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A TECHNOLOGY ASSESSMENT OF SOLAR ENERGY SYSTEMS: DIRECT COMBUSTION OF WOOD AND OTHER BIOMASS IN INDUSTRIAL BOILERS

by

H.I. Abelson, L.J. Habegger, and B.C. Liu

Energy and Environmental Systems Division

December 1981

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Safety, and Emergency Preparedness
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FOREWORD

The U.S. Department of Energy (DOE), Office of Environmental Programs, has conducted a project entitled Technology Assessment of Solar Energy (TASE) to evaluate the range of potential environmental, health, and socioeconomic consequences of rapid, large-scale commercialization of solar technologies. The goal of this project was to identify and analyze both the positive and negative effects of solar technology deployment.

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

This report is an element of the TASE Solar Technology Characterization Series. We would like to thank the TASE Project Director, Dr. Gregory J. D'Alessio of the DOE Technology Assessments Division, for his support in preparing this document.

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ABSTRACT

Direct combustion is one of the most economical ways to use biomass energy, and industrial applications consumed over 80% of the biomass energy used in the United States in 1979. This report evaluates the cost, resource requirements, and environmental characteristics of a model combustion system sized to handle an annual feed of 12,500 dry tons of forest residue. The cost of the wood combustion system is comparable to that of coal-fired boilers in industry. Atmospheric emissions of the wood system are lower in sulfur dioxide than those of coal systems, but emissions of particulate matter are potentially higher. However, the combined use of multicyclones and wet scrubbers can reduce these emissions to levels produced by coal systems. Cost and environmental characteristics of boilers that burn sugarcane bagasse are compared to those of wood-fired boilers because the two systems are similar.

1 INTRODUCTION

The U.S. Department of Energy (DOE), Office of Assistant Secretary for Environmental Protection, Safety, and Emergency Preparedness (formerly Office of Assistant Secretary for Environment) has conducted a major "Technology Assessment of Solar Energy" (TASE) program that evaluates the environmental and socioeconomic implications of developing solar energy technology in the United States. This report in the TASE series characterizes one industrial use of solar energy: the direct combustion of wood and other biomass resources in industrial boilers. The following introduction provides an overview of the literature on industrial applications of solar energy in general, on the potential use of wood and other biomass resources specifically, and on the availability of these resources. The second section describes the engineering, economic, and environmental characteristics of a midsize industrial wood boiler. Section 3 compares similar information for a comparable direct-combustion system that uses sugarcane bagasse as fuel. Finally Sec. 4 provides a summary of the potential applications and impacts of expanded use of direct combustion of biomass to provide industrial process energy.

1.1 POTENTIAL APPLICATIONS

Industrial use of energy has accounted for 40-43% of the total national energy use in the United States during the past three decades. For example, the total industrial use of energy was 30.1 quads* in 1980, or 42.8% of all

*Quadrillion (10^{15}) Btu of fossil fuel equivalents, i.e., primary fossil fuel displaced.

energy consumed in that year.[1] The Census of Manufactures, published by the Bureau of the Census, provides information on the volume and type of fuels purchased by industry for heat and power. The census data represent about 65,000 manufacturers, or more than two-thirds of the total manufacturing employment in this country. The data show that three of the 21 two-digit Standard Industrial Classification (SIC) industry groups are so energy intensive that together they use more than 75% of all process-heat energy purchased by industry.

In order of energy use, the three energy-intensive industrial groups are primary metals, petroleum products, and paper and allied products. Table 1 shows the process heat consumed by industrial groups as revealed by the Census of Manufactures. In 1971, process-heat energy consumed directly by the 21 industrial groups amounted to 9.8 quads or 10.4×10^{12} kJ; the three industries mentioned above accounted for some 7.5 quads; and the paper, lumber and wood, and furniture groups (SIC 24-26) accounted for some 1.2 quads.[2]

To assess the potential for solar energy systems to provide industrial process heat and direct heat to manufacturers whose heat requirements are functionally related to a temperature range, a survey was conducted in 1977 by the Division of Solar Energy of the Energy Research and Development Administration. The survey concluded that solar process heat has good potential applications throughout industry. Total solar process heat, according to the survey, may range from 0.35 quads to 3.7 quads in 1985 and from 4.2 quads to 6.5 quads in 2000 for the industrial applications surveyed. Table 2 presents the survey results obtained for 59.1% of the total use of industrial process heat. The total potential for solar process heat in industrial uses was extrapolated from the survey to be 13.3 quads in 2000.

As Table 2 reveals, significant potential for process heat was found in the lumber and wood products industry and the paper and allied products industry, but these industries tend to use self-generated waste products for fuel. The potential for use of solar process heat by these industries was estimated at 0.14 quad in 1985 and 2.0 quads in 2000.

A further study of biomass energy systems recently completed at Argonne National Laboratory[3] projected that the use of biomass energy in 2000 in this country will vary between 2.8 quads and 11.3 quads, depending on whether the nation promotes the use of biomass energy. With the current DOE effort, the report shows that 7.9 quads of biomass energy will be consumed in 2000. Direct combustion of wood by commercial, industrial, and utility sectors to produce steam and electricity would grow from 1.8 quads in 1985 to 4.8 quads in 2000, even without enhanced promotion of biomass. Industry consumed approximately 87% of the 1.5 quads of biomass energy used in the United States in 1979. If industrial consumption remains at this percentage, about 4.1 quads of the projected 4.8 quads of wood-derived energy will be generated through direct combustion in 2000. The data in Table 2 indicate that the lumber and wood product industries would contribute a major share of this level.

A mission analysis for the federal fuels-from-biomass program[4] indicated that direct combustion of wood or low-moisture plants to produce steam is technically and economically feasible; the process received the highest ranking among the 15 missions of biomass programs analyzed. (A mission was defined as a specific conversion route from biomass feedstock to a useful fuel or chemical product for end-use markets.)

Table 1 Summary of Process-Heat Data Base by Industry in 1971

SIC Group	Industry	Process Heat: 10^{12} Btu	Process Heat: % of Total	Process Heat: 10^{12} kJ
10-14	Mining	129.14	1.3	136.22
20	Food and kindred products	318.93	3.3	336.41
21	Tobacco products	1.36	0.01	1.43
22	Textile mills	116.40	1.2	122.78
23	Apparel	-	-	-
24	Lumber and wood products	171.80	1.8	181.21
25	Furniture	11.80	0.1	12.45
26	Paper and allied products	1,092.60	11.1	1,152.47
27	Printing and publishing	-	-	-
28	Chemicals	534.17	5.4	563.44
29	Petroleum products	2,636.67	26.9	2,781.16
30	Rubber	9.70	0.1	10.23
31	Leather	2.52	0.02	2.66
32	Stone, clay, and glass	990.94	10.0	1,045.24
33	Primary metals	3,772.42	38.4	3,979.15
34	Fabricated metal products	0.03	-	0.03
35	Machinery	-	-	-
36	Electrical equipment	1.57	0.01	1.66
37	Transportation	23.29	0.2	24.57
38	Instruments	-	-	-
39	Miscellaneous	-	-	-
Total		9,813.34	100.0	10,351.11

Source: Ref 2.

Among the sources of biomass energy, wood is the most important fuel because it is a renewable resource widely available in large quantity. Wood-burning technology is fully proven, commercially available, and can be very economical relative to nonrenewable fuels such as oil and gas. Industry has sought to reduce operating costs by recycling waste residues as fuels and for the production of useful by-products. The industries that have made or could make the most extensive and systematic use of wood fuel are the pulp/paper and lumber/wood products industries.

Table 2 Summary of Solar Process-Heat Potential by Industry

SIC Group	Industry	Solar Process-Heat Potential (10^{12} Btu/yr) 1976	1985	2000
10-14	Mining	0.05	1.49	42.84
20	Food and kindred products	0.51	42.87	291.86
21	Tobacco products	-	0.03	3.48
22	Textile mills	-	2.05	162.22
23	Apparel	-	-	-
24	Lumber and wood products	0.10	22.35	199.96
25	Furniture	-	1.30	25.02
26	Paper and allied products	0.27	118.92	1,847.94
27	Printing and publishing	-	-	-
28	Chemicals	0.22	83.40	1,003.90
29	Petroleum products	0.06	58.86	403.00
30	Rubber	-	0.46	9.42
31	Leather	-	0.10	1.90
32	Stone, clay, and glass	0.06	8.86	94.24
33	Primary metals	-	13.00	209.36
34	Fabricated metal products	-	0.004	0.06
35	Machinery	-	-	-
36	Electrical equipment	-	0.01	0.13
37	Transportation equipment	-	0.01	0.14
38	Instruments	-	-	-
39	Miscellaneous	-	-	-
Total		1.27	349.69	4,295.47

Source: Ref. 2.

Presently, more than 150 New England industries use wood fuel. Collectively, these industries employ more than 32,000 people, and their wood-fired boilers have a total output of about 4×10^6 lb of steam per hour. Wood fuel could replace 285×10^6 gal of oil each year.[5] According to the New England Regional Commission Report,[5] wood wastes are produced at more than 2400 industries throughout New England, and 90% of the industries using wood fuel consider their systems effective and reliable. Nationally, more than 2000 automated wood-fired boilers are now in operation.[6]

In 1979, the Environmental Protection Agency conducted a survey of the population and characteristics of industrial/commercial boilers in the United States.[7] The survey showed that there were 1.8 x 10^6 nonutility boilers in this country, with a total capacity of 4.5 quads/hr. Industrial boilers, which are used for generating process steam and electricity and for space heating, are relatively larger than commercial boilers. The survey recorded only 506,930 industrial boilers, but their capacity totaled 3.1 quads/hr.[7]

1.2 RESOURCE DISTRIBUTION

The energy equivalent of all the wood in the nation's standing forests is approximately 324 quads. About half the forest resource is located in the Pacific and Mountain states, 47% in the eastern states, and about 3% in the central states. Commercial forests constitute about 85% of the total standing forest. Although this resource can be completely renewed over 80 to 100 years with proper forest management, it should be treated as a "reserve" in the near term, similar to proven oil and coal reserves. Only the wood volume equivalent to the net annual growth should be considered available for commercial use.

Net annual growth of wood on commercial forest land has an energy equivalent of about 8.2 quads. Approximately one-fourth of the annual growth and salvage wood is converted into primary forest products, and about one-sixth is used as fuel. Unused wood, which includes mill residues, logging residues, and surplus growth, has an energy equivalent of about 5 quads per year.

Wood resources that can be considered for near-term fuel supplies include:

- Unused mill residues at primary and secondary wood-processing plants. This resource, along with spent black liquor from pulping operations, will be used increasingly for process energy in the forest products industries and will not be widely available outside those industries.
- Logging residues -- tops, branches, broken sections -- not removed from logging sites. The availability of this resource is expected to follow the demand for forest products.
- Surplus or underused growth. This resource is expected to decrease as the demand for forest products increases, if the present levels of forest management continue.
- Annual mortality. This resource is expected to follow the trends of forest production and, therefore, will increase slightly if present trends of forest management continue.
- Biomass from timberstand improvement. This resource is expected to follow the trends of forest production. It includes biomass generated through cultural operations

such as precommercial or commercial thinnings (commercial thinnings remove merchantable trees) that release desirable trees in overcrowded stands to increase their value at maturity. At present these operations are not performed on a large scale because they require an investment from the landowner. Given a biomass fuel/feedstock market for these thinnings, however, more biomass of this type could become available. The biomass potentially available through these cultural operations can be assessed only on a site-by-site basis. This biomass has been referred to as "managed harvest," "environmental thinning," or "green garbage." The estimates of near-term resources do not include wood from timberstand improvement.

- Noncommercial timber. A large inventory of noncommercial timber, consisting of small or defective living trees and salvable dead trees, also is potentially available for fuel use. The noncommercial timber reservoir is estimated at about 1.7 billion tons of wood or about 29 quads. About 20% of the resource consists of salvable dead trees located in the western United States. Another 66% is cull hardwood trees, which are common in the East. The remainder consists of cull softwoods, which are evenly distributed between the East and West. The following estimates of the near-term biomass resource assume that this nonreplenishable reservoir would be used each year in proportion to the ratio of annual timber removals to total growing stock.

- Surplus of noncommercial forest land. Much of this renewable resource consists of forest lands that are not available for commercial use because of aesthetic, environmental, recreational, or other reasons. The following estimates of near-term wood resource assume that none of this resource could be harvested for fuel.

Table 3 shows the near-term wood resource potentially available for fuel and feedstock use. The energy equivalent of the available wood is about 5.8 quads per year.

Table 3 Potential Wood Fuel and Feedstock Resources Available in 1977

Census Region	Potential Resources (10^6 dry tons/yr, except as noted) Mill Residues	Logging Residues	Surplus Growth	Annual Mortality[a]	Noncommercial Timber[a]	Total	Total Quads/yr[b]	% of Total Resources
Northeast	0.51	4.88	15.71	0.12	1.73	22.95	0.39	6.8
Middle Atlantic	0.51	3.65	17.53	0.08	1.74	23.51	0.40	6.9
South Atlantic	2.18	23.88	53.53	0.35	10.20	90.14	1.53	26.6
East North Central	0.85	5.80	16.35	0.23	2.01	25.24	1.43	7.4
East South Central	1.86	12.71	33.00	0.19	5.12	52.88	0.90	15.6
West North Central	0.58	2.77	7.65	0.09	2.18	13.27	0.23	3.9
West South Central	1.79	12.18	21.71	0.22	6.86	42.76	0.73	12.6
Mountain	2.55	6.06	18.53	0.10	2.37	29.61	0.50	8.7
Pacific	2.62	30.24	-	0.45	5.79	39.10	0.66	11.5
Total								
10^6 dry tons/yr	13.45	102.17	184.01	1.83	38.00	339.46	-[c]	-
Quads	0.23	1.74	3.13	0.03	0.65	-	5.7	-

[a]Annual availability estimated by multiplying total resource in category by ratio of annual timber removal to total growing stock.

[b]Based on average wood heating value of 17×10^6 Btu/dry ton.

[c]Potential resource could be increased by several quads if timberstand improvement were practiced on a large scale.

Source: Ref. 9.

2 DIRECT COMBUSTION OF WOOD AND FOREST RESIDUES IN INDUSTRY

2.1 MODEL SYSTEM DESCRIPTION

This section describes the combustion of wood and forest residues to supply heat energy for small and midsize industrial processes. The engineering, economic, and environmental characteristics of this technology are presented for a model system that represents the wide variety of actual systems using the technology. The data provided on process residuals, capital and operating costs, and system thermal performance were obtained from the literature, from manufacturers and researchers, and by computation (see Bibliography). These quantities are estimates or the best available data. Actual values vary from system to system, depending on design and configuration, operating conditions, and fuel batch characteristics.

The model system for direct combustion of forest residue, depicted schematically in Fig. 1, comprises four general subsystems: fuel handling and processing, energy conversion, emissions control, and waste product handling. The fuel handling and processing subsystem physically converts raw forest residue into fuel that meets the feed requirements of the energy conversion subsystem. The specific components of the fuel handling and processing subsystem depend on the composition and condition of the forest residue (e.g., moisture and impurity content, size distribution), design and size of the combustion system, and other factors. The energy conversion subsystem uses direct combustion to chemically transform the energy contained in the processed fuel into heat. This heat can then be used to produce steam, hot water, hot air, or power, depending on the application. This study addresses only the production of steam for industrial process heat. The design of the energy conversion subsystem (in this case, a boiler) depends largely on fuel composition, feed rate (i.e., unit size), and desired steam conditions. The emissions control subsystem reduces the atmospheric emissions of various pollutants to levels imposed by regulations governing the site. In wood-fired systems, emissions of particulate matter are of primary concern. The specific control equipment selected depends on fuel characteristics, boiler design and operating conditions, and of course the site where the plant is located. The waste-product-handling subsystem removes solid products of combustion (bottom ash and collected fly ash) from the boiler and control devices as well as unusable residue from fuel processing operations. Liquid effluents from, for example, a wet scrubber would be handled by this subsystem as well.

<u>Energy Conversion Subsystem</u>. A variety of boiler firing systems are employed for wood residue combustion.* For large units (greater than 150,000 lb of steam/hr), the spreader-stoker with a traveling chain grate is widely accepted, although sloping-grate stokers and suspension firing units are also gaining in popularity. Mid- and low-capacity units employ a greater variety of stoker grates, including dumping grates, vibrating grates, stationary water-cooled pinhole grates, and air-cooled grates. Dutch-oven type furnaces, the oldest form of wood-burning equipment, are still used in some low-capacity installations but have become virtually obsolete. Within a given

*Only water-tube units are addressed here; fire-tube units are limited in steam pressure and size and are not commonly used in wood combustion applications.

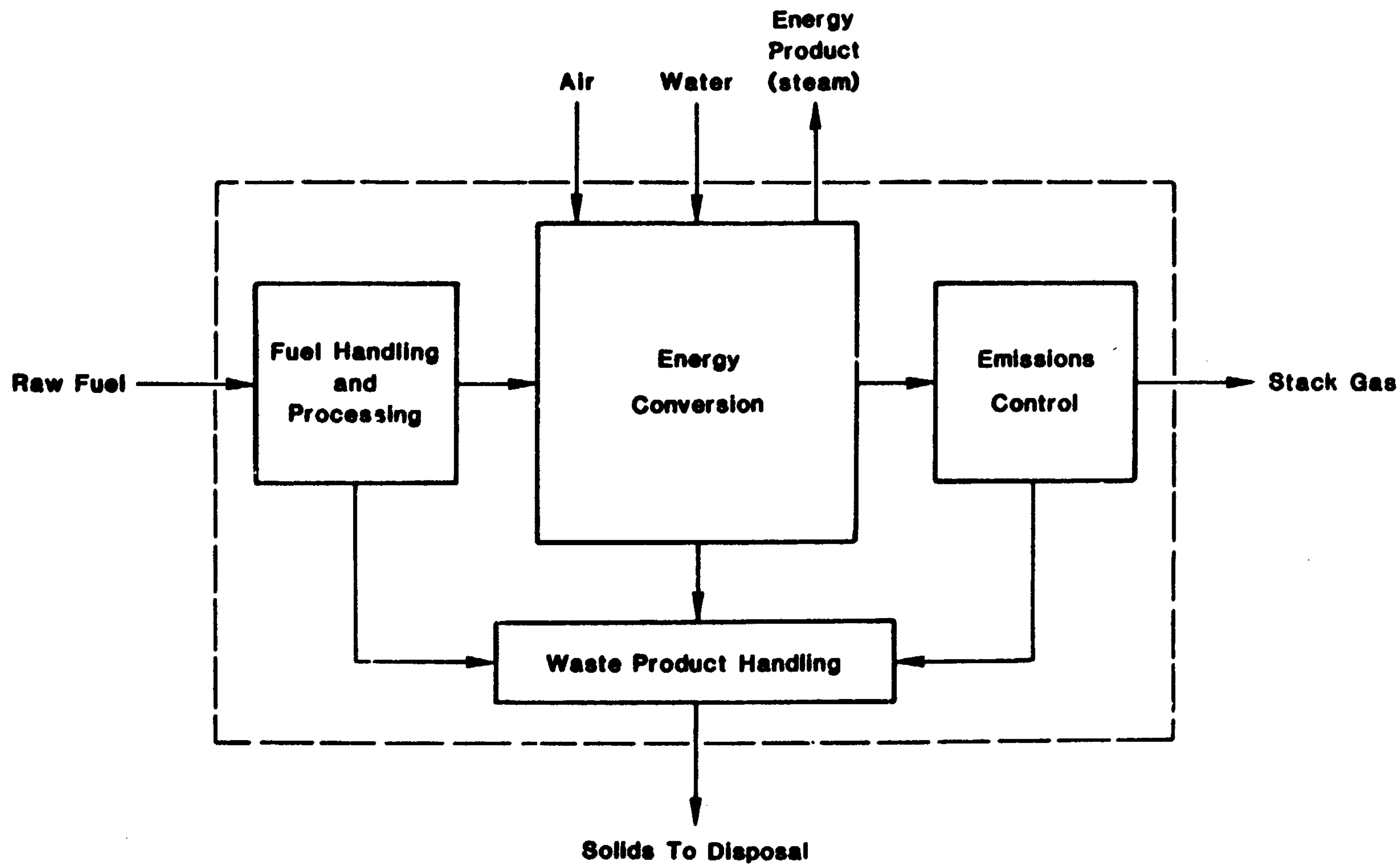

Fig. 1 Schematic of Model System

size range, the selection of a firing system is influenced by fuel characteristics such as moisture and ash content, as well as by any auxiliary fuel requirements.

The model combustion system is sized to handle an annual feed of 12,500 dry tons of forest residue. The model assumes an 8-hr/day, 5-day/week operation; a heating value of 8500 Btu/dry lb; a boiler efficiency* of 66%; and saturated steam at 150 psia with a feed water temperature of 70°F. The resulting steam production rate is 60,000 lb/hr. To account for feed rate variability in boiler sizing, a 25% capacity increase is assumed, resulting in a 75,000 lb/hr unit.

The boiler selected for the model combustion system is a field-erected, water-tube unit that employs a water-cooled pinhole grate and produces 75,000 lb/hr of 150-psi (358°F) saturated steam. This type of unit is in wide use today in the low to medium capacity range and can handle wood with a moisture content of up to 55% without auxiliary firing. The specified steam condition represents the output of most boilers used in process applications. Water-cooled pinhole grates offer low cost and low maintenance compared to traveling grates. The water-cooled grates are constructed by bending the back-wall water tubes so that they form a floor near the bottom of the furnace. Iron blocks, which are cast to fit over and between the tubes, form a solid surface that generally slopes toward the boiler front to facilitate fuel and ash flow. Underfire air is admitted through a series of holes in the blocks. Special blocks fitted with steam nozzles blow the ash off the grate to a hopper at the front of the boiler. Processed fuel is delivered by gravity feed chutes to spreaders (distributors) located in the furnace wall. Spreading is accomplished most often pneumatically or else by mechanically rotating paddle-like devices. (The model system uses pneumatic distribution.) Feed ports are located high enough in the furnace wall to assure even spreading but as low as possible to prohibit excessive suspension burning with its attendant high loadings of particulate matter. Overfire air is introduced at multiple locations above the grate and both underfire and overfire air are heated to about 400°F in an air preheater that recovers heat from the stack gases. The model includes a system for reinjecting collected combustible particulates (i.e., char) into the boiler. This practice increases combustion efficiency at the expense of higher particulate loading. The model system also includes an auxiliary gas or oil burner for start-up and other operating situations.

<u>Fuel Handling and Processing Subsystem</u>. A typical subsystem for fuel handling and processing is shown schematically in Fig. 2. A belt or chain conveyor transports rough forest residue from a storage area to a screen separator. En route, the residue passes a metal detector, which is tied in with a diverting gate to remove any ferrous and nonferrous metals that could damage downstream equipment. The screen separator segregates oversize pieces of residue that require further size reduction and removes sand from the remaining residue. Allowing the properly sized residue to bypass the downstream size-reduction equipment greatly reduces power requirements. Separators with fixed-screen design or the more efficient disk-screen units (rotary classifiers) are commonly employed.

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*Based on 50% fuel moisture, 50% excess air level, and a 400°F stack temperature.

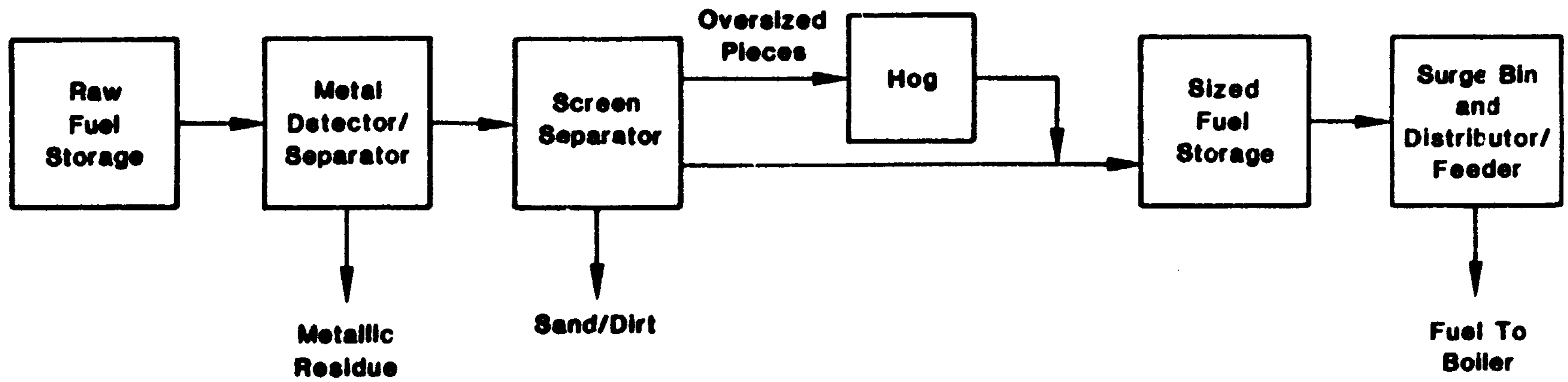

Fig. 2 Fuel Handling and Processing Subsystem

Size reduction is normally done in a unit called a hog. Depending on the nature of the residue, either knife-type hogs (chippers) or hammer-mill hogs are used. Chippers can handle large logs and require a relatively low horsepower per ton of product. However, they are sensitive to foreign materials (sand, rock, metal, etc.) in the residue. Hammer-mill hogs are widely used on bark residue, which normally contains high levels of contaminants. The degree of size reduction required depends on the type of firing system and grate; generally, fuel should be hogged and screened until it is small enough to eliminate clogging of the fuel feed and distribution systems. A size range of at least 2 to 4 in. is desirable, if only from a conveying standpoint. Further hogging (for grate firing systems) will consume power unnecessarily, may adversely affect complete combustion, and may produce higher loadings of particulate matter in the stack gas.

After hogging, the reduced pieces merge with a hogger bypass stream. This stream is transported by a second conveyor to the storage area for sized fuel. From here a conveyor moves fuel to the boiler feed and distribution system, which in the model system consists of a surge bin atop a variable-speed, twin-screw feeder linked to the combustion control system. The metered fuel drops down a feed chute where an air jet supplied through a rotary damper spreads the fuel onto the grate below. The model system assumes a fuel moisture content of 50%. However, in systems where levels exceed 55%, the sized residue often passes through a mechanical press that reduces the moisture below this value.

<u>Emissions Control Subsystem</u>. This subsystem is responsible for reducing emissions of particulate matter to the allowable levels. Pollutants such as nitrogen oxides (NO_x) and carbon monoxide (CO) are normally controlled through proper boiler design and operation and require no add-on control technology. Since wood residue has a very low sulfur content, sulfur dioxide (SO_2) emissions need not be controlled unless the boiler is cofired with coal or oil. Past practice employed multicyclone mechanical collectors exclusively to control particles. The more stringent regulations imposed in recent years, however, can no longer be met using these low-efficiency units alone. Boilers now employ higher-efficiency alternatives such as wet scrubbers, dry scrubbers, and, to a lesser extent, electrostatic precipitators and baghouses. Frequently these devices are preceded by a multicyclone collector that removes most of the particles from the stack gas, especially the larger ones. This procedure reduces dust loading as well as subsequent maintenance on the secondary cleanup device. Cycling efficiencies vary from 50% to 90%, depending on distribution of particle size, draft loss (i.e., pressure drop), temperature, and dust loading.

In recent years, the wet scrubber (in combination with a multicyclone) has been the most widely accepted control method for wood-fired boilers of all sizes. Most installations consist of venturi scrubbers followed by cyclonic gas-liquid separators. Wet scrubbers offer the advantage of high efficiency at the expense of relatively high power requirements (due to draft loss) and a liquid effluent that requires disposal or treatment. Efficiencies of these devices range from 90% to >99%, depending on dust loading, particle size, rate of water flow, and draft loss.

Baghouses have not been used extensively on wood-fired boilers primarily because of the potential fire and explosion hazard from unburned and partially burned wood and carbon particles that deposit on bag surfaces. Collection efficiencies for these devices, however, can exceed 99%, depending on dust loading and particle size, gas-to-cloth ratio, cleaning frequency, and temperature. Current bag materials limit gas temperatures to about 500°F. The gas can be cooled and boiler efficiency increased by adding an air preheater or an economizer to the boiler. (An air preheater is included in the model system.)

Electrostatic precipitators are used extensively where combination fuels (i.e., wood and coal) are fired, but are rarely employed for units firing only hogged wood. This difference arises because the fly ash has a low resistivity that significantly degrades collection efficiency. Relatively high capital cost and large space requirements are other factors that inhibit the widespread use of precipitators except in high-steam-capacity applications.

The dry scrubber or gravel bed filter, a relatively new high-efficiency control device, has been generating interest recently for its application to wood-fired boilers. Several installations are in operation and others are under construction or planned. Compared with wet scrubbers, these devices so far have higher capital and operating costs and have not shown better performance. The dry scrubber, however, creates no liquid disposal problem.

On the basis of the above survey of particulate control devices and of the fuel type and boiler capacity assumed for the model system, the model emissions control subsystem is assumed to consist of a wet scrubber preceded by a multicyclone collector.

Waste-Product Handling Subsystem. This subsystem conveys the waste streams from their sources to storage locations, where they await final disposal. In the model system, the waste streams of concern are bottom ash, particulates collected by the multicyclone, residue from fuel processing, and liquid effluent from the wet scrubber. Bottom ash is blown off the grate into a hopper at the front of the boiler by steam jets located in the grate blocks. The grate also slopes slightly toward the front of the boiler to facilitate this action. Since the model system employs a fly-ash reinjection system, only part of the dust collected in the multicyclone is discarded. The remainder is recycled to the boiler. To reduce the dust loading on the downstream scrubber as well as erosive wear on the boiler tubes, the dust collected by the cyclone passes through a classifying device, normally a screen separator. Here, the large particles (mostly of combustible material) are segregated and recycled while the smaller particles, usually sand and dirt, are conveyed to a hopper. The liquid effluent from the scrubber flows to a sedimentation tank where the solids settle out and the clarified liquid recirculates to the scrubber. Solids removed from the sedimentation tank, as well as solids from the ash hopper and cyclone hopper, are hauled to a landfill.

2.2 ENERGY AND MATERIAL FLOWS

The flow of materials through the model combustion system is illustrated in Fig. 3 for a steam production rate of 60,000 lb/hr. This rate

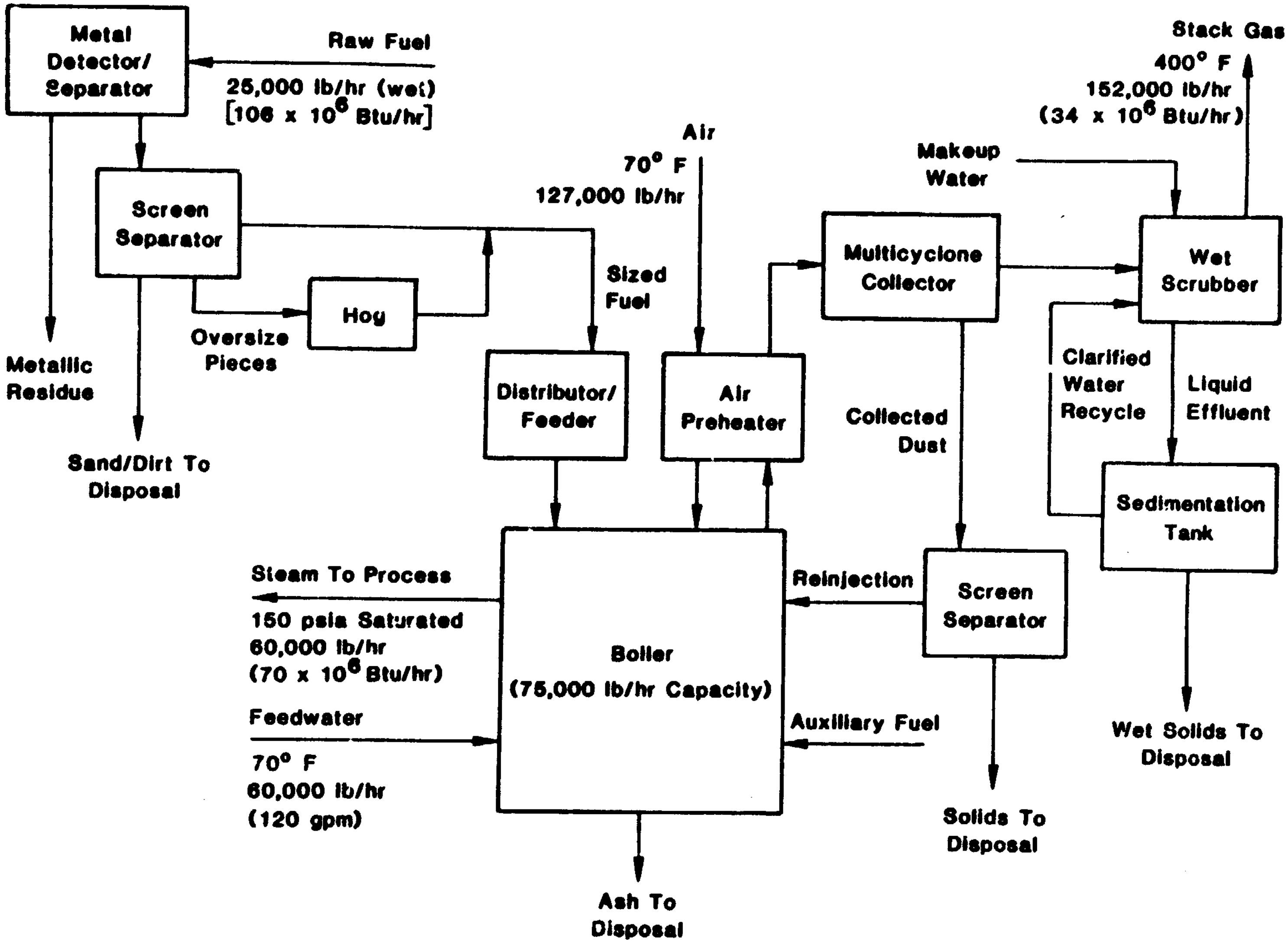

Fig. 3 Material and Energy Flows in Model System

corresponds to an annual feed of 12,500 dry tons of forest residue (assuming a 5-day/week, 8-hr/day operation) and a boiler efficiency of 66%. The efficiency was computed on the basis of the following assumptions:

- 50% fuel moisture,
- 8500 Btu/lb (dry) heating value,
- 50% excess air level,
- 400°F stack temperature,
- Radiative loss of 2% of fuel input energy, and
- Dry ultimate analysis: hydrogen, 5.6%; carbon, 56.3%; negligible sulfur; oxygen, 37.7%; and ash, 0.4%.

These values reflect the operating conditions and fuel characteristics that are typical of wood combustion with the boiler type used in the model system.

For the system to operate, electricity must power various components such as boiler feed pumps, scrubber system pumps, fans, air compressors for pneumatic feed or transport, hogging machines, and motor drives for conveyors and screen separators. This parasitic power must be accounted for when considering system energy flows and economics.

2.3 ENVIRONMENTAL DATA

2.3.1 Atmospheric Emissions

The combustion of forest residue produces five pollutants of potential concern: particulate matter, CO, hydrocarbons, SO_2, and NO_x. Of these pollutants, emissions of particulate matter are the principal concern. Particulate matter from wood-fired systems generally comprises unburned carbon (char), inorganic materials that are intrinsic to the fuel (ash), inorganic materials carried into the combustion system (sand, dirt, salt, clay, etc.), and organics that fail to burn in the combustion zone and recondense in the gas stream. Compared to particles produced by combustion of other fuels, particles from wood-fired systems are larger. The magnitude of particulate loading is a function of many factors that influence fuel characteristics both before and after combustion. These factors include, among others:

- Tree species and logging region,
- Boiler and grate design,
- Fuel size after hogging,
- Type of screen separation,
- Type of feeding system,

- Type of fly ash separation/reinjection system,
- Degree of excess air (underfire and overfire),
- Depth of fuel bed on grate,
- Temperature of combustion air, and
- Moisture content of wood.

The wide range in the published data for emissions of particulate matter from wood combustion systems can be attributed to variations in these factors. As discussed earlier, available control technology can remove up to 99.9% of particulate matter in the stack gas stream.

In addition to particulate matter in stack gas, fugitive dust emissions can originate from fuel handling and processing operations as well as from solid residue handling. These emissions can be controlled largely through proper equipment design or enclosure. Hoppers, conveyors, storage containers, and other components along the solids flow path can be made essentially dust tight.

Emissions of SO_2 from wood-fired systems are minimal because of wood's typically low sulfur content, which varies from trace amounts up to 0.1% by dry weight. Control of SO_2 emissions therefore has been required only on a very limited basis. In these cases, wet scrubbers using a soluble alkali have been employed.

Carbon monoxide and gaseous hydrocarbon emissions result from incomplete combustion. In a spreader-stoker boiler (one type of which is being considered in the model system) combustion occurs in two stages. Underfire air passes up through the grate and the fuel bed atop it, oxidizing the solid carbon contained in the fuel. The oxidized carbon appears either as CO or carbon dioxide (CO_2); the proportions depend primarily on the quantity of underfire air supplied and the combustion temperature. At the same time, the high temperatures drive off volatile organic matter (hydrocarbons) contained in the fuel, whose hydrocarbon content typically ranges from 70%-80% of dry weight. These volatile organics, as well as the combustible CO, rise from the fuel and are burned in a region above the bed where secondary or overfire air is supplied. The quantities of CO and volatile organics that escape the secondary combustion zone and appear as emissions depend on the degree of mixing and residence time in this zone, as well as on the amount of overfire air supplied. Theoretically, complete combustion occurs if any excess air is supplied to the system. However, in practice, boiler design and operating conditions also determine whether or not combustion will be complete. Emission levels of CO and hydrocarbons are therefore expected to vary widely depending on combustion conditions. Emission levels for both pollutants have been reduced by improving these conditions rather than by adding control technology.

During combustion, NO_x is formed by two mechanisms: oxidation of organic nitrogen contained in the fuel, and high-temperature oxidation of atmospheric nitrogen present in combustion air. The combustion temperature in wood-fired systems is normally below that required for the latter reaction to occur. Therefore the formation of NO_x is, for the most part, attributed to oxidation of fuel-based nitrogen.

For emissions other than particulate matter, the data for emissions from wood-fired systems are sparse. Emission factors for wood combustion in boilers have been tabulated by EPA.[10,11] These factors form the basis for the model system pollutant loadings presented in Table 4. The EPA reference[10] does not indicate whether emission factors are given on a dry weight or wet weight basis; Table 4 assumes the former.

2.3.2 Water Requirements

Figure 3 shows two water input streams to the model system: boiler feed water and scrubber makeup water. Depending on the application, the product steam may condense as it is used and recirculate to the boiler. In this case, only makeup water is required to replenish feed water losses, which result primarily from boiler blowdown. These losses amount to only a small percentage (e.g., less than 1%) of the feed-water input rate. Otherwise, if the process operates on a "once-through" basis (i.e., no steam recirculation), water requirements equal the steam production rate of 60,000 lb/hr (or 120 gal/min) plus blowdown losses.

Table 4 Emissions from Model System

Pollutant	lb/dry ton	ton/yr[a]	ton/10^{12} Btu[b]
Uncontrolled particulates[c]	45	280	2000
Well-controlled particulates[d]	0.045	0.28	2
Partially controlled particulates[e]	4.5-22	28-140	200-1000
SO_2[f]	0-4	0-25	0-180
CO[g]	2-60	13-375	93-2679
Hydrocarbons[g]	2-70	13-440	93-3143
NO_x[a]	1-5.5	6-34	43-243

[a]Based on an annual fuel feed rate of 12,500 dry tons.

[b]Btu of output energy (i.e., in steam).

[c]For boilers with fly-ash reinjection.

[d]Assumes 99.9% collection efficiency for combination multicyclone and wet scrubber.

[e]Assumes 50-90% collection efficiency for multicyclone alone.

[f]Lower value corresponds to trace amounts of sulfur in fuel (as in model system) and higher value assumes 0.1% sulfur.

[g]Lower values apply to well-designed and well-operated boilers.

Source: Based on Ref. 10.

Liquid normally enters a venturi scrubber at a rate of 7-10 gal/ 10^3 ft^3 of stack gas entering the device. To minimize water requirements, the scrubber operates in a closed loop configuration; scrubber effluent recirculates after being clarified in a sedimentation tank. Losses from this operation require a relatively small quantity of makeup water (e.g., less than 1% of the scrubber water flow). These losses result from the small amounts of water that are carried out of the tank when wet solids are removed.

2.3.3 Solid Wastes

Five sources of solid waste are associated with the model system, as shown in Fig. 3. These include bottom ash removed from the grate, dust collected in the multicyclone but not reinjected into the boiler, wet solids removed from the scrubber sedimentation tank, sand and dirt removed in the screen separator during fuel processing, and metallic residue. The quantity of sand, dirt, rock, and metallic material varies with each fuel batch and depends on the source of forest residue and on handling procedures after harvesting. Therefore this quantity cannot be estimated. The amount of ash (i.e., noncombustible material) inherently contained in the fuel is determined in an ultimate analysis of the fuel. For the model system, the assumed ultimate analysis (Sec. 2.2) shows an ash content of 0.4%. On this basis, 50 tons of solid residue would be produced per year for the specified annual fuel feed rate of 12,500 dry tons. Typically, the ash content of forest fuel ranges from 0.4% to about 5% of dry weight. (At the upper limit, 625 tons of solid residue would result from the same annual feed rate.) Figure 3 shows the solid residue divided between three streams: bottom ash, multicyclone discard, and sedimentation tank residue. Allocations between these streams depend on specific system design and operating conditions. Although technical data are somewhat limited on fly ash and bottom ash from wood combustion, the residue is considered relatively inert, consisting primarily of silica and alumina with trace amounts of heavy metals. Normal disposal procedure is to either transport the residue to a sanitary landfill or slurry it to a lagoon. Information on the uses of wood combustion residue as a by-product (e.g., as a soil conditioner) is limited.

2.4 ECONOMIC DATA

2.4.1 Capital Costs

The capital cost of a complete system that produces process steam by combustion of forest residues can vary widely. Considering the subsystems previously shown in Fig. 1, the cost of the boiler itself, on a dollars per pound of steam per hour basis, depends on boiler type, capacity, steam pressure and temperature, grate type, whether the boiler is field-erected or packaged, and numerous other design-specific features. Specific components of the wood handling and processing subsystem, and therefore its cost, depend largely on the physical characteristics of the residue and the degree of processing required. For example, residue may be purchased preprocessed in the form of chips or may arrive at the boiler site in raw form. Cost of the emission control subsystem depends on the control devices, which in turn depend on the inlet particulate loading and the acceptable level of emissions for the site.

Capital costs for wood combustion facilities range from \$60 to \$100 per pound per hour of steam produced. For the model system capacity of 75,000 lb/hr, this translates into a total cost of from \$4.5 to \$7.5 million. A boiler manufacturer indicated that the cost of a recent boiler installation with the same characteristics as the model system boiler (i.e., 75,000 lb/hr 150 psia saturated steam, water-cooled pinhole grate design) was approximately \$3 million, or around \$40 lb/hr steam. This figure includes mechanical dust collectors (cyclones), fans, sootblowers, and other boiler accessories and controls, but does not include secondary emission control, wood handling and processing equipment, or ash handling equipment.

2.4.2 Operating Costs

Operating costs for a wood combustion facility fall into four categories: plant operation and maintenance costs, wood feedstock costs, cost of purchased utilities (i.e., electric power, water), and fixed costs (i.e., general and administrative expenses, property taxes and insurance, and depreciation). For the first category, 10% of capital cost is a reasonable estimate of annual expense, which consists of total labor plus maintenance material costs.

The components of wood feedstock costs are transportation cost, processing cost, and the value of the residue itself (i.e., stumpage value). Costs vary considerably with geographical region, as well as within a particular region, and are influenced by terrain, type of forest, type of material harvested, and other factors such as competing demand. Feedstock costs also vary according to the amount of processing done after harvesting (e.g., whether the fuel is purchased in uncontaminated chip form or as raw residue). The cost of transportation, of course, depends on the distance hauled; the maximum economic hauling distance is generally 50 miles. A feedstock cost of \$5 to \$30 per ton for wood with a 50% moisture content is commonly accepted. Purchased utilities and fixed costs are expected to be less than costs for the first two categories.

3 COMPARISON WITH BAGASSE COMBUSTION

In addition to wood and forest residues, another potential major biomass resource for direct combustion in industrial processes is agricultural crop residues. An estimated 1.5 quads of end-use energy are potentially available from this source.[8] The current major user of this resource is the sugarcane industry, which in 1975 used an estimated 23×10^{12} Btu from cane residue (bagasse) in the processing of sugar.[4]

This section compares the engineering, environmental, and economic characteristics of bagasse combustion with the corresponding characteristics described previously for wood-combustion systems.

The sugarcane industry is located in Louisiana, Florida, Texas, Hawaii, and Puerto Rico. In all locations except Hawaii, the industry is seasonal; work lasts from two to five months per year. For example, an inventory of sugar factories in Louisiana and Puerto Rico indicates the normal grind of sugarcane for each factory ranges from 1,650 tons to 5,500 tons per day, while Florida factories each handle 5,500 tons to 12,000 tons per day. These installations produce approximately 250 to 1800 dry tons of bagasse per day.

Bagasse makes up about 30% of the weight of raw sugarcane and consists of matted cellulose fibers and fine particles. To reduce the cost of required power and eliminate large quantities of solid waste, sugar mills burn bagasse as a primary fuel to produce steam for on-site power generation. Bagasse typically contains about 50% moisture and has a heat content (as fired) of 3600-4200 Btu/lb, similar to corresponding values for forest residue. The composition of bagasse, as given by its ultimate analysis, is also very similar to that of wood waste, reflecting a low ash content and trace amounts of sulfur. Although raw-sugar mills produce sufficient quantities of bagasse to satisfy their steam requirement, mills that also refine usually require supplementary fuel oil to meet the steam demand.

In modern sugar-milling practice, sugarcane is washed, cut by a revolving-knife shredder, and passed in series through sets of grooved rolls, each set with finer grooves than the preceding set. Bagasse fiber size and the amount of fines (particulates less than approximately 15 mm in diameter) present depend on the degree of shredding and milling employed. Figure 4 is a schematic of the milling and power generation process.

Several types of furnaces are employed to burn bagasse. In the older sugar mills, refractory hearth furnaces are most common. In these units, bagasse is gravity-fed through chutes and piles up on the hearth. Primary and overfire combustion air flows through ports in the furnace walls; burning begins on the surface of the pile. Many of these units have dumping hearths that permit ash removal while the unit is operating. In the more recently built sugar mills, bagasse is burned in spreader-stoker type furnaces. These units operate much like the model system spreader-stoker described earlier but generally have a higher capacity. As a result, grate design and certain other design features may differ; for example, a traveling grate rather than a fixed pinhole grate might be employed. Successful burning of bagasse in this type of unit requires a high percentage of fines and a moisture content not exceeding 50%. Boiler efficiencies for bagasse-fired units are very similar

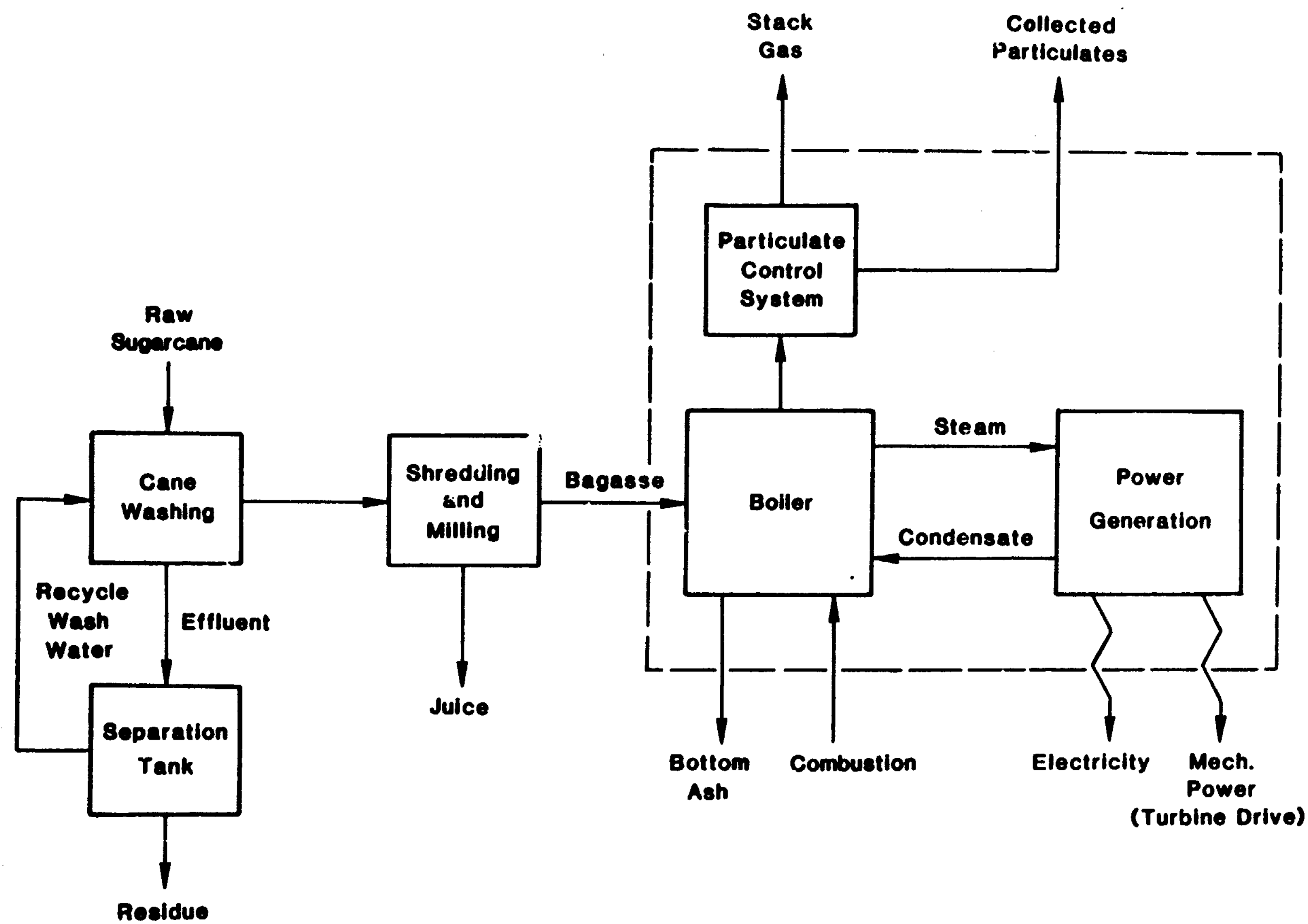

Fig. 4 Schematic of Sugarcane Milling and Bagasse Power-Conversion

to those for wood-fired boilers. An efficiency of 65-70% is the upper limit and would require use of an air preheater to recover heat from the stack gases. Since power rather than process heat is the end product of bagasse combustion in a sugar mill, superheated steam is generated at pressures of 400-600 psi at temperatures up to 750°F. The steam drives turbine-generators or direct turbine drives.

With regard to pollutant emissions, particulate matter is the primary concern in bagasse-fired boilers. As with wood-fired boilers, the principal control methods are multicyclones and wet scrubbers; baghouses and electrostatic precipitators have been used with little success. The factors that affect particle loading and size distribution in bagasse-fired systems are similar to those of wood-fired systems and include fuel variability, degree of milling, and boiler design and operation. Cofiring with fuel oil, of course, will alter particle characteristics, loading, and collection efficiency. Sulfur oxide emissions are negligible since sulfur is present in bagasse, as in wood, in only trace quantities. Emissions of CO and hydrocarbons are again expected to vary widely depending on combustion conditions.

The data base for emissions from bagasse-fired boilers is sparse, even more so than for wood-fired systems. The EPA document "Compilation of Air Pollution Emission Factors"[10] and its companion "Background Document: Bagasse Combustion in Sugar Mills"[12] provide data on emissions of particulate and NO_x matter from bagasse-fired boilers. The latter presents particulate emission factors for three cases: no control, multicyclone control, and scrubber control. The factors are given in "lb particulate matter per 10^3 lb steam" rather than "lb particulate per dry ton of fuel," because most installations monitor steam production rate, rather than bagasse firing rate. If one assumes a boiler efficiency of 65%, a heating value of 7800 Btu/dry lb, a 50% moisture content, steam produced at 600 psi and 750°F, and 70°F feed water, then 3.8 lb steam are produced per lb dry bagasse fired. If this conversion factor is applied, the particulate emission factors become:

uncontrolled: 29 lb particulate matter per dry ton bagasse

multicyclone controlled: 21 lb particulate matter per dry ton bagasse

scrubber controlled: 2.4 lb particulate matter per dry ton bagasse.

These values are significantly higher than those corresponding to both uncontrolled and controlled emissions from wood-fired boilers. Multicyclones applied to bagasse-fired boilers are reported to have collection efficiencies from 20% to 60%. The emission factor above is based on the low end of the range. The value given for scrubber-controlled units represents about a 90% collection efficiency. References 10 and 12 do not specify whether scrubbers are used in combination with multicyclones (as in the case of wood-fired boilers) or independently. The emission factor for NO_x lies within the range specified earlier for wood combustion. Applying the above conversion factor yields an emission factor of 2.3 lb NO_x per dry ton of bagasse.

Water requirements for bagasse-fired boilers and wood-fired boilers are similar, consisting of feed water makeup and, where applicable, scrubber recycle makeup. As noted earlier, these are small quantities.

The sources of solid waste in bagasse-fired boilers, as in wood-fired boilers, include bottom ash and, where applicable, material collected in the multicyclone and from the scrubber sedimentation tank. Since the ash contents of bagasse and wood are similar, the amounts of solid waste produced per ton of fuel fired are likewise similar. Another source of solid waste is the dirt, sand, rocks, and other transport to the mill. Washing the cane separates much of this material from the raw cane before shredding and milling, but a certain amount is carried over into the boiler. Mechanical harvesting of cane increases the dirt content of bagasse to as much as 5% to 10%. Normal disposal procedure is to either transport the solid waste to a sanitary landfill or slurry it to a lagoon, usually located on site.

The capital cost of a bagasse-fired power generation system can vary widely, depending on characteristics of the boiler and its supporting components as well as the balance of the turbine cycle. Boiler cost is a function of boiler type, capacity, steam conditions, grate design, and other design features. No cost differential is expected between bagasse-fired and wood-fired boilers with similar sets of characteristics. The same applies to the balance of the turbine cycle for wood-fired and bagasse-fired power conversion systems. These components are selected on the basis of capacity, steam pressure and temperature, and other factors, but not on fuel type. The influence of steam conditions and capacity on boiler cost, according to a major boiler manufacturer, can be estimated in the following manner. For each additional 100 psi design pressure, cost increases by 1%. Similarly, for each additional 25°F design temperature, cost increases by the same percentage. For increased capacity, the cost-multiplying factor, F, is employed as follows:

$$F = 1 + 0.66 \left(\frac{S'-S}{S}\right)$$

where S' and S are the new (increased) and base capacities, respectively. These estimates apply regardless of fuel type. Operating costs, exclusive of fuel cost, are comparable for bagasse-fired and wood-fired power conversion facilities.

4 SUMMARY

The industrial sector has historically demanded approximately 40% of the total U.S. energy consumption. In 1980, this industrial consumption was over 30 quads, of which over 20 quads was directly obtained from sources other than purchased electricity, i.e., from coal, natural gas, and petroleum products. The use of direct combustion of wood and other biomass as an alternate energy source depends on the availability of wood and wood by-products and on the availability of a technology that is economically feasible and does not produce unacceptable environmental impacts. This report characterizes the principal engineering features of industrial boilers that use wood resources, and describes various material flows, environmental residues, and system costs. It also includes a brief overview of wood fuel and feedstock availability. The overview indicates a potential current annual availability of 5.7 quads from mill and logging residues, surplus growth in commercial forests, and other noncommercial timber. Analysis of the various economic and environmental implications of harvesting, processing, and transporting wood and wood by-products is beyond the scope of this report.

The technology characterization concludes that direct combustion of wood in boilers is a well-established technology. The capital cost of wood boilers is comparable to that of fossil-fuel-burning boilers, although tradeoffs exist between the need for wood preprocessing and handling equipment for wood boilers and the need for sulfur removal equipment for coal boilers. Relative operating costs for wood boilers depend largely on the local supply of wood, which ranges from $5 to $30 per ton.

Compared to oil and gas boilers, wood boilers have the disadvantage of requiring disposal of ash and collected particulate matter from flue gas, although the quantities of these materials are greater from coal boilers. The solid wastes from wood may present somewhat different problems than those from coal because of the presence of soil, dirt, rock, or metallic materials. However, these are usually nontoxic and disposal is straightforward.

Sulfur dioxide emissions from wood boilers are usually low because of the low sulfur content in wood. Atmospheric hydrocarbon, CO, and NO_x emissions can also be maintained at acceptable levels through proper boiler design and operation. However, improper combustion could lead to high emissions of hazardous compounds such as polycyclic organic matter (POM).

A major concern with direct combustion of wood products is the atmospheric release of particulate matter. Emissions of particulate matter depend on many factors, but are generally estimated at approximately 45 lb/ton dry wood for uncontrolled industrial boilers.[10] Multicyclones reduce the particulate emissions by 50-90%, and more-efficient technologies that are available (baghouses, electrostatic precipitators, and wet and dry scrubbers) can further increase the overall removal efficiency to over 99%.

The following example illustrates the significance of alternate levels of particulate control. As part of the DOE Technology Assessment of Solar Energy, two scenarios were developed to illustrate the impacts and benefits of solar technology deployment.[13] A "business as usual" scenario projected that 6.0 quads of conventional fuel would be displaced by energy from solar and biomass technologies by the year 2000, including 0.1 quads from direct combustion of wood in industrial boilers. A second "maximum practical solar" scenario projected 14.2 quads from solar energy in 2000 with 0.916 quad from direct industrial wood combustion. (These wood combustion scenarios do not include the use of residues for cogeneration of process heat and electricity in the pulp and paper industry. This use of wood, projected at over 2 quads by the year 2000, uses a somewhat different technology than the one evaluated in this report.)

The increased direct combustion of wood and wood by-products would increase emissions of particulate matter. The estimated impact of these emissions in the year 2000 from the high and low solar scenarios is presented in Table 5. Particulate emissions of 0.4 $lb/10^6$ Btu heat input appear to be a maximum level permissible for industrial boilers in most applications. A survey of State Implementation Plans[14] indicates that a boiler with 20×10^6 Btu/hr capacity would be permitted to emit at this level in at least some regions within 29 of the 48 coterminous states. Fourteen of the states would require either a unit with a smaller capacity than 20×10^6 Btu/hr at this emission rate per Btu, or reduced emission rates. State Implementation Plan data were not available for five states. The emission rate of 0.03 lb/10^6 Btu in Table 5 is a lower level considered as a possibility for New Source Performance Standards for new industrial boilers.[15]

For comparison, national emissions of particulate matter for the scenarios in the year 2000 are estimated at 11×10^6 tons for all sources and approximately 4×10^6 tons for energy-related sources.[13] On the basis of Table 5, the expanded use of direct combustion of wood would thus contribute approximately 5% to the energy-related emissions at the 85% control level and less than 0.5% at the higher 99% control level. (Reference 13 gives a more detailed discussion of further tradeoffs due to displacement of conventional fuels by wood.)

These examples lead to the conclusion that emissions of particulate matter need not prohibit direct combustion of wood in industrial boilers because efficient control technologies are available. Other considerations such as the reduction of SO_2 emissions and the availability and cost of wood for fuel may be equally important in the final analysis.

Table 5 Particulate Emissions for National Scenarios for Direct Combustion of Wood in the Year 2000 (tons)

Emission Level	Low Solar Scenario[a]	High Solar Scenario[b]
Uncontrolled (2.7 $lb/10^6$ Btu)	135,000	1,240,000
85% Control (0.4 $lb/10^6$ Btu)	20,000	183,000
99% Control (0.03 $lb/10^6$ Btu)	1,500	13,740

[a]0.1 quad from direct combustion of wood.

[b]0.916 quad from direct combustion of wood.

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