonate. This process can produce an oil very similar to No. 6 fuel oil.¹¹ The properties of the two oils are summarized in Table 5.2.

Table 5.1. Conversion of Various Cellulosic Wastes to Oil^a

Raw Material	Amount (gm)	Time at Reaction Temp. (hr)	Maximum Pressure (psig)	Conversion (%)	Oil Yield (%)	CO used (gm/100 gm oil)
Cornstalks	50	1	1,760	95	42	21
Corncocks	100	1	2,400	95	38	9.7
Rice Hulls	50	1	1,600	97	40	25
Newsprint	50	0.5	1,640	88	40	21
Pine Bark	50	1	1,600	83	32	45

Source: ref. 11.

^a200 ml water, 10 gm NaHCO₃, 500 psig initial CO pressure, 482°F reaction temperature.

Table 5.2. Properties of No. 6 Fuel Oil and Pyrolytic Oil

Property	No. 6 Fuel Oil	Pyrolytic Oil
Btu/lb	18,200	10,500
Specific Gravity	0.98	1.30
Pounds per Gallon	8.18	10.85
Flash Point (°F)	150	133
Viscosity (SSU) at 190°F	340	3,150
Pumping Temperature (°F)	115	160
Atomization Temperature (°F)	220	240

Source: ref. 11.

Methane is the main gas component of pyrolysis if the reaction is carried out at high temperature and pressure (2,000°F, 1,000 psig). Methane production is boosted by injecting water into the reactor.¹² The water reacts with the hot char to produce carbon monoxide and hydrogen, and methane generation then proceeds by the following routes:

Under even higher pressures (up to 4,000 psig), methanol can be formed from the reaction of carbon dioxide and hydrogen gas.^{13,14} The use of various chemical catalysts also can affect the volume and composition of gas produced.^{15,16}

In this section, pyrolysis is examined for the production of a low-Btu fuel gas from wheat residues under conditions of low pressure and relatively high temperature (about 1,600°F). The reaction is a two-stage process in which part of the biomass in the reactor is combusted, with a limited

air supply, to raise the temperature in the gasifier to about 1,600°F to pyrolyze the remaining biomass. Steam is often injected to react with the char to generate hydrogen and carbon monoxide gas.

The composition of the gas produced by such a gasifier unit and that of a true pyrolysis gas is given in Table 5.3. The large amounts of nitrogen present in gasifier gas are from the air burned to increase the temperature in the unit. It should also be noted that gasifiers convert eight to nine times more of the feedstock to gas than occurs with pyrolysis.

Table 5.4 shows the char composition for different biomass feedstocks. The heating values of these pyrolytic chars range from 5,500 to 8,300 Btu/lb, similar to the heating values of many coals. The ash content reported in various chars from gasifiers is much lower--between 1% and 20%.^{17,18} Tars are often generated in gasifiers, but the tar content is usually less than 5%.

5.1.2 Resource Distribution

There are many significant wheat producing regions throughout the U.S. The distribution of average wheat harvest is presented in Fig. 5.1. Because of regional variations in productivity, the wheat residue resource selected for study has been analyzed on a regional basis to determine the impacts of residue removal on the environment. A six-state area, the wheat belt, which accounts for 54.6% of the U.S. wheat crop,²⁰ has been selected for this study. In these six states (Kansas, Montana, North Dakota, Oklahoma, Texas, and Minnesota), an estimated 96.7 million tons of straw residue were produced, with average residue yields from 1.80 to 2.65 tons/acre. These data were estimated from grain yields with a dry-weight grain:residue ratio of 1:2.73.²¹⁻²⁵ Table 5.5 summarizes the crop and crop residue production for wheat in this six-state area.

The soil in this wheat growing area is subjected to high winds, and serious erosion occurs if little residue is left in the field. As with other crops and conversion strategies, careful consideration needs to be given to the soil impacts of crop residue removal for energy production.

5.2 DESCRIPTION OF MODEL SYSTEM

5.2.1 System Description and Equipment

As for corn residues, the model system selected for this study is an updraft gasifier unit that produces low-Btu gas and char and operates at approximately 1,600°F. A commercial unit is in operation at Diamond/Sunsweet, Inc., Stockton, California.²⁷ The unit has a capacity of 28.6 tons per day and produces enough energy to sustain a steam production rate of 8,500 lb/hr (15 psig) at a fuel rate of one ton of mulled walnut shells per hour. A natural gas pilot flame is used. A laboratory-scale model similar to this unit has been built at the University of California at Davis.¹⁸

Fig. 5.1. Wheat Harvested, 1969

Table 5.3. Characteristics of Pyrolytic Gas and Gasifier Gas

Characteristics	Pyrolytic Gas ^a (wt %)				Gasifier Gas ^b (vol %)		
	Annual Waste	Rice Hulls	Grass Straw	Fir Bark	Cubed Cotton Gin Trash	Raw Cracked Walnut Shells	Broken Corncobs
Components							
H ₂	6.1	23.3	9.6	6.3	18.3	18.4	16.1
CO	21.9	28.5	53.9	14.7	16.4	20.1	18.7
CO ₂	55.9	40.8	26.9	64.7	11.6	8.7	9.8
CH ₄	6.1	3.5	3.8	10.5	-	-	-
C ₂ H ₂	0.5	0.8	0.8	1.0	-	-	-
C ₂ ⁺	1.8	0.8	2.8	1.2	-	-	-
THC	-	-	-	-	1.8	5.1	4.3
N ₂	-	-	-	-	51.4	47.3	50.9
O ₂	-	-	-	-	0.5	0.4	0.2
H ₂ S	7.8	2.4	2.2	1.7	-	-	-
Other Characteristics							
Btu/ft ³	226	214	349	222	118	159	141
Gas Yield (%)	10.8	12.1	5.2	8.2	88	91	93
Char Yield (%)	48.1	35.9	23.2	41.2	11	9	5

^aPober and Bauer.¹¹^bHodam and Williams.¹⁷

Table 5.4. Analysis of Pyrolytic Chars from Organic Solid Wastes

Characteristics	Animal Waste	Rice Hulls	Fir Bark	Grass Straw
Components (wt%)				
Carbon	34.5	36.0	49.9	51.0
Hydrogen	2.2	2.6	4.0	3.7
Nitrogen	1.9	0.4	0.1	0.5
Sulfur	0.9	0.1	0.1	0.8
Oxygen	7.9	11.5	24.3	19.2
Ash	48.8	49.2	21.4	24.3
Btu/lb	5,450	6,100	8,260	8,300
Char Yield	48.1	35.9	41.6	23.2

Source: ref. 11.

Table 5.5. Wheat -- Grain and Residue Production and Energy Value of Residues: Six States and U.S., 1976

Location	Grain ^a (bushels/ acre)	Grain (tons/acre)	Residue ^b (tons/acre)	Total Acreage (10 ³ acres)	Total Residues (10 ⁶ tons)	Total Residue Energy Value ^c (10 ¹² Btu)
Kansas	30.3	0.90	2.50	11,300	27.8	301.9
Montana	30.9	0.93	2.53	5,415	13.7	148.8
N. Dakota	24.7	0.74	2.02	11,655	23.6	256.3
Oklahoma	24.0	0.72	1.97	6,300	12.4	134.7
Texas	22.0	0.66	1.80	4,700	8.5	92.3
Minnesota	32.2	0.97	2.65	4,056	10.7	116.2
Six-State Total	-	-	-	43,426	96.7	1,050.2
U.S. Total	30.3	0.91	2.50	70,824	177.1	1,923.3

^aData from ref. 20.^bRatio of 1:2.73 (grain:residue) was used.^{24,25}^cBased on 5,430 Btu/lb = (10.86 x 10⁶ Btu/ton).²⁶

The laboratory model system was studied for corn residue gasification. No test run was conducted for wheat straw, so some inferences had to be made concerning the conversion efficiency of this process for straw, although this material can be readily gasified.⁵ Table 5.6 presents the chemical analysis of corn residue and straw. The chemical constituents in the two residues are almost identical, although straw has less carbon. The most pertinent distinction between the two materials is that the heating value of corn residues is 12.7% higher than that of wheat straw.

For development of the model system for wheat residue gasification we assume that the energy and material conversion percentages for wheat straw during gasification are identical to those of corn residues. However, a 12.7% increase in fuel consumption is required to account for the differences in heating values. Therefore the gas and char produced will have lower heating values. Wheat residue is assumed to have a 15% moisture content.

Chopped wheat straw would be the feedstock for the unit. Eighty-four percent of the input fuel is assumed to be gasified, and the principal product is a low-Btu gas (100-200 Btu/ft³) with a char residue (30% of input energy) as a by-product. The remaining heat is not recovered. The mean heating value for dry straw is 6,445 Btu/lb.²⁶ To account for differences of fuel consumption rate because of the moisture in the straw, the following formula is used to approximate the increased wet fuel consumption:

$$\text{Wet Fuel Consumption} = \frac{\text{Dry Fuel Consumption}}{1.0 - \text{Fraction of H}_2\text{O in Residue}}$$

This formula simply corrects wet fuel to a dry basis consumption; the wetness of the fuel will also affect the efficiency of the reactor.

5.2.2 Energy and Material Flows

The major material and energy flows for our model gasification system are given in Table 5.7. The model system is of a moderate scale so it may be used on the farm near the site of production to reduce the cost of the wheat residue fuel. The Low-Btu gas is primarily designed for use in grain drying, but could be used to operate machinery such as irrigation pumps or grain dryers.

5.3. ENVIRONMENTAL DATA

5.3.1 General Soil Effects

Total removal of residues from wheat, corn, and cotton fields has the same ultimate effect on the soil although the rate will vary because of differences in crop root system, plant physiology, climatic conditions, and soil properties. Soil destruction begins with the first harvest of residue because the soil is completely exposed to water and wind. Brady²⁸ reports

Table 5.6. Analysis of Corncob³ and Wheat Straw (Dry Basis)^a

Component	Corn Residue	Wheat Straw
Carbon (%)	44.8	42.7
Hydrogen (%)	6.1	6.0
Oxygen (%)	43.6	45.1
Nitrogen (%)	0.6	0.6
Ash (%)	4.9	5.6
Heating Value (Btu/lb)	7,268	6,445

^aAdapted from wet basis analysis of Johnson and Auth.²⁶

Table 5.7. Material and Energy Flows for Gasification^a
of Wheat Residues at 20% Moisture Content

System Variable	Material Flow	Energy Flow
Residue Utilization Rates	1.58 tons (wheat residue)/hr (15% moisture)	17.4 x 10 ⁶ Btu
Utilities		120 kWh/day 10 gallons gasoline/day or natural gas equivalent
Production Efficiency	73,846 ft ³ (gas)/hr (130 Btu/ft ³) 0.2 ton (char)/hr (12,800 Btu/lb)	9.6 x 10 ⁶ Btu/hr 5.2 x 10 ⁶ Btu/hr

^aPlant Capacity: 24 hr/day, 330 stream days/yr.

that Wischmeir and Mannering found that removing residues increased runoff from 0.52 inch to 0.98 inch on 678 plot-years of corn. When residues are removed, the raindrop effect destroys surface soil structure, causing puddling, decreased water infiltration, soil compaction, reduced porosity, and a loss of organic matter. In the wheat and cotton growing areas, wind takes over after the soil has dried. Wind sorts the surface material, blowing away the fines and leaving only the semi sterile skeletal matter.²⁷

Organic matter acts as a binding agent to develop and maintain soil structure, which maintains good tilth, increases infiltration, maintains soil porosity, and is a counter force against soil compaction.^{26,28} Organic matter serves as a storehouse for nutrients, increases cation and anion exchange capacity, and chelates micronutrients, protecting plants from potentially toxic concentrations.^{26,28-30} Organic matter in high-organic-matter soils releases approximately 40-80 lb/acre of nitrogen per year for crop uses.^{29,30} Removal of all residues from fields where corn was grown continuously during a period of 18 years resulted in a decrease in organic matter of 15,000 lb/acre.²⁹

Not all residues need to be returned to the soil to maintain organic carbon content. Larson and others³³ found that by using conservational tillage (e.g., chisel plow) 1% to 57% of the corn area in selected land resource areas of Minnesota and Iowa could have all the residues removed without losing more than 4 tons of soil per acre per year. However, these are only calculated data; the amount of residues that can be safely removed from an area depends on the soil, climatic conditions, and especially management practices such as type of tillage and fertility programs.³³

The adverse effect of removing wheat residues can be partially overcome by increased fertilizer application. Data presented in this report are only for the first year that crop residues are removed. The second crop year, fertilizer rates must be increased to replace that portion of the nutrients removed by the grain, residue, and erosion. Maintaining usable chemical properties over a period of several crop years could be more costly in terms of energy than the amount of energy in the residue. Unfortunately, the adverse impact on the physical properties of the soil can only be slowed down with higher fertilizer rates. It takes the continual passing of crop residues through the soil and being transformed into organic matter to stop the deterioration of soil physical properties.^{30 32}

5.3.2 Some Aspects of Wheat Residue Removal

Only 64% of the wheat acreage received any fertilization in 1975 although a fertilization program is required for growing wheat on a continuous basis.^{24,30,34} Some of the nutrients in Table 5.8, particularly calcium and magnesium, may not be needed. More fertilizer is needed in the humid eastern region of the Central Plains than in the semiarid western region.²⁴

Fallowing, as a farming system, is used in the drier areas of the Great Plains. The soil is plowed to control weeds and left in a bare, unprotected state until the next wheat crop is planted. This system conserves plant nutrients, and it allows soil moisture to accumulate for the next crop. The detrimental part of fallowing is the exposure of the soil to the erosive forces of water and wind. Fertilizers are used to ameliorate the depletive results of erosion during the fallow year.^{24,36,37} Unfortunately there is no way to replace the fine material eroded from the soil surface.

Table 5.8. Inputs Needed to Obtain a Wheat Yield of 30 Bushels of Grain and 2.5 Tons of Residue per Acre in a Monoculture Cropping System

Input	Pounds Per Acre	Pounds Per Ton of Residue
Nutrients		
Nitrogen	47	18.8
Phosphorous	17	6.8
Potassium	30	12.0
Calcium	145	58.0
Magnesium	76	30.4
Seed	90	36.0
Active Ingredients in Pesticides	0.5	0.2

Sources: refs. 24,34,35.

Removal of all wheat crop residues would not adversely affect the nutrient supply of the soil except for nitrogen (Table 5.9). Nitrogen losses would be 1.1 times the amount applied. Potassium losses would be 1.04 times the amount applied, but supplies of this nutrient in the soils are adequate to handle this loss. Continual removal of the entire crop over time would result in the need to fertilize with sulfur and some micronutrients.

The major effects of total crop removal in the Great Plains are erosion and depletion of organic matter. Estimates have been made that soils in this area have lost approximately 50% of their original organic content.^{30,31} Lyles²⁹ reports that Stallings found that wind erosion in the Great Plains reduced wheat yields by 4.2 bushels per acre in 30 years. Lyles²⁹ found that in Geary County, Kansas, wheat yields were reduced 1.3 bushels per acre per inch of topsoil lost by wind erosion. He concluded that even with proper residue management (residues returned to soil), wheat yields were reduced from 0.39 to 1.92 bushels per acre per year, depending on the chemical and physical properties of the surface soil.

Skidmore and Siddoway⁴⁰ indicate that when all wheat residues are removed from a field with a soil erodibility of 44.6 tons/acre/yr, the potential annual soil loss due to wind erosion can be as high as 26.8 tons/acre. Soils that have an erodibility of 89 tons/acre/yr can have a potential annual soil loss of approximately 54 tons/acre when all residues are removed. However, when 1,250 lb/acre flat small grain residue is left on the surface of the soil, potential annual soil loss is only 2.2 and 4.9 tons/acre, respectively. In terms of nutrient removal, only the losses due to erosion would seriously affect soil fertility. Table 5.10 lists the amounts

Table 5.9. Nutrients and Mineral Matter Removed by Wheat Crop^a

Nutrient	Grain		Residue	
	Pounds per Acre	Pounds per Ton of Grain	Pounds per Acre	Pounds per Ton of Residue
Nitrogen	37.5	41.7	14.7	6.0
Phosphorous	8.0	8.9	1.3	0.53
Potassium	9.4	10.4	22.0	8.9
Calcium	0.7	0.8	4.6	1.9
Magnesium	4.6	5.1	2.0	0.8
Sulfur	2.0	2.2	4.0	1.6
Copper	0.02	0.02	0.007	0.003
Manganese	0.07	0.08	0.12	0.05
Zinc	0.01	0.01	0.04	0.02
Boron	0.07	0.08	0.15	0.06
Iron	0.14	0.16	0.37	0.15
Mineral Matter	-	-	407.9	166.0

Sources: refs. 30,34,38,39.

^aThe assumption was made that a linear relationship exists between crop yield and nutrient uptake; therefore, data were adjusted for a yield of 30 bushels/acre.

Table 5.10. Nutrient Replacement Required when Wheat Residue is Removed for Pyrolysis

Nutrient	Replacement per Ton of Residue (15% moisture) (tons/ton)	Replacement per 10^{12} Btu (Tons/ 10^{12} Btu)
Nitrogen	0.0081	1,333
Phosphorus	0.0029	477
Potassium	0.0052	856
Calcium	0.025	4,115
Magnesium	0.013	2,140

of soil nutrients that must be returned to the soil to maintain its productivity per ton of wheat residue removed and per 10^{12} Btu generated by gasification of residue.

5.3.3 Operating Residuals

The major environmental problem associated with pyrolysis is air pollution. The oil and char produced have been marketable in the past⁷ and may be considered by-products instead of pollutants. Although negligible amounts of oil and tar are generated during gasification of wheat residue, a significant quantity of combustible solid waste is generated. It is estimated that 21,094 tons of char (heating value about 29×10^6 Btu/ton) is produced per 10^{12} Btu output. This solid waste should have a market value as a solid fuel resource.

There are three major air pollutants: NO_x , particulates, and hydrogen sulfide. Experimental data have shown emissions from gasifiers burning wood residues to be 0.703 lb/hr of particulates and 129 ppm of NO_x . On the basis of these data, we have estimated NO_x emissions for wheat residues to be about 1.0 lb/hr or 52.1 tons of NO_x and 36.6 tons of particulates per 10^{12} Btu of energy output. A review of pyrolysis by Nelson and Loehr⁴¹ suggests that 25-30% of the sulfur goes into hydrogen sulfide. This suggests from our data that from one wet ton of wheat residue (1.6 lb sulfur/ton) at 25% conversion of the sulfur to H_2S , 0.34 lb sulfur or 0.36 lb H_2S are emitted per ton of residue (15% moisture content). This is equivalent of 29.6 tons H_2S per 10^{12} Btu output. However, the H_2S from pyrolysis is mostly converted to SO_2 upon combustion of the gas.

5.3.4 . Land Requirements

The land required for the conversion facility is 0.25 acres. The land requirement for residue production is quite large, approximately 0.34 acre/ ton.

5.3.5 Water Requirements

No water requirements are anticipated for the gasification of wheat residues.

5.4 ECONOMIC DATA

5.4.1 Capital Costs

The system described for the gasification of wheat residues is the same as for corn: a gasifier unit, a materials handling unit, and the gasifier with piping and controls. The gasifier has a dry-fuel rating of 28.6 tons/day (330 stream days/yr). Tables 5.11 and 5.12 identify and summarize the capital costs of the system for major equipment purchases and for 10¹² Btu output. The total estimated capital cost for the system is \$112,040 (1972 dollars).

5.4.2 Operating and Maintenance Costs

Labor cost as a percentage of process equipment cost is taken at 9%, and overhead and profit is 10% of the materials subtotal.

Annual labor (1977 dollars) and maintenance costs for this unit have been calculated by Goss²⁷ as follows:

- Annual Labor (1,000 hr at \$10/hr) \$ 10,000
- Repairs and Maintenance (3% of new cost) \$ 4,800

In addition, the following expenses should be added:

- Supervision (20% of labor) \$ 2,000
- Overhead (60% of labor plus supervision) \$ 7,200
- Residue Cost (85% dry) (12,513 tons/yr at \$20/ton) \$250,272

Table 5.11. Construction Costs for Model Gasification Unit

Component(Industrial Category)	Cost in 1977 Dollars
Gasifier, 28.6 Tons/Day (Fabricated Metal Product)	79,794
Piping, Burner, and Controls (Plumbing and Heating Equipment)	37,200
Storage Bin, 12 Ft x 35 Ft (Fabricated Metal Product)	6,138
Conveyor Unit (Material Handling Machinery)	2,083
Labor, 932 Hr at \$13/Hr	12,116
Transportation	9,425
Overhead and Profit	13,464
Total	160,220

Table 5.12. Capital Costs per 10^{12} Btu Output
for Model Gasification Unit

	1977 Dollars	Deflator	1972 Dollars
Total Capital Cost	160,220	1.43	112,042
Materials	125,215	1.43	87,563
Transportation	9,425	1.43	6,591
Construction Labor	12,116	1.43	8,473
Profit and Overhead	13,464	1.43	9,415
Annual System 10^{12} Btu Output			0.07575
Total Capital Cost/ 10^{12} Annual Btu		1,479,102	
Number of Years to Construct Facility		1	
Expected Life of Facility (years)		10	
Man Years to Construct Facility		0.466	
Man Years/ 10^{12} Btu Annual Output		6.15	
Estimated Land Use (acres)		0.25 ^a	

^aFor plant site. Additional land also needed to supply residue (approximately 0.34 acre/ton residue).

The residue cost, taken from a study on rice straw utilization by Doble, Miller, and Parson,⁴² applies to a 10-mile transportation distance and to either rectangular or rolled bale. The cost estimate is also applicable to chopped straw, which is needed for the gasifier. The cost per ton can range from \$16.52 to \$29.19.

Removal of 12,513 tons of residue would require 101 tons of nitrogen, 37 tons of phosphorus, and 65 tons of potassium (residue removal rate is 2.5 tons/acre).

5.5 SUMMARY OF FINDINGS

The material, energy, residual, and cost inputs and outputs for this system have been calculated on the basis of 10^{12} Btu of energy output by the gasifier. These results are summarized in Table 5.13. It would require 13.2 systems to produce 10^{12} Btu to substitute for natural gas or other appropriate fuel.

Table 5.13. Input/Output Summary for Pyrolysis of Wheat Residues

<p>SIZE: System is designed to gasify 11,880 tons of residues/yr during 330 stream days of operation. Annual fuel production average is 6.076×10^6 Btu per ton of residue, or 7.6×10^{10} Btu/yr @ capacity</p> <p>DESCRIPTION: Thermochemical conversion of wheat residues occurs in a medium-sized gasification unit; primary energy resource produced is a low-Btu gas for use in drying or machinery operation. An energy by-product is generated in char</p> <p>COMPONENTS: Storage facility, gasifier and controls, and materials handling systems</p> <p>MAJOR ENVIRONMENTAL PROBLEMS: Air emissions, soil nutrient depletion</p>	<p>INPUT (per 10^{12} Btu): <u>Fuel</u> Residue requirement: 164,583 tons wheat residue, 15% moisture content (heating value = 10.96×10^6 Btu/ton) Electricity: 521,000 kWh Gasoline: 43,421 gallons (or natural gas equivalent). Requires 13.2 gasifier units operating at capacity to produce 10^{12} Btu.</p> <p><u>Water:</u> None.</p> <p><u>Land:</u> 0.25 acre/plant site, 3.3 acres/10^{12} Btu, 65,833 acres of corn residue/10^{12} Btu (0.34 acre/ton/residue).</p> <p>COST (1972 dollars): Capital costs: \$1,479,102 Operation and maintenance: \$2,514,160 (including residue cost of \$20/ton)</p>	<p>OUTPUT (per 10^{12} Btu): <u>Air pollutants</u> Particulates: 36.6 tons Hydrogen sulfide: 29.6 tons NO_x: 52.1 tons</p> <p><u>Water pollutants</u> Negligible</p> <p><u>Solid waste</u> Solid by-product has market value and does not enter environment as a pollutant</p> <p><u>Energy</u> Low-Btu gas: 10^{12} Btu; can replace natural gas or petroleum fuel Char by-product: 0.54×10^{12} Btu combustible material (21,094 tons) heating value = 25.6×10^6 Btu/ton</p>
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6 FERMENTATION OF SUGAR PROCESSING RESIDUES (MOLASSES)

ABSTRACT

This section estimates capital and environmental costs of energy recovery through fermentation of molasses obtained from the processing of sugar from sugarcane and sugar beets. A large-scale model for producing ethanol from molasses was developed from industrial references on molasses fermentation. The model plant would consume nearly 700,000 tons of molasses per year (almost half the U.S. molasses production in 1976) and would produce about 650 tons of anhydrous ethanol per year (annual system energy output 5.475×10^{12} Btu). Operation of the plant would interfere with use of molasses as a livestock feed supplement, but some of the demand for molasses could be offset by marketing the yeast and perhaps some stillage produced by the plant for use as animal feed. Air and water pollution would be the main environmental problems associated with ethanol production from molasses.

6.1 INTRODUCTION

6.1.1 General System Description

The technology for ethanol production coincides with that of the fermentation industry for alcoholic beverages. The processes typically use three types of raw material: sugary materials (mainly molasses), starchy materials (mainly corn and potatoes), and cellulosic materials (mainly waste pulp liquor).¹ Yeasts (usually *Saccharomyces cerevisiae*) are then used to ferment the simple sugars (mostly monosaccharides and disaccharides) to ethanol.² The feedstock for fermentation in this study is molasses, a by-product of sugar processing. There are two major sugar crops in the U.S., sugarcane and sugar beets. The system proposed in this report mainly applies to molasses derived from the processing of these two crops. However, because fermentation is such an adaptable process, almost any starch-containing crop (e.g., corn or wheat) could be used.

6.1.2 Resource Distribution

It has been estimated that the United States mainland production of molasses for 1976 was 133,676,000 gallons from sugarcane, 191,700,000 gallons from beets, 50,312,000 gallons of refiners' blackstrap, 10,140,000 gallons from citrus, and 20,500,000 gallons from hydrol processing, for a total of 406,328,000 gallons.³ In the same year, the U.S. mainland imported about 411,194,000 gallons and exported close to 11,215,000 gallons. Figures 6.1 and 6.2 depict the distribution of sugar beet and sugarcane acreage in the U.S. It is assumed that molasses will be produced at sugar refineries in major producing regions.

Molasses is the final liquor released in the processing of sugar that contains noncrystallizable sucrose. The expressed juice from the feedstock

Fig. 6.1. Sugar Beets Harvested for Sugar, Class 1-5 Farms, 1969

Fig. 6.2. Sugarcane Harvested for Sugar, Class 1-5 Farms, 1969

(cane, beet) is cleared of impurities, and the raw sugar is concentrated and crystallized by evaporating the juice. The sugar granules are removed by repeated centrifugation, washing, and reconcentration until no more sucrose crystals can be economically formed. The remaining effluent is a dark syrup containing fermentable sugars called molasses.

On the average, molasses contains about 55% total sugar by weight; sugar from cane molasses is about two-thirds sucrose and one-third invert sugar (glucose and fructose), whereas sugar from beet molasses contains very little invert sugar.⁵ Cane molasses is preferred by distillers because of the higher invert sugar concentration, although both types of molasses will support fermentation. According to Paturau's information,¹ the chemical composition of cane molasses is as follows: 17-25% water, 30-40% sucrose, 4-9% glucose, 5-12% fructose, 1-5% other reducing compounds, 2-5% other carbohydrates, 2-6% nitrogenous compounds, 2-8% nonnitrogenous acids, 7-15% ash, and some miscellaneous substances. He has also tabulated the constituents of ash: 30-50% K_2O , 7-15% CaO , 2-14% MgO , 0.3-9% Na_2O , 0.4-2.5% Fe_2O_3/Al_2O_3 , 7-27% SO_3 , 12-20% Cl , 1-10% P_2O_5 , and 1-7% SiO_2 and insolubles.

6.2 DESCRIPTION OF MODEL SYSTEM

6.2.1 System Description

A process diagram (Fig. 6.3) has been developed for production of ethanol from molasses using various references on industrial fermentation of molasses.^{1,5-12} The first phase of the process involves lowering the sugar content from 55% to 15% by dilution and adjusting the pH to between 4 and 5 with sulfuric acid. Other nutrients are not usually required if blackstrap molasses is used, because it contains nonsugar nutrients, although ammonium sulfate and phosphates may be needed. The mash (as the acidified diluted molasses is called) is now transferred to the fermentation vat. Some authors recommend sterilization, others recommend pasteurization, and still others claim that treatment of the mash is not necessary. For this system we chose a middle-of-the-road approach to help control bacterial contamination of the mash, namely, pasteurization.

A laboratory is required to maintain the purity of the yeast used to inoculate the mash, and special fermenters are necessary to grow the purified strains under aseptic conditions. The yeast is kept in a storage vat until inoculation, and some yeast may be recycled to the vat after fermentation. The volume of the yeast inoculum should range between 5 and 10% of the volume of mash.

Fermentation begins upon inoculation and continues for 28 to 72 hours (average 45 hours), producing an alcohol concentration between 6 and 10%. The temperature may vary between 77°F and 95°F, but it should be usually kept close to 90°F. During fermentation, carbon dioxide is released at a rate of 5 pounds per gallon of ethanol produced; 0.5% to 1% of the ethanol escapes with the gas.⁵ The fermentation liquor is now transferred to a centrifuge, and a yeast-rich stream is separated out. Part of the yeast will be returned to the vat for reuse; most will be dried and sold. Approximately 1.5 lb of yeast (50% solids) is generated per gallon of ethanol.⁸

Fig. 6.3. Ethanol Production by Fermentation

The light stream from the centrifuge is passed through a heat exchanger and into the beer still. The still residue, known as stillage, is then concentrated and dried to 10% moisture content. It is estimated that 6.4 lb of dry stillage (10% moisture) is produced per gallon of ethanol.⁸ The overhead from the still is passed through a condenser; the condensate contains 60% ethanol and a mixture of aldehydes.

The condensate is then charged into the aldehyde column, where these and other highly volatile compounds are boiled off. The ethanol fraction comes off after the aldehyde fraction and then enters the rectifying column. The lower fraction is known as fusel oil, which is a complex mixture of higher alcohols (see Table 6.1). About 0.024 lb of fusel oil per gallon of ethanol is produced.⁸ Water known as Lutter water leaves the system from the bottom of the column.

The final step in the process is the production of anhydrous ethanol. To achieve this product, benzene is added (10 times the quantity of water present) and the system of ethanol and benzene will distill until essentially all the benzene is exhausted. Loss of entraining agent is about 0.036 gallons per 100 gallons of ethanol. Ethanol loss is 0.1 gallon per 100 gallons of ethanol.

6.2.2 Material, Energy, and Equipment Requirements

Table 6.2 identifies the main material and energy flows through the system. These estimates of material and energy flows were taken from references 1, 5-12.

Many pieces of process equipment are needed to equip this facility. (These items are listed in Table 6.5). The major reference for identifying equipment requirements for this system was Lipinsky et al.⁸

6.3 ENVIRONMENTAL DATA

6.3.1 Resource Factors

Since molasses is a by-product of crop processing, its use has none of the soil effects discussed in previous volumes on corn, wheat, and cotton residues. The major impact of molasses utilization for ethanol production is economic and not related to land resources. Because the proposed fermentation

Table 6.1. Composition of Fusel Oil

Component	Weight Percent
Ethyl Alcohol	5
n-Propyl Alcohol	12.5
Isobutyl Alcohol	15
Amyl and Iso-Amyl alcohol	62.5
Residue Distilling Higher than 284°F	5

Source: ref. 1.

Table 6.2. Material and Energy Flows For Fermentation of Molasses

System Variable	Material Flow	Energy Flow
Plant Capacity	2,884 tons/day molasses (55% moisture)	
330 Stream Days/Year	anhydrous ethanol 197,214 gallons/day	1.66 x 10 ¹⁰ Btu/day
Fermentation	0.25 lb H ₂ SO ₄ /gal ethanol 0.015 lb ammonium sulfate/ gal ethanol 150 gal H ₂ O/gal ethanol 5 lb CO ₂ /gal ethanol 1.5 lb yeast/gal ethanol	16 lb steam/gal ethanol 0.1 kWh gal ethanol
Distillation and Rectification	80 gal H ₂ O gal ethanol 6.4 lb stillage/gal ethanol 0.024 lb fusel oil/ gal ethanol	161 lb steam/gal ethanol 0.02 kWh/gal ethanol
Anhydrous Distillation	0.5 gal benzene/gal ethanol 40 gal H ₂ O/gal ethanol	140 lb steam/ gal ethanol 0.02 kWh/gal ethanol

system is so large (it requires about 160 million gallons of molasses per year), it would consume almost half of the 1976 U.S. molasses production. Molasses is a major livestock feed supplement in many areas and there would be serious competition for it, but some of the demand for molasses for feed could be offset by marketing yeast and some stillage as feedstuffs.

Yeast is an excellent high-protein, feed supplement, and about 50,000 tons per year would be produced in the system. Yeast is a much more nutritious feed than molasses and would have a high market value. About 2,000 tons of stillage would be produced each year. Stillage is also a good feedstuff, and if it were used as such, more than 25% of the demand for molasses for feed could be offset by substituting it and yeast.

If adequate molasses cannot be obtained for the system, an alternative would be to satisfy some of the demand for molasses with a high-starch grain like corn. The corn would have to be mashed with malted barley or α -amylase (a fungal enzyme) to convert the starch to a fermentable sugar, but this would require only minor alterations in the process design.

Typically one could expect an anhydrous ethanol yield of about 2.65 gallons from one bushel of corn. If corn were used as feedstock it would perhaps be possible to gasify the residue to provide energy for fermentation.

This approach would allow the mixing of two biomass conversion methods in one system, corn grain for ethanol and corn residue for process energy.

6.3.2 Operating Residuals

Air and water pollution are the two main environmental problems associated with ethanol production. Hydrocarbon air contamination has been estimated to be of the magnitude of 0.01 ton of ethanol and 0.00041 ton of benzene per ton of ethanol produced, that is, a total of 407 tons of hydrocarbons per 10^{12} Btu. In addition, carbon dioxide from fermentation enters the atmosphere at a rate of 29,710 tons per 10^{12} Btu.

The main water pollutant is from contamination occurring during cooling and distilling and amounts to 2.96 lb BOD/ton ethanol produced or 57.9 tons per 10^{12} Btu generated.¹²

By-products of the process (stillage, fusel oil, and yeast) could be pollutants but usually are considered marketable commodities.

6.3.3 Land Requirements

An estimated 300-acre area is needed for the model plant for fermenting sugar-processing residues; 54.8 acres are needed per 10^{12} Btu.

6.3.4 Water Requirements

The water requirements in fermentation are for cooling (12,770 gallons/ton ethanol) and processing (3,040 gallons/ton ethanol), equaling 618,060,000 gallons per 10^{12} Btu.

6.4 ECONOMIC DATA

6.4.1 Capital Costs

A bottom-up approach was used for estimating the capital costs and material inputs of the molasses fermentation system. Plant costs were based on estimated process equipment costs by using previously published cost data for similar equipment¹⁴ and modifying where necessary. Once the process equipment costs were established, other direct and indirect costs were determined from the process equipment estimates. Table 6.3 gives a breakdown of capital costs for a typical multiprocess chemical plant. These estimates are within the ranges incurred during chemical plant construction.¹⁵ Using Table 6.3 other costs were inferred on the basis of the process equipment cost estimates. These results are found in Tables 6.4 and 6.5. The total capital cost for the system was estimated at \$52,883,360 (1972 dollars).

Table 6.3. Anticipated Distribution of Capital Costs for a Multiprocess Plant

Cost Component	Percent of Total Cost
Site and Preparation	1.5
Buildings and Auxiliaries	10.0
Construction Labor	6.5
Process Material (includes concrete substructures, piping and ductwork, electrical, insulation, process structural, instrumentation, paint)	13.0
Process Material Labor	8.0
Process Equipment	32.5
Process Equipment Labor	3.0
Home Office Expense (including overhead)	15.5
Field Office Expense (including overhead)	10.0

6.4.2 Operating Costs

Operating costs were taken from estimates of Lipinsky et al.¹⁴ for a comparably sized fermentation plant that used sugarcane juice. These costs were assumed suitable to our application, and the breakdown is given in Table 6.6.

In addition to the above operating costs, the amount to be paid for the molasses has to be considered. The estimated value of this commodity is 4.9 cents per pound of fermentable solids (1976 dollars).

Credits may be realized for the following by-products: dried stillage \$60/ton, yeast \$100/ton, and fusel oil \$.10/lb.¹⁴ No value was assigned to the carbon dioxide produced.

6.5 SUMMARY OF FINDINGS

The material, energy, residual, and cost inputs and outputs for the system were calculated on the basis of 10^{12} Btu of energy output by the system. These results are summarized in Table 6.7. It requires only one fifth of the system's annual production to produce 10^{12} Btu.

A major residual effect is the substantial BOD load. It is necessary that all by-products from the system be marketed to reduce such residuals and to increase the energy effectiveness of the system.

Table 6.4. Capital Costs for Fermentation of Molasses

Component (Industrial Sector)	Cost in 1977 Dollars	Component (Industrial Sector)	Cost in 1977 Dollars
Process Equipment		Alcohol Column, 1,000 Ft ² (Other Fabricated Metal Products)	22,692
Sterilizer Unit, 18,000 Gal (Plumbing and Heating Equipment)	77,376	Alcohol Column Reboiler, 3,500 Ft ² (2) (Metal Plate (Boiler))	623,100
Heat Exchanger, 1,500 Ft ² (Other Fabricated Metal Products)	29,667	Alcohol Cooler, 500 Ft ² (Plumbing and Heating Equipment)	14,415
Yeast Juice Cooler, 2,000 Ft ² (Other Fabricated Metal Products)	38,688	Alcohol Storage, 3 x 10 ⁶ Gal (2) (Other Structural Metal Products)	503,595
Air Compressor, 4,500 CFM (Pump, Compressor, and Blowers)	16,740	Fusel Oil Storage, 20,000 Gal. (Other Structural Metal Products)	61,938
Laboratory Equipment (Engineering and Scientific Equipment)	37,200	Stillage Evaporator, 5,800 Ft ² (Plumbing and Heating Equipment)	514,290
Yeast Vessels (Other Fabricated Metal Products)		Stillage Condenser, 3,300 Ft ² (Plumbing and Heating Equipment)	113,460
25 Gal (4)	12,741	Stillage Cooler, 900 Ft ² (Plumbing and Heating Equipment)	20,925
100 Gal (4)	12,741	Stillage Storage, 1.6 x 10 ⁶ Gal (Other Structural Metal Products)	167,772
400 Gal (4)	15,717	Spray Dryer, 10 Ft x 20 Ft (2) (Spec. Industrial Machinery)	167,400
3,000 Gal (4)	306,807	Stillage Surge Tank, 50,000 Gal (Other Fabricated Metal Products)	123,504
12,000 Gal (4)	634,818	Anhydrous Column (Other Fabricated Metal Products)	623,100
Pasteurizers, 2,142 Gal (4) (Plumbing and Heating Equipment)	65,007	Anhydrous Column Condenser 1,000 Ft ² (Plumbing and Heating Equipment)	22,320
Molasses Surge Tank, 50,000 Gal (Other Fabricated Metal Products)	123,504	Anhydrous Column Reboiler, 3,500 Ft ² (2) (Metal Plate (Boilers))	623,100
H ₂ SO ₄ Make-Up Tank, 50,000 Gal (2) (Other Fabricated Metal Products)	67,890	Anhydrous Vent Condenser, 1,000 Ft ² (Plumbing and Heating Equipment)	22,320
Mash Make-Up Tank, 20,000 Gal (Other Fabricated Metal Products)	69,378	Anhydrous Cooler, 500 Ft ² (Plumbing and Heating Equipment)	14,415
Fermenters, 100,000 Gal (155) (Other Fabricated Metal Products)	9,575,280	Benzene Make-Up Tank, 30,000 Gal (Other Fabricated Metal Products)	139,500
Coolers, 1,000 Ft ² (25) (Plumbing and Heating Equipment)	1,269,915	Benzene Decanter, 10,000 Gal (Other Fabricated Metal Products)	55,800
Fermenters, 50,000 Gal (3) (Other Fabricated Metal Products)	348,192	Materials	
Yeast Centrifuges (5) (Spec. Industrial Machinery)	327,360	Process Materials	8,184,000
Yeast Bins, 3,000 Ft ³ (7) (Other Fabricated Metal Products)	1,860	Buildings and Auxiliaries	6,295,170
Defoamer, 400 Gal (Special Industrial Machinery)	744	Site and Preparation	
Beer Heater, 5,000 Ft ² (3) (Plumbing and Heating Equipment)	216,690	Construction Labor, 400,000 Hr at \$11/Hr	4,400,000
Beer Still, 13 Ft Diam (Other Fabricated Metal Products)	274,350	Process Materials Labor	
Beer Still Condensers, 5,000 Ft ² (6) (Plumbing and Heating Equipment)	433,380	492,272 Hr at \$11/Hr	5,415,000
Vent Condenser, 1,500 Ft ² (Plumbing and Heating Equipment)	32,271	Process Equipment Labor	
Beer Still Reboilers, 5,000 Ft ² (4) (Metal Plate (Boilers))	1,548,450	184,636 Hr at \$11/Hr	2,031,000
Topping Column, 13 Ft Diam (Other Fabricated Metal Products)	185,721	Home Office Expense	10,492,000
Topping Column Condenser, 500 Ft ² (Plumbing and Heating Equipment)	14,229	Field Office Expense	6,769,000
Topping Column Reboiler, 500 Ft ² (Metal Plate (Boilers))	81,561	Transportation	
Alcohol Column, 15 Ft x 60 Trays (Other Fabricated Metal Boilers)	622,077	Total Capital Cost	67,690,700
Alcohol Column Condenser, 4,250 Ft ² (3) (Plumbing and Heating Equipment)	185,721		

Table 6.5. Capital Costs for Fermentation of Molasses per 10^{12} Btu Output

	1977 Dollars	Deflator	1972 Dollars
Total Capital Cost	67,690,700	1.28	52,883,360
Materials	34,938,891	1.28	27,296,000
Transportation	2,629,809	1.28	2,054,537
Construction Labor	11,846,000	1.28	9,254,688
Profit & Overhead	18,276,000	1.28	14,278,125
Annual System 10^{12} Btu Output		5.475	
Total Capital Cost/ 10^{12} Btu		9,659,062	
Number of Years to Construct Facility		3	
Expected Life of Facility (Years)		20+	
Man-Years to Construct Facility (2,000 Hr/Man Year)		538.5	
Man-Years/ 10^{12} Btu Annual Output		98.35	
Estimated Land for Facility (acres)		300	

Table 6.6. Estimated Annual Operating and Maintenance Costs for Ethanol facility

Cost Element	1976 Dollars
Ammonium Sulfate	121,000
Phosphoric Acid (feed grade)	361,000
Sulfuric Acid	304,000
Turkey Red Oil	631,000
Utilities	
Steam, 5.95 billion Pounds/Year at \$2 per Thousand Pounds	11,900,000
Power	156,000
Cooling Water	450,000
Labor	1,419,000
Supervision	213,000
Maintenance Labor	614,000
Maintenance Supervision	123,000
Maintenance Materials	1,106,000
Payroll Burden	711,000
Supplies	221,000
Indirect Costs	1,478,000
Fixed Property Taxes and Insurance	1,650,000
Total	21,458,000

Source: Lipinsky et al.¹⁴

Table 6.7. Input/Output Summary for Fermentation of Molasses

<p>SIZE: System is designed to produce 197,214 gal (648.5 tons) of anhydrous ethanol using 1,408 tons/day of fermentable sugar-processing residue (2,070 tons of molasses at 85° Brix with an 80% fermentable sugar content) during 330 stream days of production per year.</p>	<p>INPUT (per 10¹² Btu): <u>Fuel</u> Residue requirement: 125,098 tons 85° Brix molasses (3.2 tons of residue/ton ethanol) Steam (100 psig): 1,884,282 tons (48.2 tons of steam/ton ethanol)</p>	<p>COSTS (1972 dollars): Capital cost, \$9,510,192 Operating and maintenance, \$15,000,000 per year Sugar residue (molasses), \$58,144,000 per year Credits can be obtained for stillage, yeast, and fusel oil.</p>
<p>DESCRIPTION: Process involves fermentation of sugar-processing residues (molasses), primarily for production of anhydrous ethanol; the system is a large-scale operation, and other by-products include fusel oil, yeast, stillage, and carbon dioxide.</p>	<p>Electricity: 16,651,351 kWh (42.6 kWh/ton ethanol) Process chemicals: ammonium sulfate, 89.1 tons (0.00228 ton/ton ethanol); sulfuric acid, 1,485 tons (0.038 ton/ton ethanol); benzene, 22,282 tons for first 10¹² Btu (0.57 ton/ton ethanol), 16 tons for each additional 10¹² Btu (0.00041 ton/ton ethanol) Requires 0.1826 plant per 10¹² Btu</p>	<p>OUTPUTS (per 10¹² Btu): <u>Air pollutants</u> Ethanol, 391 tons (0.01 ton/ton ethanol) Benzene, 16 tons (0.00041 ton/ton ethanol) Carbon dioxide, 29,710 tons (0.76 ton/ton ethanol) <u>Water pollutants</u> BOD, 57.9 tons (2.96 lb BOD/ton ethanol)</p>
<p>COMPONENTS (main process operations): Yeast preparation, mash preparation, fermentation, yeast recovery, distillation, and storage.</p>	<p><u>Water</u> Cooling water, 499 x 10⁶ gallons (12,770 gallons/ton ethanol) Process water, 118.8 x 10⁶ gallons (3,040 gallons/ton ethanol)</p>	<p><u>Solid by-products</u> Stillage (10% moisture), 38,030 tons (0.973 ton/ton ethanol) Yeast (50% solids), 8,952 tons (0.223 ton/ton ethanol)</p>
<p>MAJOR ENVIRONMENTAL PROBLEMS: Water pollution, air pollution.</p>	<p><u>Land</u> 300 acres for facility (i.e., 54.8 acres/10¹² Btu)</p>	<p><u>Energy</u> Ethanol, 10¹² Btu (39,093 tons) Substitute for refined petroleum products (heat of combustion is 12,790 Btu/lb) Fusel oil, 2.9 x 10⁹ tons (0.0036 ton/ton ethanol) or 142.6 tons/10¹² Btu (assume heating value of 10,000 Btu/lb)</p>

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