WOOD AS AN ENERGY SOURCE IN THE KRAFT PULP-PAPER INDUSTRY OF THE SOUTHEASTERN UNITED STATES

By

William Michael Liebenow

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APPROVED:

William A. Duerr, Chairman

Sandra S. Batie

Richard Oderwald

Harry Haney

Harold Wisdom

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This study could not have been completed without support from the following sources:

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  I appreciate especially their patience in dealing with me through the mails after I left Blacksburg. Special recognition is in order for Sandra Batie. She *taught* me something. She read my papers, thought about them, and questioned my logic. While she has been the toughest committee member to satisfy, I knew that my dissertation would mean nothing to me without her signature.

- My wife, Dianne.

  She always thought that I could do it; I never did. She retained this belief even after I rammed my fist through the closet door and stormed out of the house in frustration and despair. Why she has remained with me for these 13 years, I'll never understand.

- Leroy Coker, Mill Manager at the Hopewell Mill.

One morning in the spring of 1977, a young graduate student made an unsolicited visit to the office of the manager of a large pulp-paper mill in eastern Virginia. This brash student asked to be trained in the art of pulp and papermaking, and to have access to the mill's financial records so that he might use the data in a study that he was conducting. Not only did Leroy Coker listen to this drivel, he accepted the offer.

This mill manager instructed his people to orient me to the operation with tours and briefings. He allowed me to sit in on virtually any meeting that took place in the mill and to ask any questions that I cared to ask. He gave me a desk in his accounting office and assigned his best analyst the task of responding to my querries. He talked with me in the early mornings before his staff arrived, and took me into his confidence. In the ranks of mill managers, this man is one in ten million.

My present job finds me in pulp mills much of the time. None have measured up to the Hopewell Mill. There was some magic element of inspired leadership there that caused people to work together in harmony. It was a "squared-away unit," in the Marine vernacular; a standard to which all others should be compared.

- Mark Lembersky, the Director of my division at Weyerhaeuser.

Mark *demanded* that I take a two-month leave of absence with pay to finish this dissertation. His decree came at a time when the company was in the throes of a recession and my services were sorely needed. His decision was politically unpopular. Without his final prod, however, I don't believe that I would have finished. And as I promised, the diploma didn't make old Mike any smarter. I owe Mark Lembersky a great debt.

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I think back over these past eight years to all the periods of frustration and doubt. He was never too busy to listen; never too busy to offer advice.

"This PhD business isn't for me," I argued. "I'm not cut from that mold. I'm an ex-Marine: a *doer*, not a thinker. You've got the wrong man here!"

Sometimes I silently cursed him. His standard was too high! I imagined his stare over my shoulder as I wrote. I pictured him shaking his head sadly as the logic and grammar of my agrument crumbled to dust. Even now, I don't really believe that I fully measured up. I have always been afraid to turn in this last paper because I know it isn't good enough.

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- Cindy Miller, Diane Riden, Midori Howell, and Mary Selig, my typists; Cathy Williams, my "draftsperson;" and Diane Johnson, the girl who put the whole thing together.

Surely, I don't deserve a support group as fine as this one. Their efforts have gone far beyond the call of duty. They somehow sandwiched this dissertation in among all of their normal activities and completed it on schedule. I owe them all a great debt.

I must say something about the fourth most important girl in my life (behind wife, mother, and daughter), Diane Johnson. We attack the problems of the day as a team of two. Thus, at least half of the burden of this dissertation has fallen to her. Without her warm smile in the morning, her unflagging support on days when support is hard to come by, and her willingness to tackle the menial tasks associated with a project such as this one, there would be no dissertation. She is, without question, the finest secretary in the world. I would be lost without her.

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I. INTRODUCTION

A. An Overview of the Energy Crisis

From one perspective, the "energy crisis" is nothing more than a shift in the relative costs of production input factors. As the energy input into the production process becomes more expensive relative to other inputs, producers economize on energy and thereby preserve or improve the competitive positions of their products. Perhaps the "crisis" label is applied because we Americans do not happen to control sufficient quantities of the new sources of wealth to maintain the world's economic status quo. Within this new economic environment, continued operation of our fluid fuel-intensive technology results in a transfer of wealth from Americans, who have grown quite accustomed to it, to others who are thought to be less deserving. We find this transfer to be a wholly unpleasant experience.

This shift in the world's balance of economic power likely will continue until non-fluid fuel technology is developed and embodied into our capital structure. Today's consumption of energy is determined largely by the stock of energy-inefficient capital assets left over from an era of low-priced energy (McRae 1977, pg. 3; U.S. Congress 1977, pg. 52). The task is one of capital renovation. Unfortunately, the development of capital assets requires long lead-time and large inputs of labor and materials. Given our finite productive capacity and the fact that our asset production technology, too, is fluid fuel-intensive, new and renovated capital that embodies the existing price structure will be long and expensive in arriving.

The technological problems of capital renovation are exacerbated by a fluid-fuel market that is far from perfectly competitive and a government that has maintained an artificial price structure which encouraged consumption of fuels in shortest supply. The use of energy pricing as a welfare, or income redistribution, tool by the federal government has resulted in shortage, overconsumption, and inhibited resource development. For example, since the price that Americans have paid for petroleum products has been based upon an average price of expensive foreign oil and cheaper domestic oil, consumption has been overstimulated as consumers were led to believe that this depleting resource could be had for less than its replacement cost. Such policy has encouraged the importation of foreign oil (McRae 1977, pg. 5), and further widened the balance of trade deficit. Absence of a clear social and political consensus on the direction of America's future energy policy has bred economic uncertainty and reluctance on the part of the business community to make long-term investment in new capital assets. Indeed, the greatest social cost to be imposed by the energy crises may well result from the time lag required for society to reach an acceptable decision.

The ability of a concerted OPEC to dictate the rise and fall of the world market price for oil and to possess the power to disrupt the western economy are reflections of monopolistic supply[1] and inelastic demand. Long-run price elasticity of demand for energy in general has been estimated to fall between -.15 and -.5 (Naill 1977, pg. 25; U.S. Congress, pg. 16). Naill's model predicts an average response time of 10 years for consumer demand to react to energy price changes (pg. 26). Such figures do not reflect the readiness of consumers to substitute between energy sources in response to relative price changes - no consensus on these cross-price elasticities has yet emerged (U.S. Congress 1977, pg. 15) - nonetheless, they indicate the magnitude of the delay that can be expected before technology and asset development are able to respond to fuel price changes.

These may be only surface problems, and the development of capital that allows for substitution among fuels may be only a short-term solution. Kenneth Boulding once termed our existing economy as "essentially suicidal," depending, as it does, upon past accumulations of natural capital. Indeed, Beardsly (1976, pg. 73) reports that of all material consumed during the century 1870 to 1970, mineral materials rose from 20 to 31 percent, energy materials increased from 44 to 58 percent, and forest materials declined from 36 to 11 percent. These figures suggest increased dependence on non-renewable resources.

Our reliance upon such natural capital is readily understandable if one considers the cost of the alternatives. It has been far cheaper to mine, transport and convert concentrated energy sources (e.g., oil, coal, uranium) than to assemble the capital that would be required to collect and process the same amount of energy from more diffuse, "renewable" sources (sun, wind, biomass). The mining and processing of naturally-occurring ores has been far cheaper than the creation of metals in the laboratory. While no economy can continue to consume its capital foundation and remain viable, capital resources may be redefined by advancing technology. Material feedstocks of today's economy may be rendered obsolete as production inputs by new scientific advances and discoveries: a process that is encouraged by an unencumbered market. The natural capital of today's economy will be replaced ultimately by the new capital of tomorrow's economy. The only question is one of cost. What will be the cost to society of the substitution?

B. Energy Consumption and Economic Output

In a 1973 study, the National Research Council drew the following conclusions regarding the future of American energy and materials consumption:

> Given the present level of technology and what may reasonably be expected to evolve over the next decades, and given the prevailing view that materials consumption is the way to a better life, the facts indicate: (1) materials throughput will double, and then double again, over the next 30 to 40 years, (2) the quality of ores and other natural resources will decline and readily available sources will be exhausted, (3) *only by increased use of energy per unit of output and per capita will the intensity of materials throughput be maintained*, and (4) the environmental stress per unit of production will increase correspondingly.
>
> (pg. 2, emphasis added)

One question that arises here is whether one's economic well-being can be tied directly to "materials throughput" that the economy makes in his behalf. Surely this is an absurd contention. We must think in terms of *value* in consumption: this is the factor that each consumer seeks to maximize. The value that one attaches to a consumable may or a may not relate to the quantity of materials that has been sacrificed in its production. Undeniably, the consumption of materials (to include fossil fuels) has progressed at an increasing rate over time. The principal questions are: (1) whether such a process *must necessarily* continue in order for the economic product (the value of goods and services produced) to grow, and (2) whether such a process *will* continue.

Historically, energy consumption in this country has closely paralleled economic growth, as measured by changes in real gross national product (Figure 1). Until relatively recent times, one finds that both GNP in constant dollars and energy consumption have grown at a fairly constant rate of 3 to 4 percent (U.S.

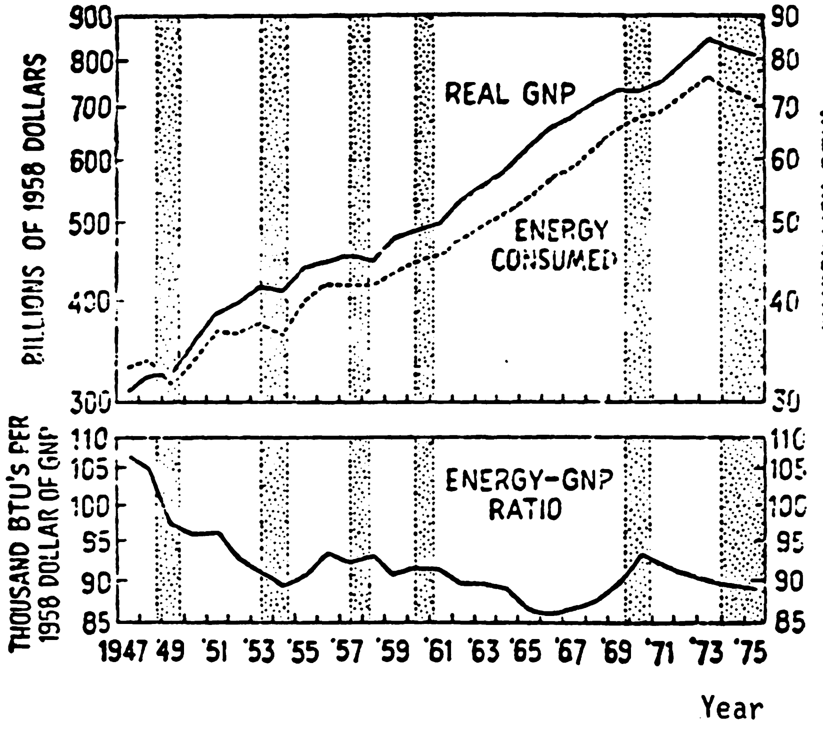


FIGURE 1

Energy Consumption, Real Gross National Production, and their Ratio in the U.S., 1947-1975 (Shaded periods represent recessions)

Source: U.S. Congress 1977, pg. 6

Congress 1977, pg. 4). In a study prepared for the Joint Economic Committee of the U.S. Congress, Ross and Williams (U.S. Congress 1977) argue that substantial opportunities exist for uncoupling economic growth from its apparent historical dependence on energy. They base their thesis upon a number of factors:

(1) Past growth in energy consumption has been stimulated by low and stable or declining energy prices: a situation that no longer exists (Figure 2 shows dramatic increases in prices of coal, oil, and natural gas following the 1973 OPEC embargo).

(2) The economy is evolving toward less energy-intensive activities: from goods to services, and within the goods sector from energy-intensive primary materials processing to materials fabrication activities (Figures 3 and 4 combine to show an evolution toward less energy-intensive services).

(3) Considerable opportunities exist for substituting other inputs[2] for energy throughout the economy. Even when allowances are made for climatic variation and distances over which economic exchange must take place, Western European nations having per capita incomes comparable to ours get by on energy-GNP ratios of about two-thirds the U.S. level (Figure 5 compares the industrialized nations of the West with respect the energy consumption per unit of GNP).

The contention that a given level of economic output is not tied inexorably to a specific number of BTUs seems reasonable, but only for the long run. It is the short-run period of adjustment that poses the "crisis." Naill (1977, pg. 5) describes

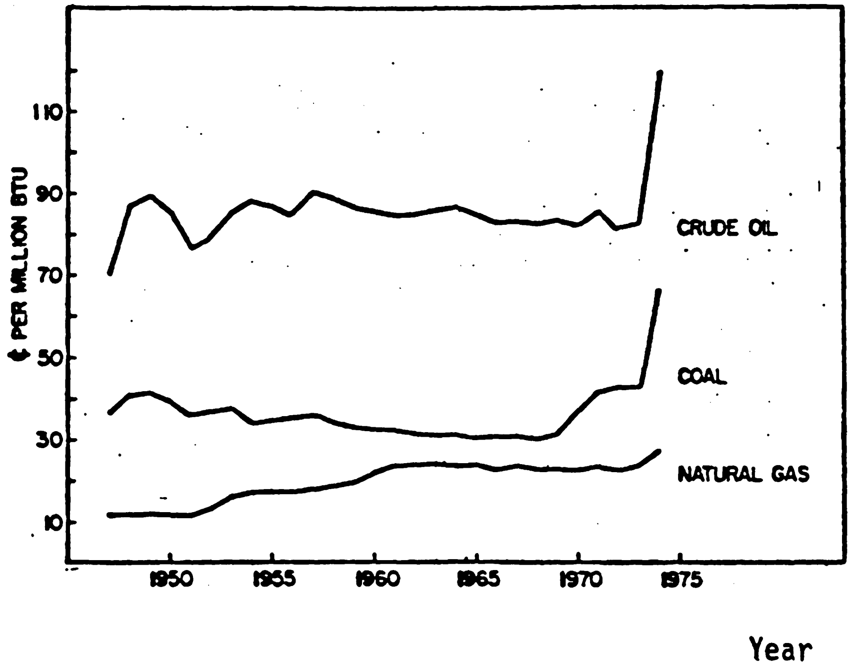


FIGURE 2

Real Energy Prices in the U.S., 1945-1975
(Wholesale fuel prices (1974 dollars). Fuel prices at the wellhead or minemouth were deflated by the wholesale price index for industrial commodities.)

Source: U.S. Congress 1977, pg. 8

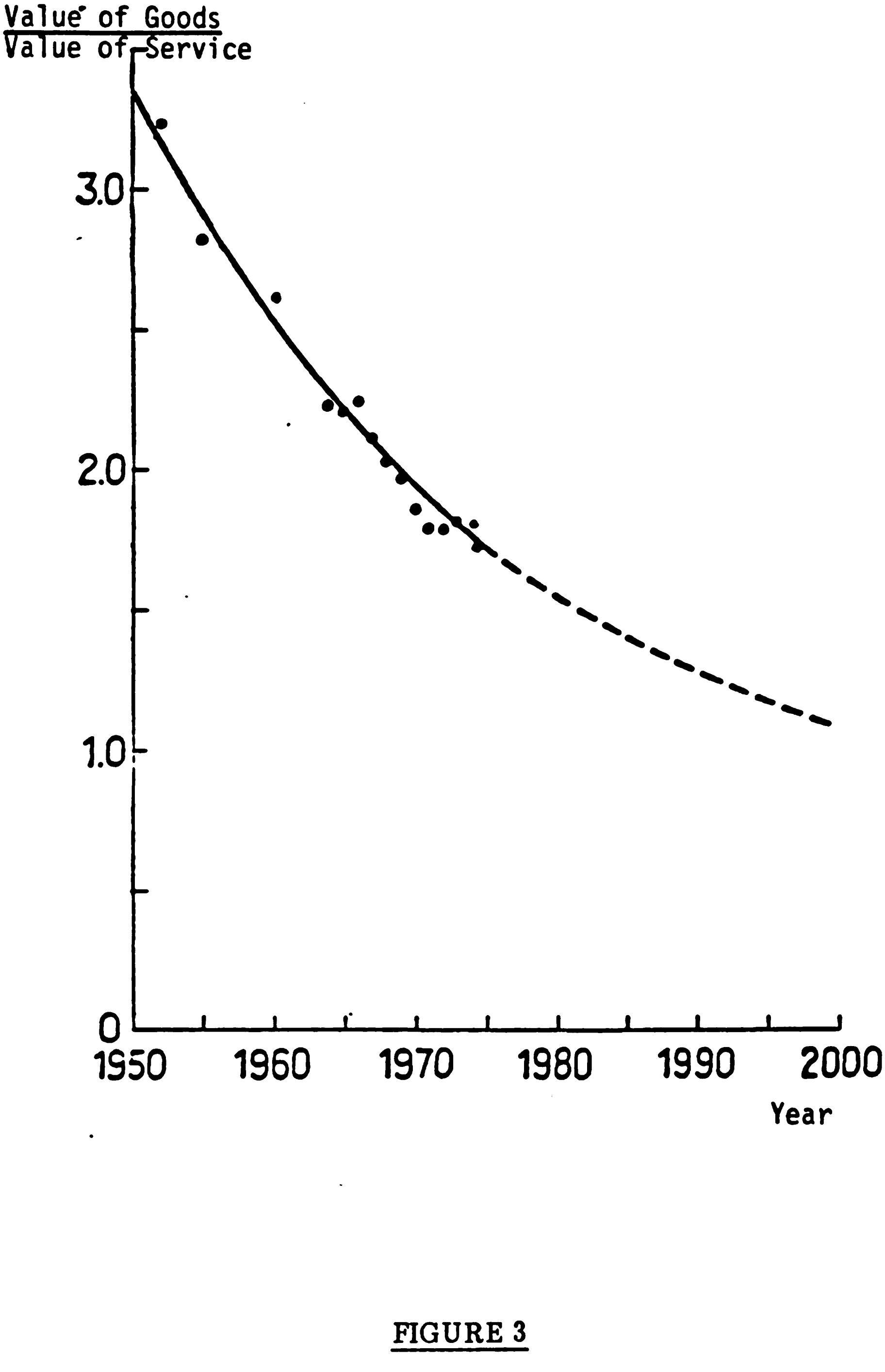


FIGURE 3

The Ratio of the Value of Goods to the Value
of Services in Current Dollars in the U.S. Economy

Source: U.S. Congress 1977, pg. 25

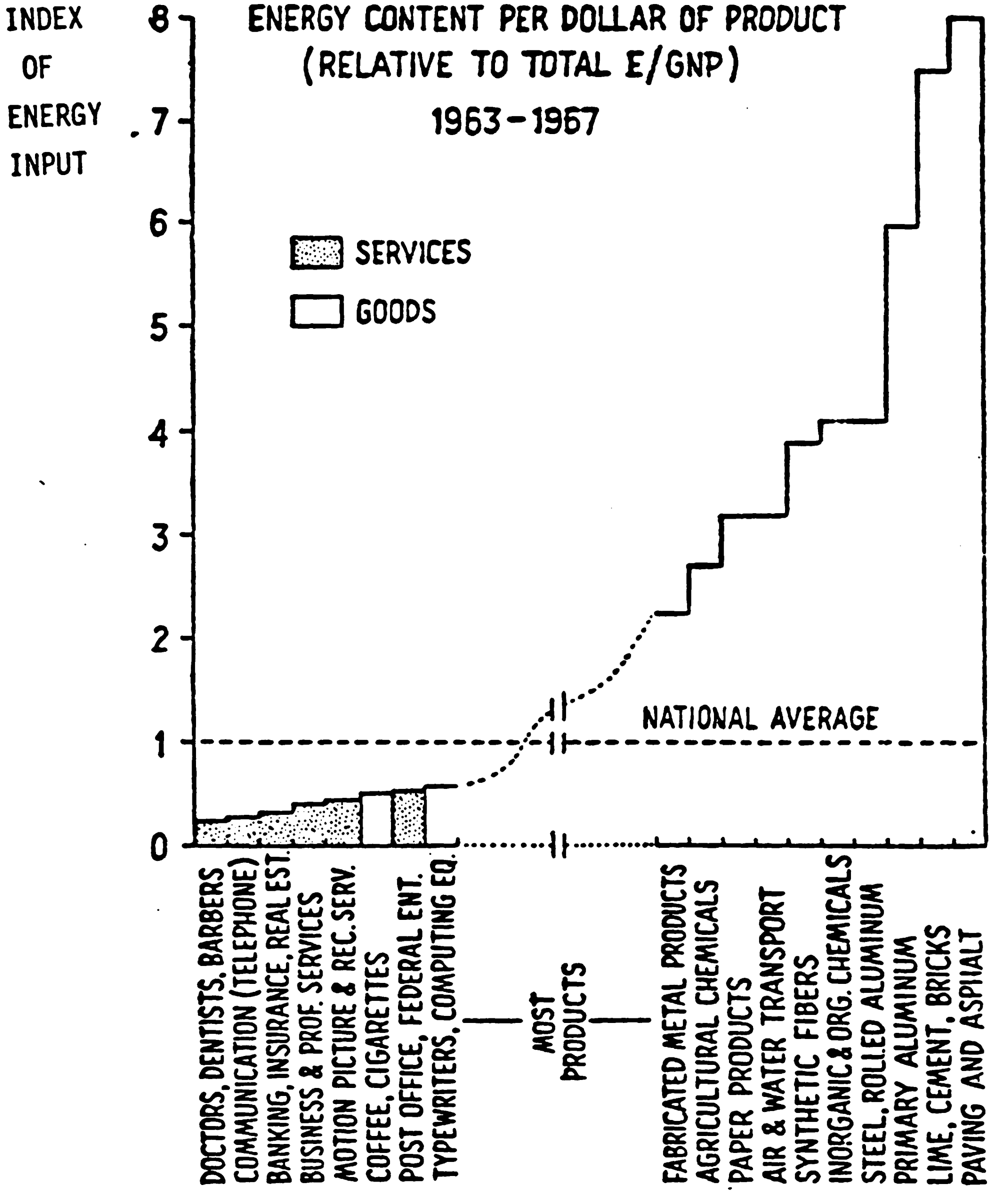
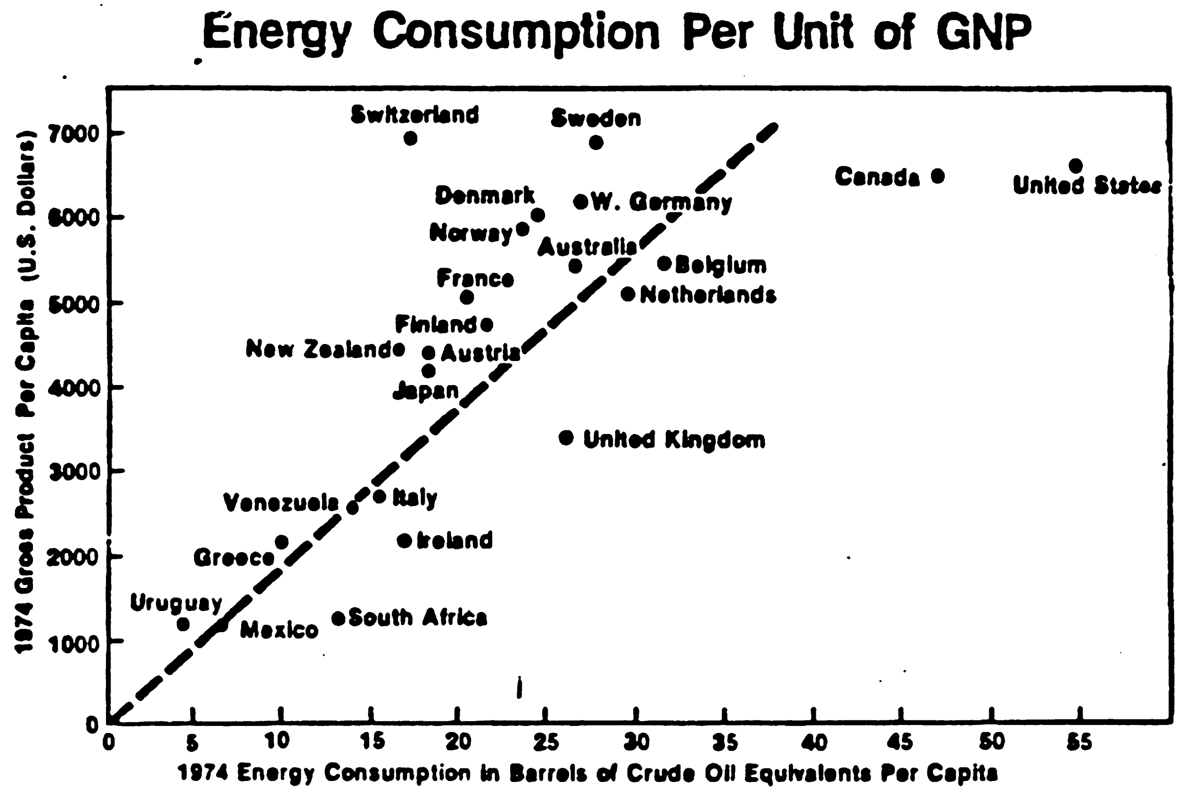


FIGURE 4

Total Energy Consumption Associated with each Dollar of Product Purchased (1963-1967 average)

Source: U.S. Congress 1977, pg. 22



Energy Consumption Per Unit of GNP

Source of Data: U.N. Statistical Yearbook, 1975

FIGURE 5

Energy Consumption per Unit of GNP

Source: McRae 1977, pg. 12

an "energy gap" between domestic energy supply and demand which extends well beyond the year 2000 and which must be filled by increased energy imports. The consequence of heavy dependence upon imports, he says ". . . could well be several decades of rising prices, increasing government intervention in both supply and demand decisions, supply interruptions and stagnation or decline in the material standard of living." This scenario he finds to be the most likely outcome of current energy policies and consumption trends. Between the conventional energy sources and the "ultimate" sources are "transition" sources than can reduce the energy gap and lessen economic disruption (Figure 6). The part that wood fuel can play in this transition - at least in one major industry - is the subject of this thesis.

C. Thesis Objective and Approach

The purpose of this study is to assess the capacity of fuelwood to shoulder a greater share of the energy burden in kraft pulp/paper manufacture. More specifically, we will attempt to provide guideines to aid in selection of a fuel for use in the near-term, and fuel conversion assets for the longer term. Throughout our discussion, we will assume that the firm's managers have as their objective the maximization of the firm's present net worth, as reflected in the value of its common shares.

This will be the approach:

(1) to describe the nature of wood as an energy source in comparison with fossil fuels, and to describe how its energy value may be increased;

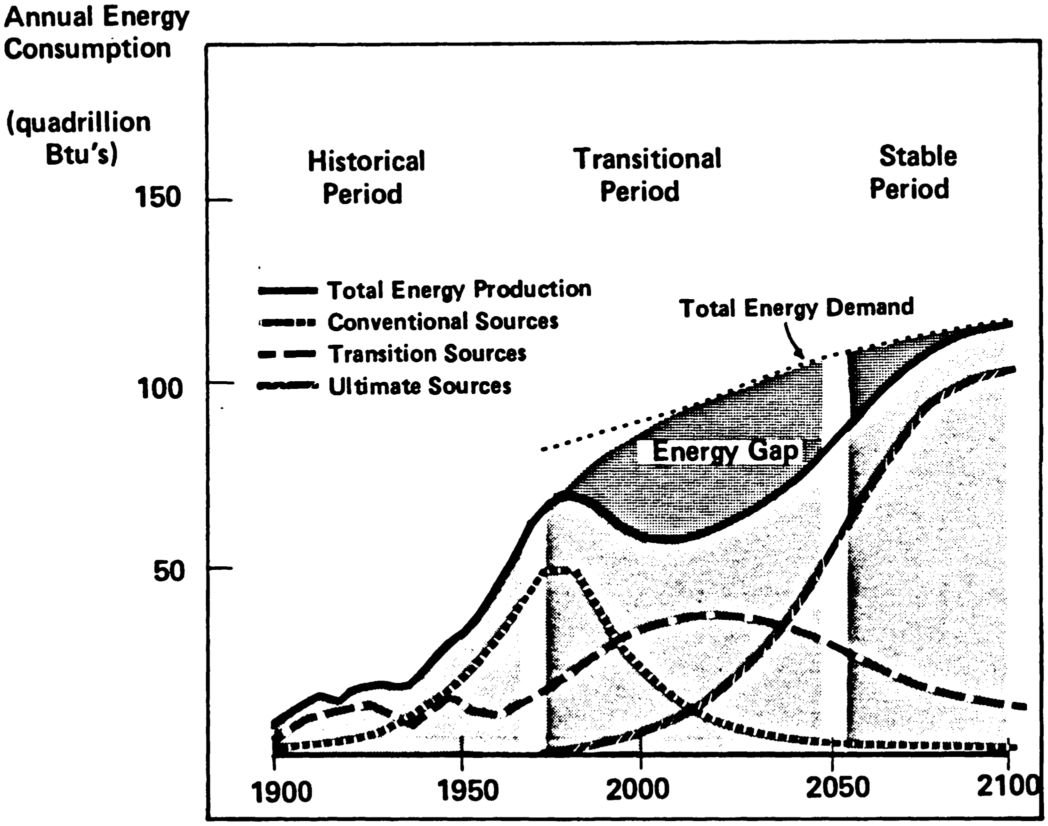


FIGURE 6

The United States Energy Transition Problem

Source: Naill 1977, pg. 5

(2) to propose a theory of fuelwood supply, and to describe the economic forces that interact to determine the wood types and sources that will be used for energy;

(3) to develop, by means of a case study, a framework for analysis of a kraft mill's energy substitution alternatives in the short run; and

(4) to provide guides to the industry's managers and analysts that will enable them to better assess wood's potential as an energy source in the economic short- and long-run.

This paper will show that wood's future as an energy source depends upon relative prices. These are among the most important:

- the future price of wood and alternate fuels;
- new technologies for energy conversion and the capital investment required to implement these technologies;
- the cost of capital; and
- the cost of social regulation.

Forecasting the direction that these prices will take lies beyond the scope of this paper. It is a job for industry planners. The emphasis here will be on how such forecasts can be used to select the best energy source for a given set of circumstances.

Why address the topic of fuelwood utility in the kraft industry?

- because energy costs are significant in kraft pulp-paper manufacturer and hold the promise of becoming more significant in the future;
- because the kraft industry is in a nearly unique position to be able to make use of a portion of its primary raw material to satisfy its energy requirements; and
- because the wood will be around for as long as the kraft industry: there is no danger of running out.

With wood as an energy source, there appear to be opportunities for the kraft industry to reduce substantially its operating costs. The problem reduces to one of directing the wood raw material to its most profitable end use: an economic problem in resource allocation.

II. WOOD AS AN ENERGY SOURCE

This section investigates the technical aspects of wood as a source of energy, and compares its properties with those of fossil fuels. Most important are the comparisons of heating value and atmospheric emissions associated with fuel combustion. Energy conversion devices (e.g., boilers) that use wood as a fuel are described, as are methods of fuel form conversion.

Wood may be used as a fuel in its raw form, or it may be converted to alternative gaseous, liquid, or solid forms prior to combustion. The advantage of converting wood to other fuel forms, of course, is that more desirable characteristics may be imparted and the value increased. In general, wood energy that is concentrated into gaseous or liquid form is more easily transported and combusted, and is suitable for applications where solid fuels are inappropriate (e.g., modern transportation). Industrial boilers designed to fire gaseous or liquid fuels are converted to fire solid fuels, such as coal or wood, only with extensive and costly modification. As this type boiler comprises the vast majority of the capital stock of boilers in the size-class for which wood might be considered as an alternative fuel,[1] these modification problems are significant. A large portion of the existing stock of assets may be used with wood only if wood's form is changed.

The use of wood in coal-fired stoker boilers presents the fewest technical conversion problems (Battelle 1976, pg. 55), but as the heat value of unprocessed wood is significantly less than that of coal, the substitution results in boiler "derating" and less steam production. Such problems can be partially overcome by drying the wood before combustion, or by processing it into charcoal or fuel pellets: all at a cost.

MITRE (1979, pgs. 11-12) reports that wood is a potential candidate for all combustion and conversion processes that use organic material as an energy feedstock, but notes that wood's complex chemical structure limits its suitability in the present market to direct combustion and, perhaps, thermochemical gasification. While wood can be converted to ethyl alcohol through a process of hydrolysis[2] and fermentation, for example, the process is expensive and inefficient when compared with use of grains, sugar beets, or sugar cane.[3] MITRE (1979, pg. 12) lists the following processes as commercially available and economically feasible for deriving energy from wood:

- Direct combustion to produce process heat, steam, and electricity.
- Thermochemical gasification to produce low-BTU fuel gas.
- Pyrolysis[4] to produce low-BTU fuel gas, fuel oil, and char.
- Densification to produce fuel pellets.

These processes will be described in some detail further on.

All wood-form conversion imposes costs: not only in terms of capital and operating expenses for conversion facilities, but in terms of energy inefficiencies as well.[5] In the present market, the benefits to be derived from use of wood-derived fluid fuels with existing capital assets do not appear to outweigh the costs of boiler derating and fuel-form conversion.[6] Our attention in this discussion will focus principally on direct firing applications using wood in some solid form, where the near-term economic balance appears more favorable.

Before considering the various combustion system alternatives, however, it is important that we have a thorough understanding of wood's fuel properties as they compare with the alternatives.

A. The Caloric Value of Wood

The extent to which recoverable energy is concentrated in a fuel is a principal determinant of the fuel's utility and, in consequence, its financial value. Diffuse energy sources (e.g., sun, wind, biomass) require relatively large investments in collection and conversion assets per unit of useful energy output when compared to more highly concentrated sources (e.g., coal, oil, uranium). Thus, in comparing alternative fuels, the most likely starting point is relative heating values. We note here that, for the remainder of this chapter, the word "value" will be used in its physical - not financial - sense.

The caloric value of dry wood results from wood's chemical composition: a factor that shows remarkably little variation among forest species. In the absence of water, resins, and extractives, all wood provides roughly 8,300 BTU/lb when combusted (Corder in FPRS 1975, pg. 30; and Battelle 1976, pg. 38). The higher heating value of resins and extractives (ranging from about 16,900 to 17,000 BTU/lb) cause the dry wood of resinous species to yield more energy when fired than non-resinous species (Battelle 1976, pg. 38). Bark has a slightly different chemical composition than wood and, in general, produces more heat when burned than wood of the same species. Corder (in FPRS 1975, pg. 30) shows the following heating value ranges for dry wood and bark of resinous and non-resinous species:

General Range of Heating Values for
Wood and Bark, in BTU/dry pound

Species	Wood	Bark
Non-resinous	8,000-8,500	7,400-9,800
Resinous	8,600-9,700	8,800-10,800

Southern pine bark reportedly has a heating value of roughly 8,900 BTUs per oven dry pound, while the wood averages about 8,600 BTUs per oven dry pound (Koch 1971, pg. 36).

The most significant factor affecting wood's caloric value is its moisture content. Moisture reduces wood's fuel value in three ways. First, as the water must be evaporated before the wood will burn, part of the fuel's heat must be expended to raise the temperature of the water to the boiling point (1 BTU per degree F per pound of water) and to vaporize it (1,000 BTUs per pound of water) (Sherwood 1978, pg. 6). Since water vapor generally may not be allowed to condense before it exits the stack, this heat is lost to the atmosphere. Second, boiler efficiency is lowered because increased fuel moisture requires a larger volume of excess air[7] to ensure complete combustion. The greater the volume of excess air for a given exiting stack gas temperature, the greater the heat loss to the atmosphere (Cheremisinoff 1976, pg. 170). Third, moisture lowers the temperature of combustion gases from which energy is extracted in the boiler. While perfectly dry wood may generate combustion gases of 3,000°F, wood at 50 percent moisture[8] yields gases of only 2,500°F (Sherwood 1978, pgs. 7-8).

The boiler efficiency-fuel moisture content relationship is plotted in Figure 7. When wood's moisture content reaches 55 to 60 percent, it becomes difficult to sustain combustion without the use of supplementary fuels. Above roughly 65 percent moisture, the fuel no longer provides recoverable heat and must either be dried or put to non-fuel use. (See Babcock & Wilcox 1963, pg. 19-7; Roberson 1968, pg. 92A.)

Tillman (1978, pgs. 81-82) cites Rogot's study of "as-received" moisture content for 17 species as demonstrating that green hardwoods contain 30 percent moisture on average, as compared to 46 percent for green softwoods.[9] If these figures are accurate for resinous and non-resinous species in general, one can estimate an average, as-received heating value of 6,500 BTUs/lb for hardwoods and 4,000 BTUs/lb for softwoods: an abrupt reversal of the dry-weight heating values (Tillman 1978, pg. 81). Thus, if we consider wood delivered shortly after harvest and given no intermediate processing to facilitate drying, hardwood becomes relatively more desirable as fuel: a fact that doubtless has been known by woodburners for centuries.

Table 1 shows the comparative heating values of wood and fossil fuels. Unless intermediate processing or drying is contemplated for wood fuel, the heating values to use for comparison are the "as-received" figures. Unprocessed wood is seen to be a low-grade fuel, yielding roughly 29 to 46 percent (depending on whether resinous or non-resinous species are considered) of the heating value of bitumious coal, and 21 to 33 percent (by weight) of the value of low-sulfur No. 6 fuel oil.

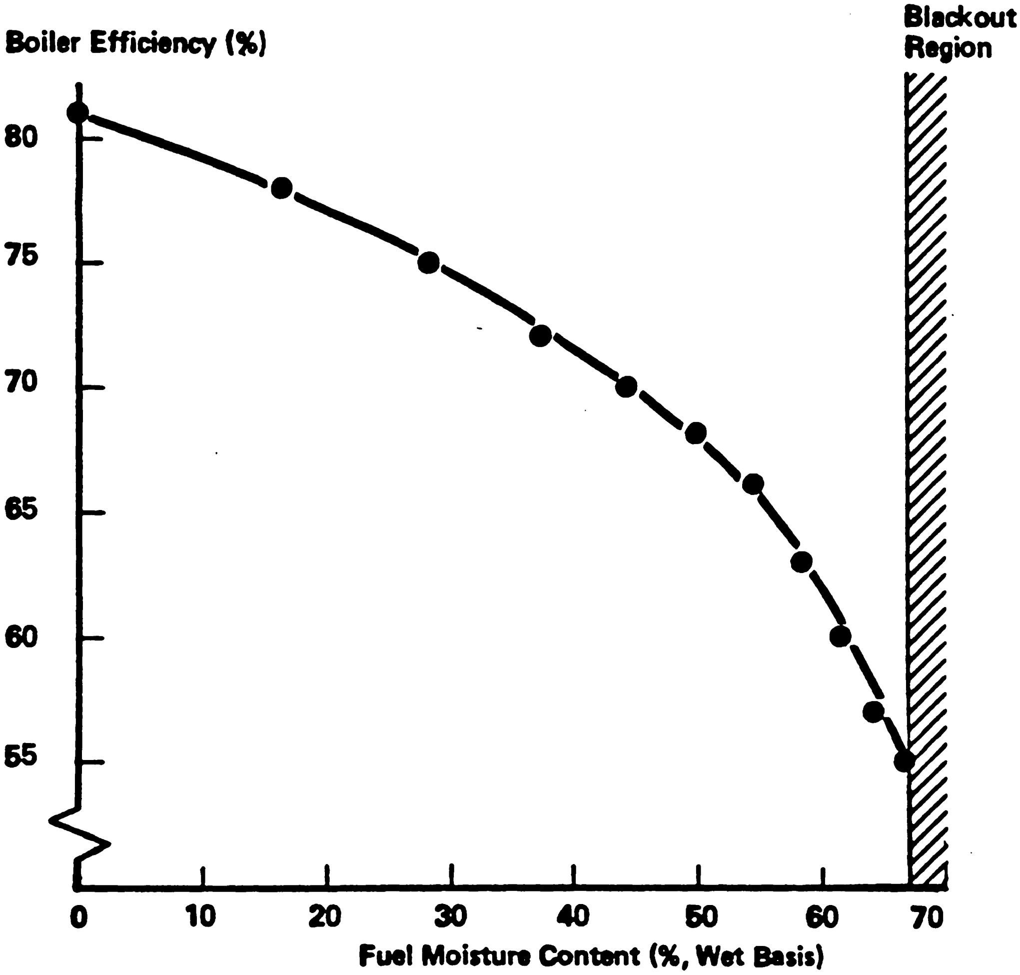


FIGURE 7

The Influence of Fuel Moisture on Boiler Efficiency

Source: Derived from a table given by Stanley E. Corder, Wood and Bark as Fuel. OSU Forest Research Lab Bul. No. 14. Corvallis, Oregon. 1973. As quoted in Tillman (1978, pg. 103)

TABLE 1

Comparative Heating Values of Wood and Fossil Fuels

Fuel	Heat Value/Unit		Average/lb. (BTU)
Kerosene[1]	134,000 BTU/gal. @ 6.814 lb./gal.	=	19,665
No. 2 Burner Fuel Oil[1]	140,000 BTU/gal. @ 7.022 lb./gal.	=	19,937
No. 5 Heavy Fuel Oil[1]	144,000 BTU/gal. @ 7.612 lb./gal.	=	18,917
No. 5 Heavy Fuel Oil[1]	150,000 BTU/gal. @ 7.676 lb./gal.	=	19,541
No. 6 Heavy Fuel Oil[1] (2.7%S)	152,000 BTU/gal. @ 8.082 lb./gal.	=	18,807
No. 6 Heavy Fuel Oil[1] (0.3%S)	143,000 BTU/gal. @ 7.041 lb./gal.	=	19,430
Natural Gas[1]	1,000 BTU/cu. ft.		23,000
Anthracite Coal[1]			13,900
Bituminous Coal[1]			14,000
Sub-Bituminous Coal[1]			12,000
Lignite Coal[1]			11,000
Western Coal[3]			9,420
Oven-Dry Hardwood Wood[2]			8,530
Oven-Dry Hardwood Bark[2]			8,040
"As-Received" Hardwood[4]			6,500
Oven-Dry Softwood Wood[2]			8,910
Oven-Dry Softwood Bark[2]			8,950
"As-Received" Softwood[4]			4,000

[1] Arola 1976, pg. 37

[2] Arola 1978, pg. 44

[3] Perry 1969, pg. 9-3

[4] Tillman 1978, pg. 81

This comparison does not consider the lower efficiencies at which moisture-laden wood is converted to usable energy, however, which may be as much as 18 percentage points lower than coal or oil conversion (Hall in FPRS 1976, pg. 141). Green wood fired in stoker boilers, for example, typically yields efficiencies of 70 percent or less, while boilers firing fossil fuels provide efficiencies in the neighborhood of 85 percent. If typical combustion efficiencies are used with the heating values given in Table 1, an *effective* heating value comparison can be made. This comparison shows wood's recoverable energy to be only 24 to 41 percent that of bituminous coal and 17 to 30 percent that of low-sulfur No. 6 fuel oil.[10]

Furthermore, it should be recognized that wood provides its effective energy at a cost of higher fuel bulk, which translates to higher costs of transportation, fuel-handling, and storage. Roughly 7.8 ft^3 of bark containing 45 percent moisture supply the same effective heat energy as 1 ft^3 of bituminous coal,[11] and 11 ft^3 equate to 1 ft^3 of oil (Corder in FPRS 1975, pg. 31).

Considering these factors along with the fact that the capital investment required for the boiler and peripheral fuel-handling and storage facilities for a wood-fired installation typically exceeds the cost of, say, a comparably-sized oil or gas-fired installation by a factor of approximately 2 to 1 (see Koch 1971, pg. 37, and Cheremisinoff 1976, pg. 71), it is easy to understand why wood fuel has not experienced great popularity in the past. Consumption has been confined largely to the forest products industry, where wood byproducts have presented a disposal problem. But relative prices are shifting in wood's favor; one major factor being the increasing cost of burning fossil fuels in an environmentally acceptable manner.

B. Ash and Pollutants

Tillman theorizes that the resurgence in popularity of wood fuel in industrial applications has been due, not primarily to relative fuel prices, but to increasingly stringent environmental regulations. He finds quantum leaps in wood-fired boiler sales that are coincident in time with passage of the Clean Air Act and its major amendments. He finds no significant correlation between sale of these boilers and the cost of alternative fuels (see pgs. 47-51).

1. Wood Ash

Wood ash is composed of non-combustible mineral constituents of the wood structure, non-combustible contaminants (e.g., sand), and incompletely combusted organic constituents. It may either be retained in the boiler as bottom ash or become entrained in the exhaust gases as fly ash. The bottom ash/fly ash proportions are highly variable among combustion systems and depend on such factors as method of firing (e.g., suspension or stoker), whether fly ash reinjection is practiced, and fuel moisture content (affecting the volume and velocity of exhaust gases). Bottom ash interferes with the combustion process (Corder *in* FPRS 1975, pg. 30), fouls heat transfer surfaces, and reduces thermal efficiency. Fly ash carried in the exhaust gases causes erosion of the heating surfaces and ducting of the furnace (Corder *in* FPRS 1975, pg. 30) and requires the establishment and operation of costly collection systems to reduce particulate emissions.

Although wood's theoretical ash content (i.e., its mineral fraction) is very low[12] in comparison, say, to coal (see Table 2), the practical aspects of logging and

TABLE 2

Comparative Ash Fractions

Fuel	Ash Content (% by Dry Weight)
Semibituminous, Pocahontas No. 3, Kilpoa, Va.[1]	5.3
Bituminous, Freeport Logans Ferry, Pa.[1]	12.15
Bituminous, No. 5 Springfield, Ill.[1]	11.7
Wyoming Coal[2]	13.8
Residual Fuel Oil[3]	0.10-0.15
Natural Gas	Neg.
Southern Pine Bark[4]	2.9[5]
Oak Bark[4]	5.3[5]

[1] Babcock & Wilcox 1963, pg. 18-2

[2] Tillman 1978, pg. 73

[3] Babcock & Wilcox 1963, pg. 18-16

[4] Babcock & Wilcox 1963, pg. 3-4A

[5] While not specified, the magnitude of these numbers when compared to other sources suggests that these are operational, as opposed to laboratory figures. Koch (1971, pg. 36) lists a dry-weight ash percentage of 0.6 percent for Southern pine bark, for example.

other processing cause sand and grit to become embedded in bark and wood crevices, and the level of these contaminants may easily exceed wood's mineral fraction. In practice, wood ash contents as high as 5 percent may be anticipated (Battelle 1976, pg. 54). While this figure also appears low relative to most coals, wood's lower caloric value requires that a greater volume of fuel be combusted to produce the same effective heat. Thus, the ash-burden in a wood-fired boiler is roughly comparable to that of a boiler firing 13,000 BTU/lb bituminous coal having an ash content of 7 to 8 percent (Battelle 1976, pg. 54).

Although the chemical composition of wood ash varies widely between species and within species found on different sites, Wise (1946, pg. 434) reports that the principal metallic constituents are potassium, calcium and magnesium. Wood ash is particularly rich in calcium, and calcium oxide may comprise one-half to three-quarters of the total (Wise 1946, pg. 435). The high variability in wood ash composition is illustrated in Table 3.

Coal ash composition is even more variable, and any attempt to present a "representative" coal ash analysis would be pointless. Wide variation may be found in coal samples taken from the same coal seam in the same mine. Although agricultural application of coal ash shows some degree of promise because the material is a low-grade source of essential plant nutrients,[13] fresh coal ash in disposal rates of application is initially toxic to plant growth due to the presence of high boron levels and high alkalinity[14] (Terman n.d., pg. 1). Additionally, depending on the source of the coal and the surrounding strata, its ash may contain levels of heavy metals that exceed EPA's current public water supply guidelines (Terman n.d., pg. 15).

TABLE 3

Wood Ash Composition
(% by weight)

Compound	Southern Pine Bark[1]	Pine Bark[2]	Oak Bark[2]
CaO	27	25.5	64.5
Al_2O_3	21	14.0	0.1
SiO_3	19	39.0	11.1
K_2O	9	6.0	0.2
SO_3	6	0.3	2.0
MgO	5	6.5	1.2
P_2O_5	4	-	-
Na_2O	3	1.3	8.9
Fe_2O_3	1	3.0	3.3
TiO_2	-	0.2	0.1
Mn_3O_4	-	Trace	Trace
Cl	-	Trace	Trace
Unidentified	5	4.2	8.6

[1] Koch (1971, pg. 37): These are averages derived from a limited sample.

[2] Babcock & Wilcox (1963, pg. 5-1-24)

While trace concentrations of these heavy metals may be found in some wood,[15] wood ash disposal is seen to pose no environmental problems (Battelle 1976, pg. 81). Indeed, it may have significant potential benefit as a soil conditioner[16] and fertility agent. Wood ash contains all of the non-organic soil nutrients required for plant growth with the exception of nitrogen (Battelle 1976, pg. 81). As with any fertilizer, the rate of application is critical, and this fact poses a problem for the use of wood ash. In order to apply the material to agricultural or forest sites so that concentrations of some elements present in the ash are not so high as to be detrimental to plant growth, the minimum application area must be made very wide. This, in itself, is not troublesome, but when considered with the fact that nitrogen usually is one of the limiting nutrients and, therefore, that addition of other nutrients may not significantly improve plant growth, the benefits are quickly outweighed by application costs.[17]

There undoubtedly are some situations in which wood ash application would prove both beneficial and economical, and this would be true especially if a better nutrient balance could be achieved (e.g., through addition of a nitrogen compound) at low cost. Additionally, none of the foregoing detracts from wood ash's potential as a *source* of plant nutrients, as it has been used traditionally as a source of potash.[18]

While wood ash poses fewer fouling and disposal problems than coal ash, the ash generated by the co-firing of wood and coal seems to pose more. First, the combined ash has a lower melting temperature than either ash taken separately, and this property results in the formation of slags. These slags increase the difficulty and expense of ash removal, further reduce heat transfer, and adversely affect grate performance (Fryling 1967, pgs. 27-4 to 27-5; Babcock & Wilcox 1963, pg. 19-7; Battelle 1976, pg. 54). Second, while markets exist for some coal ashes,[19] and wood ash is, at the very least, an environmentally innocuous substance, the combined ash would seem to possess neither of these advantages. Not only is there the possibility that hazardous substances are contained in concentrations that require special (and costly) handling and disposal, but there is little industrial experience with this material and, to the author's knowledge, no commercial applications.

2. Atmospheric Pollutants[20]

The Clean Air Act of 1963, as amended, regulates the discharge of atmospheric pollutants from fixed installations. Six pollutant categories are defined by the Act[21] and, for each, a primary and secondary air quality standard is established. The primary standard is an emission limit designed to protect human health, while the more stringent secondary standard is designed to protect human welfare and property values. Each state is charged with adopting an implementation plan for achieving the federal standards and for enforcement of this legislation within its own boundaries. In addition to establishing national standards for the six pollutant categories, the Clean Air Act authorizes the Environmental Protection Agency to identify and regulate other hazardous pollutants which may be of isolated concern (e.g., mercury and asbestos), and to develop "standards of performance" for new stationary sources of atmospheric emissions. It is in this second area that federal regulations affect construction or modification of energy conversion systems in the pulp and paper industry.

One of the industrial categories regulated under the "new sources" clause is fossil fuel-fired steam generating plants. Although new source standards have not been adopted under the act for wood-fired installations, it will be instructive to consider the comparative emissions of wood and fossil fuels for the pollutant categories defined. Additionally, the state laws that *do* regulate wood combustion emissions, while establishing varying limits, generally address these same pollutant categories.

The federal new source standards for fossil fuel-fired steam generators and refuse incinerators are given in Table 4. Note that the three pollutants of potential concern are particulates, sulfur dioxide, and nitrous oxide. These pollutants and the contribution of wood combustion to their formation are addressed below.

a. Sulfur Dioxide[22]

Of the three pollutants that have been discussed, sulfur dioxide, poses the most serious environmental threat: affecting not only the health of humans, plants, and animals, but acting as a corrosive agent to fibers and metals as well (Battelle 1976, pg. 86). Most man-made sulfur dioxide is produced through combustion of naturally occurring sulfur compounds that are found as constituents of ores or fossil fuels. Seventy percent of the total results from the combustion of coal alone, but significant quantities of sulfur dioxide may be released during combustion of residual fuel oil as well.[23]

TABLE 4

Standards of Performance for New Stationary Sources

Fossil fuel-fired generators larger than 250 million BTU/hour input:

Particulates - 0.10 lb/million BTU
- 20% opacity (40%, 2 min./hour)

Suphur Dioxide - 0.80 lb/million BTU
- 1.20 lb/million BTU

Nitrous Oxides - 0.20 lb/million BTU (gas)
- 0.30 lb/million BTU (oil)
- 0.70 lb/million BTU (coal)

Incinerators having grater than 50 tons per day charging rates, of which greater than 50 percent is refuse:

Particulates - 0.08 grains/Standard Cubic Foot (12% Carbon Dioxide)

Source: 41 Federal Register 24885, June 21, 1976; as quoted in Gillespie (FPRS 1976, pg. 146).

Given our national objective of increased reliance on domestic coal as a means of reducing consumption of foreign oil, the problem becomes one of balancing environmental costs with cost savings that may be possible with such fuel substitution. Sulfur dioxide emissions can be reduced drastically through use of low-sulfur coal (coal having less than 1 percent sulfur) but, unfortunately, the bulk of these deposits is concentrated in the West: away from population centers and energy requirements. In the eastern region, only West Virginia and eastern Kentucky possess significant deposits of low-sulfur coal. And, of course, costs are high because of strong demand and limited supply.[24]

Aside from low-sulfur coal substitution, several methods of sulfur dioxide control exist:

High Stacks. The greatest concentrations of sulfur dioxide are found in the immediate vicinity of the facility emitting the pollutant, where atmospheric conditions may cause the gas plume to bend back to earth before it has had sufficient opportunity for dispersal and dilution. The obvious solution to local problems has been to erect higher stacks[25] and spew the pollutants out over a wide area (preferably, beyond political boundaries[26]). One result of this control method has been the increased incidence and severity of "acid rain," which has destroyed aquatic life in areas of the northeastern United States and southeastern Canada.

Stack-gas Cleanup.[27] Combustion exhaust gases may be cleansed of sulfur dioxide (with an efficiency of 80 to 85 percent) through the costly process of "scrubbing." The gases first are cleaned of particles and then thoroughly mixed with an alkali solution that works chemically to absorb the sulfur dioxide. The process may be a regenerative one in which the SO_2 is recovered as elemental sulfur or sulfuric acid, and the absorbing medium is regenerated or recycled. Or, it may be a throwaway process in which the SO_2 and alkali react to form a "scrubber sludge" of insoluble sulfates and sulfites of calcium. This latter method has proven most economical, but has the disadvantage of converting atmospheric pollution to solid wastes that also pose a disposal problem.

Physical Cleaning of High Sulfur Coal. The sulfur found in high-sulfur eastern coals generally is distributed into organic and inorganic (pyritic) fractions. While the former portion is bound into coal's chemical structure and is difficult to remove, a significant portion of the latter can be removed by washing or physical cleaning. Battelle (1976, pg. 86) reports that, in general, up to one-third of the coal's total sulfur content can be removed through this method. Unfortunately, the process is expensive and results in an energy loss of roughly 10 percent.

Fuel Substitution. In past years, this method has involved substitution of oil or natural gas for high-sulfur coal. As we have discussed, such substitution requires extensive asset modification, as solid fuel boilers are incompatible with fluid fuels. Modern boilers may be so fuel-specific in design as to experience significant losses in efficiency if low-sulfur coal is substituted for high-sulfur coal (Slack 1979, pg. 17). However, as we shall see, one promising fuel substitution approach that does not require asset modification involves mixing of coal and wood fuel for the purpose of reducing both fuel cost and sulfur dioxide emissions.

It is well established that wood contains negligible sulfur[28] and, thus, that all of the problems that have been discussed are avoided when wood is used as a fuel.

This lengthy discourse on sulfur dioxide's detrimental effects, its virtually unavoidable generation by combustion of certain other fuels, and the costly control measures that are required to meet existing regulations was intended to support Tillman's thesis that environmental regulations have been principally responsible for wood's resurgence in popularity as an industrial fuel. Of all the comparative statistics that have been given thus far, the sulfur dioxide emission statistics are most impressive. With increasingly stringent environmental regulations, the cost of burning high sulfur fuels has increased at a faster rate even than the cost of the fuels themselves.

b. Nitrogen Oxides

Nitrogen oxides are a principal component of smog, and their detrimental effects are similar to those of sulfur dioxide. Fortunately, ambient concentrations of this pollutant are low in most areas, and only Chicago and Los Angeles have found the need to limit emissions from stationary sources (Battelle 1976, pgs. 82-83). To date, control measures have focused upon internal combustion engines - the principal source of nitrogen oxide - but roughly half of man-made emissions originates from stationary sources: 30 percent of this fraction being emitted by coal-fired utility boilers (Yaverbaum 1979, pg. 3).

Nitrogen oxide originates from two sources during combustion: the oxidation of nitrogen compounds in the fuel (fuel NO_x), and the combination of atmospheric nitrogen and oxygen which is induced by high combustion temperatures (thermal NO_x) (Yaverbaum 1979, pg. 3). A fuel's potential for forming NO_x during combustion generally is a function of its nitrogen content. Natural gas contains no nitrogen, so its combustion results only in formation of thermal NO_x. Oil contains some fuel-bound nitrogen and generates slightly higher NO_x emissions, and coal, which generally contains a relatively high nitrogen content, emits the highest levels of the fossil fuels (Yaverbaum 1979, pg. 7).

Although the nitrogen content of wood is low - on the order of 10 percent that of coal[29] - its combustion produces significant quantities of NO_x. Battelle (1976, pg. 95) reports that the nitrous oxide emissions from wood combustion appear to be higher - significantly - than those presently allowed under new source emission standards for coal-fired installations, but concedes that the accuracy of its data is uncertain. The problem would appear to be the manner in which wood is fired. Two of the most promising NO_x control techniques involve reduction of excess air input into furnaces. (See Battelle 1976, pg. 83.) We have seen that wood fuel, especially when wet, must be fired with significantly greater quantities of excess air than are required for fossil fuels. (See footnote 7.) If the problem is related to the method of firing, as seems to be the case, and is not inherent in the fuel itself, relatively inexpensive solutions are possible. (See Yaverbaum 1979, pg. 3.)

In any case, wood fuel's contribution to nitrogen oxide formation remains open to question. Arola (FPRS 1976, pg. 38) foresees no nitrous oxide emission problem with wood fuel combustion; Flick (FPRS 1976, pg. 150) maintains that such problems can be satisfactorily controlled.

c. Particulates

The most serious problem caused by wood combustion is the emission of ash and unburned carbon particles with the exhaust gases. Battelle (1976, pg. 61) cites a study undertaken for the Environmental Protection Agency showing that wood and bark combustion in boilers having no exhaust gas reinjection results in the release of 25 to 30 lb of particulates per ton of fuel. This compares with essentially no particulate emissions from natural gas, negligible quantities from oil (unless heavy residuals are considered), and highly variable quantities from coal, depending upon such factors as ash percentage and method of firing. Comparative wood-coal fly ash generation figures for the Hopewell Mill may be as representative as any. There, the firing of pulverized coal having 15 percent ash is expected to result in production of 255 lb of fly ash per ton of coal fired, compared to 75 lb per ton of wood fired on a grate in the same boiler. The absolute values may be somewhat overstated to ensure that disposal systems are adequate, but the relative magnitudes are interesting. These estimates show pulverized coal generating roughly 3-1/2 times the quantity of particulates that is expected to be produced by wood.

One must remember, however, that wood fuel is less efficient in producing effective output energy than coal. If we consider particulate emissions as a function of effective energy output as opposed to fuel input, we find rough equivalence.[30] Thus, to produce the same quantity of steam, both wood and coal generate approximately the same quantity of ash. This is only an isolated example, of course, and one could expect great variation from case to case.

Regardless of the relatively slight advantage that wood or coal may possess in particulate emissions under given circumstances, control technology is highly developed and collection efficiencies of 99.9 percent are attainable (Battelle 1976, pg. 86).

In summary, while particulate and nitrogen oxide emissions from wood combustion are of sufficient magnitude to be of concern, effective control at relatively low cost appears feasible under existing technology.

C. Energy Conversion Systems

The direct-firing of wood in solid form for the purpose of generating steam normally is accomplished in one of four general types of combustion systems, each of which will be described briefly.[31]

(1) Dutch Oven. Hogged fuel is fed continuously through the top of the furnace and allowed to pile up in a cone. Here, a portion of the fuel is burned and most of the remainder is converted into combustible gas that is directed through the boiler (see Figure 8), where the remaining combustion occurs[32] and heat is transferred to water-filled tubes. This system is able to tolerate relatively high levels of fuel moisture, but efficiency declines rapidly after 45 percent moisture is exceeded. The Dutch oven was the most popular type of boiler for producing useful energy from wood prior to World War II, but its operation is labor-intensive and its combustion efficiency is low when compared to modern systems.

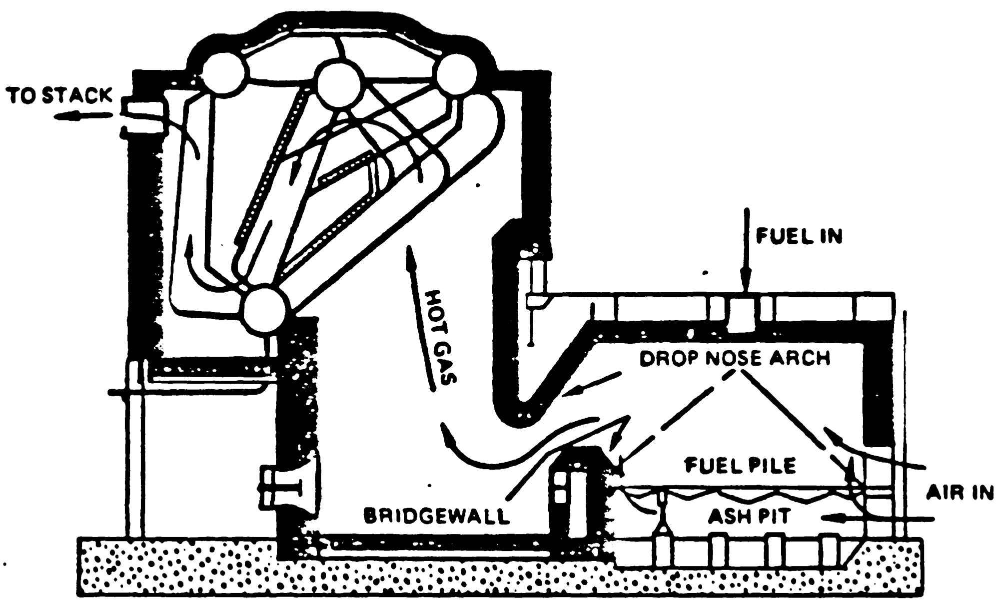


FIGURE 8

Two-Stage Dutch Oven Furnace

Source: MITRE 1979, pg. 14

(2) Spreader-Stoker. Today, the most widely used boiler for converting wood into usable energy is the spreader-stoker. Wood fuel in varying-sized chunks is blown into the combustion chamber, where the majority burns in suspension. The remainder falls to some form of self-cleaning or traveling grate, where final combustion occurs. (See Figure 9.) Like the Dutch oven, heat transfer is accomplished by means of water-filled tubes placed in the path of the hot combustion gases. This type of system can handle wood fuel containing up to 55 percent moisture without using supplementary fuels, but, as was the case with the Dutch oven, there is a marked decline in efficiency above 45 percent moisture. The size-distribution of the material being fired is an important consideration in determining combustion efficiency. Usually, efficiency ratings given by the manufacturer specify ranges of maximum and minimum size distribution percentages for a given efficiency.

(3) Suspension-Firing Boilers. This system is similar to pulverized coal furnaces, in that fine particles of dry wood are sprayed into the combustion chamber, where they combust in suspension. For a given steam output, suspension-fired boilers can be made smaller and more cheaply than spreader-stokers, but the fuel requires extensive preparation. Additionally, to sustain high combustion temperatures, it generally is advisable to carry 50 to 60 percent of the boiler's total heat load with fossil fuels.

(4) Fluidized-Bed.[33] Fluidized-bed boilers employ comparatively new technology that involves blowing air through a grate covered with a mixture of inert material and fuel (in a ratio that exceeds 99:1) in a manner that keeps the fuel bed in suspension. (See Figure 10.) Initially heated by oil burners, the hot inert

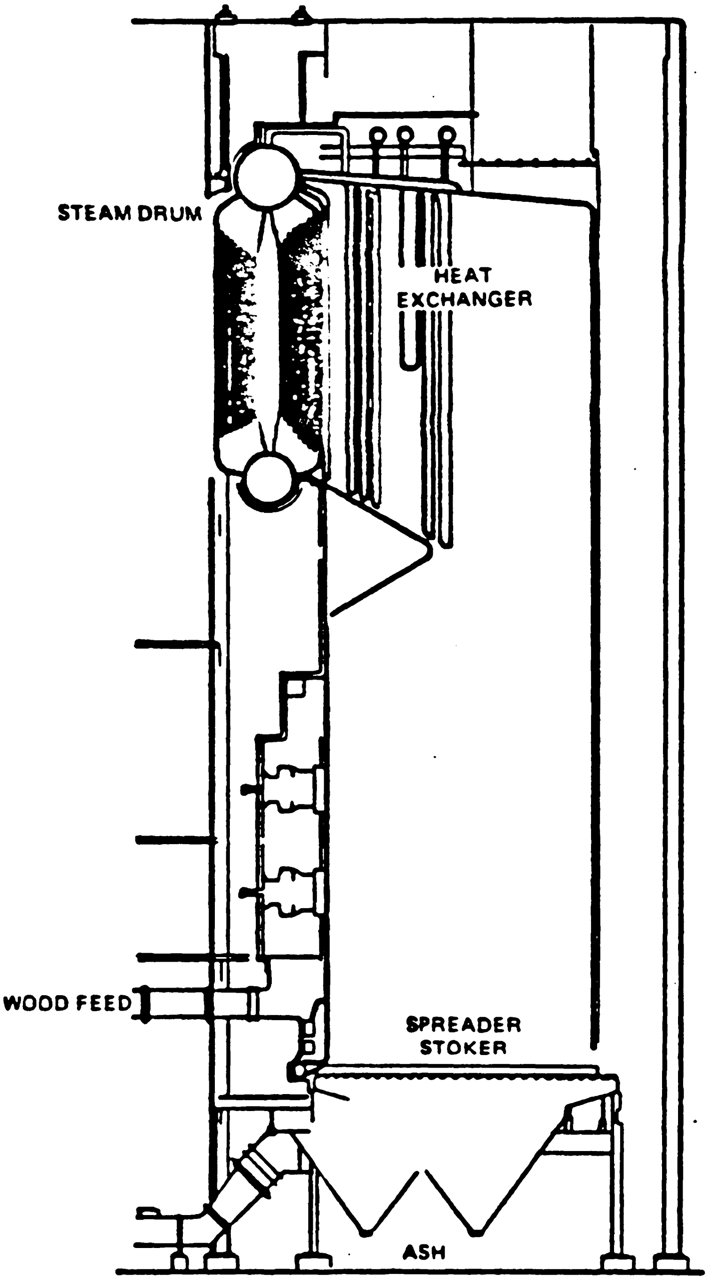


FIGURE 9

Spreader-Stoker Boiler

Source: MITRE 1979, pg. 15

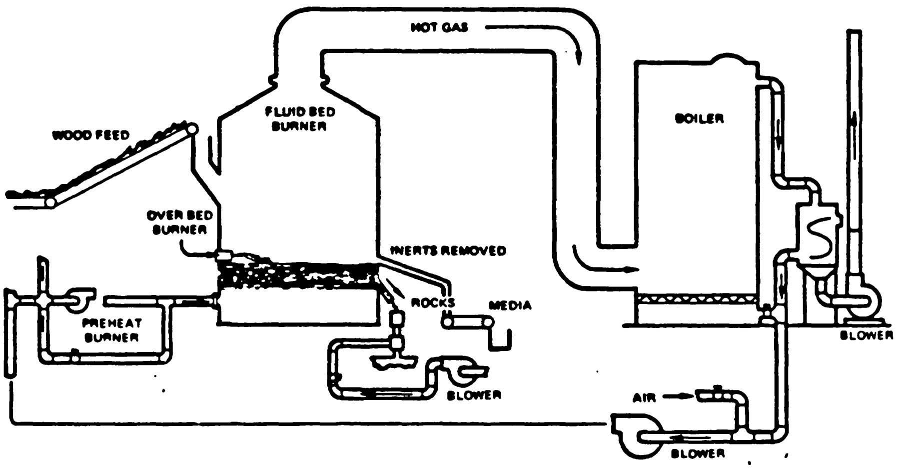


FIGURE 10

Schematic Flow of Fluid-Bed Wood-Fired Steam Generation

Source: MITRE 1979, pg. 16

particles ignite the fuel and absorb much of its heat of combustion. Heat transfer may be accomplished in the traditional fashion with water tubes placed in the path of the combustion gases, or the tubes may be immersed in the fluid bed. This latter approach reportedly results in more efficient heat transfer through direct contact between the tubes and the hot particles. Fluidized-bed boilers have other advantages. They are able to accept non-uniform fuels containing inert material and high moisture: Daman (1979, pg. 50) asserts that black liquor is a good prospect as fluidized-bed fuel. Using this type boiler, combustion temperatures can be maintained below the ash fusion level and thereby inhibit slagging. Most importantly, this system offers a means of substantially reducing sulfur and nitrogen oxide emissions if limestone is used as the bed material.

Although the maximum capacity of fluidized-bed boilers presently is rather small (on the order of 60,000 lb of steam per hour), MITRE (1979, pg. 17) claims that the technology of this process is advancing rapidly. Daman (1979, pg. 47) predicts that this will become the preferred method of firing solid fuels in the future.

D. Conversion to Alternative Fuel Forms

As noted earlier, wood need not be fired in its raw form, but may be processed and converted into fuel forms having more desirable characteristics. Direct firing applications have been afforded central attention here because they appear to offer the greatest economic feasibility in the near term; however, it seems prudent to briefly discuss the principal conversion processes that may become economical under a new set of relative prices or with new technology.

(1) Wood Fuel Drying. Perhaps the simplest means of imparting greater fuel value to raw wood is to remove a portion of its moisture. This process can be as unsophisticated as piling roundwood in stacks, where it reportedly dries to about 25 percent moisture over the course of one year (Sherwood 1978, pg. 8), to densification processes in which the wood not only is dried but also converted into homogeneous pellets having higher density than raw wood. Pelletized wood processing will be addressed separately below.

We have seen that not only does wood's caloric value per green ton increase as water is removed, but also that it may be combusted and converted to other forms of energy with greater efficiency. Sherwood (1978, pg. 8) reports, for example, that the production of a given amount of steam requires nearly 30 percent more energy with wood at 50 percent moisture content than would be needed if the wood were perfectly dry.

Factors affecting the natural drying of wood fuel are not well understood. The optimum wood dimension and storage condition that will promote natural drying most economically are not known, nor are the effects of prolonged storage and drying known for other factors affecting wood's fuel value, such as changes in the volatile-fixed carbon ratio and wood decay.

If green and moisture-laden wood is to be dried immediately prior to combustion, some heat source and drying facility is required that would not be required if the wood were to be burned green. In addition to the added capital investment, such an approach requires that BTUs be expended outside the boiler in order that those generated inside the boiler may be converted to useful energy with greater efficiency. This process would prove cost efficient only under special circumstances:

- "Waste heat" is available from other processing that can be used economically to dry wood fuel prior to boiler loading.

Unfortunately, if an existing mill is being considered, "excess heat" of any consequence already is being used for other purposes, such a pre-heating of boiler feedwater and combustion air. Design engineers place all sorts of heat collectors and "economizers" in the path of exiting gases and liquids to reduce heat losses to the minimum consistent with economy and thereby raise the overall thermal efficiency of the process. The waste heat that is available generally is sufficient only to remove surface moisture from wood fuel (such as would result from open storage in rain or snow) and not that which is present in wood's structure. The benefits of surface water removal probably are insufficient to justify the added capital investment required.

If a new facility is being considered, the marginal benefit that wood fuel drying would contribute should be compared with the marginal benefit of alternative uses of excess heat, such a feedwater pre-heating.

- Wood may be substituted for higher cost fuel in a combination boiler, the extent of this substitution is a function of wood's moisture content, and the cost savings provided by dry wood is sufficient to justify the cost of drying.

An example of this situation might be found in the case of an industrial boiler designed to fire wood fuel and No. 6 oil simultaneously. The quantity of wood fuel that may be fired at a given time is constrained by the boiler's grate capacity, and steam demand not satisfied by wood must be produced with, let us assume, higher priced oil. It is quite conceivable, under these circumstances, that the cost of additional oil that dry wood fuel could replace would be sufficient to justify, for example, the use of additional wood fuel as a heat source in an external drying facility. The economic feasibility of such an arrangement would depend on the physical constraints of the combination boiler and its supporting fuel and ash-handling systems, the price differential of the alternative fuels, and the cost of installing and operating the drying facility.

(2) Pelletized Wood. The densification process involves conversion of wood into small pellets of uniform size and low moisture content. The product that emerges reportedly has a density of about 1.3 times that of raw wood, is easily handled and metered (relative to hogged fuel), has reduced bulk for lower transport cost, has lower moisture (approximately 12 percent of total weight) for greater heating value, and can be sold competitively with fossil fuels in some parts of the country (MITRE 1979, pgs. 36-37). Its heating value is comparable to some lower grades of coal and, as we have discussed, ash and emissions are more acceptable from an environmental standpoint. Disadvantages include a requirement for covered storage, less handling convenience than fluid fuels, and lower heating value per unit of volume than average grades of coal (MITRE 1979, pg. 37). Pelletized wood can be used in existing wood-fired boilers, or in boilers designed for pulverized or stoker coal.

(3) Pyrolysis.[34] Pyrolysis, or destructive distillation of organic material, is carried out by heating in the absence of oxygen. The products of pyrolysis are charcoal, volatile gases that may be condensed into a synthetic oil, and non-condensable gases having a heating value of roughly 30 percent that of natural gas.

The product mix is dependent upon the temperatures at which the conversion is carried out: at low temperatures charcoal predominates, while higher temperatures yield more oils and gases.

Although a number of pyrolitic processes are available commercially,[35] the Tech-Air system has received the most attention in forestry literature. Without going into the details of the process, it reportedly results in the following product mix per ton of dry wood input:

Product	Volume of Product Produced per Ton of Dry Wood	Energy Content	Percentage of Total Output Energy
Char	460 lb	13,000 BTU/lb	39
Oil	600 lb	9,900 BTU/lb	38
Gas	12,000 ft^3	300 BTU/ft^3	23

Source: Tillman (1978, pg. 109)

Disregarding non-wood energy inputs into the system (e.g., electricity), the thermal efficiency of the process reportedly is 80 percent.

(4) Gasification.[36] The gasification of wood is accomplished through heating in the presence of oxygen at sufficiently high temperatures to limit production of oils and char. If the wood is decomposed by heating in the presence of air, a mixture of combustible and non-combustible gases is generated that has a heating value of approximately 150 BTU/ft^3. This low-BTU gas must be used on-site; that is, it must be combusted immediately after being produced if excessive energy loss is to be avoided. If pure oxygen is used in place of the air, a medium-BTU gas (300-350 BTU/ft^3) can be produced. This latter process is slightly more efficient

than the former, and the gas that is generated can be stored for short periods and transported over modest distances. The principal drawback to medium-BTU production is the cost of the oxygen generating facility, which may account for 40 to 45 percent of the total capital cost of the gasification plant. Additionally, Tillman reports that the efficiency of both processes is as vulnerable to wood moisture as combustion efficiency.

(5) Liquification. While much attention has been given in the literature to production of such liquid fuels as methanol and ethanol from wood, the processes do not appear to be cost competitive in the present market. Due to wood's complex structure, the thermochemical processes involved are carried out with greater efficiency and at lower cost when other materials are used as a feedstock. The magnitude of this differential can be seen from a glance at the processes required to produce methanol from wood *versus* those required when natural gas is used as the raw material. (See Figures 11 and 12.) Similar statistics can be shown for ethanol production, but suffice it to say that the product enjoys a decided cost advantage when ethylene or grain is used. (See USFS 976, pg. 163.)

Other systems transform wood entirely into heavy oils, but relatively complex processes are involved, conversion efficiencies are low, and the resulting products exhibit combustion characteristics that make them less valuable than petroleum (Tillman 1978, pg. 116).

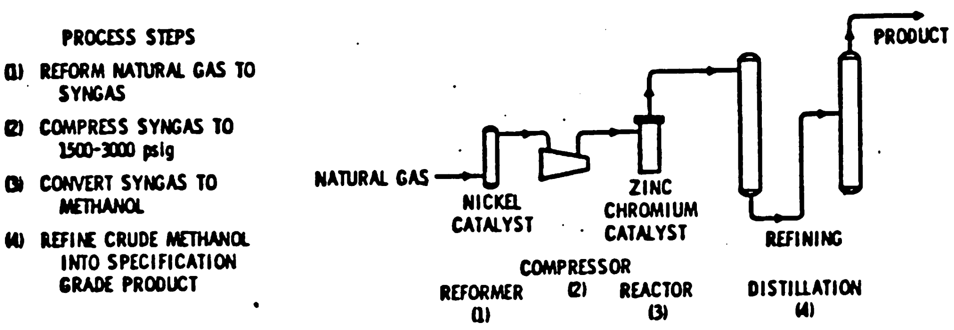


FIGURE 11

Methanol Synthesis from Natural Gas

Source: USFS 1976, pg. 147

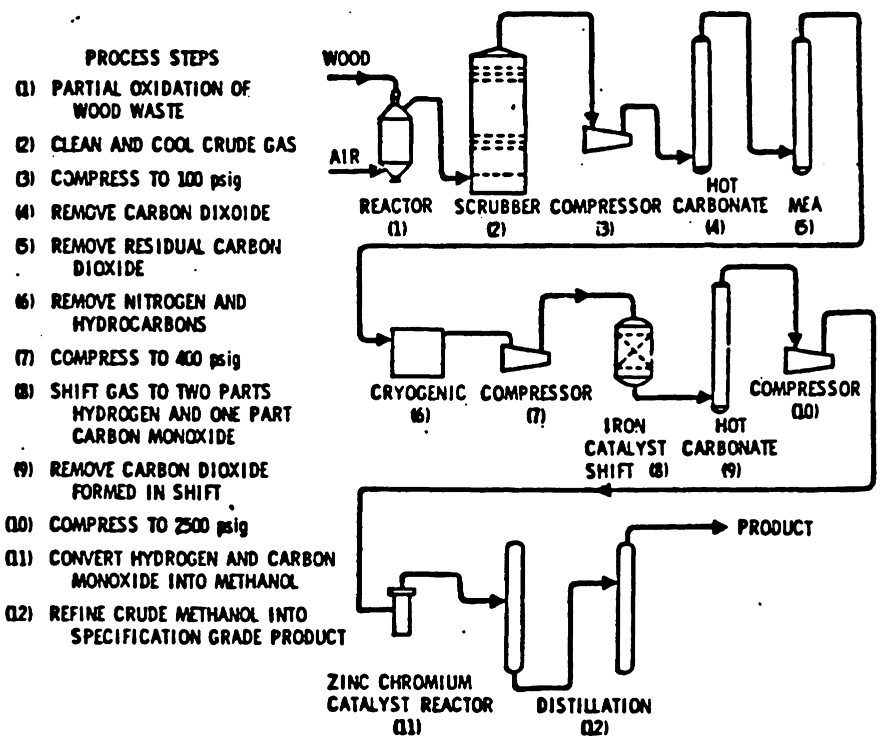


FIGURE 12

Methanol Synthesis from Wood

Source: USFS 1976, pg. 151

Comparative Efficiencies of Conversion

Tillman (1978, pg. 118) provided rough thermal efficiencies for the processes that have been discussed, from fuel form conversion through combustion and useful energy recovery:

Process	Thermal Efficiency After Combustion (%)
Direct combustion	70
Pyrolysis	70
Gasification	70
Methanol production	30
Heavy oil production	30

This ranking agrees with MITRE's assertion that the first three processes are the only ones showing economic promise for the near future. But even given comparable conversion efficiencies, the process of converting wood to other forms prior to combustion is a more costly proposition than burning it directly, and the advantages that can be realized from these alternate fuel forms do not appear to outweigh the costs in the present market. (See MITRE 1979, pg. 33.) Far more promising appear to be methods of fuel drying that would rely on solar energy and time to significantly increase the value of the wood fuel.

E. Summary

We have seen that green wood has the heating value of a low-grade fuel that is able to provide roughly one-third the effective energy of bituminous coal when fired directly. Hogged fuel is bulky and unwieldy in comparison to fossil fuels, and its relatively low value prevents it from being transported economically over long distances. It is in the environmental area that wood fuel displays its greatest relative advantage. As wood contains negligible quantities of sulfur, its combustion does not generate the high sulfur dioxide emissions that plague most coal and residual fuel oils. While nitrogen oxide and particulate emission levels may exceed those of coal and oil, these pollutants at least are controllable under existing technology at reasonable cost. Wood ash does not contain the high heavy metals concentrations found in some coal ashes, and its disposal poses few environmental problems. Indeed, as a soil amendment and fertility agent, it may well prove beneficial.

While conversion to fluid fuel forms does not appear justified under present economic conditions, wood can be fired in its solid form in a number of different types of combustion systems. The spreader-stoker boiler currently is most prevalent, but advances in fluidized-bed technology may cause this process to become commercially important.

III. WOOD FUEL SUPPLY

A. Introduction

With the advent of the energy crisis in 1973, considerable attention has focused on the feasibility of using wood as a "renewable" energy alternative to fossil fuels. The feasibility of such application hinges upon questions of wood fuel supply: For a potential customer at a given location, what fuelwood quantities are available at what price? How competitive is this price with expected prices of alternative fuels? From what sources would fuelwood be derived, and with what impact upon the availability and price of other timber products? These questions are complicated by the fact that wood has utility for myriad non-energy applications which may compete for the same raw material. Wood fuel supply may not be considered apart from supply-demand relationships of other timber products. This section investigates the economic forces that interact to establish the price and quantity of wood that will be supplied as fuel.

With regard to possible sources of fuelwood supply, two paths of investigation have emerged: (1) the use of so-called residual wood (to include some standing timber) that has proved unsuitable for use as a source of fiber, and (2) the production of fuelwood on energy farms where the silvicultural objective would be production of "biomass" as opposed to timber having desirable fiber characteristics. While energy farms hold some promise for price-competitive production of energy feedstocks in the future, their establishment on a broad scale must await developmental research and commercial adaptation (MITRE 1977, vol. 1, pg. 3). For the near term (through the year 2000), significant supplies of fuelwood must depend upon existing raw material sources. It is upon these sources that our discussion will focus.

Estimates abound regarding the volume of wood residue[1] of one form or another that exists within given regions and industries, and the energy value that such volumes represent. In general, the physical supply of residue is afforded central attention, while the *economic supply of wood fuel* is ignored.

The cost comparisons that are made between this residual wood and alternative fossil fuels often fail to consider *all* of the costs involved in converting the fuel to useful energy. The fundamental problem is that a BTU in one fuel does not equate economically to a BTU in another: they are not worth the same on the market. This inequality results from at least four factors:

(1) All fuels may not be converted to usable energy with equal efficiency.

(2) The variable costs of energy conversion are not the same for all fuels.

(3) The capital investment required for energy conversion assets varies markedly among fuels.

(4) All fuels are not equally suited for all applications.

Thus, such statements as:

> *Sufficient additional wood fuel is potentially available in the near term to replace all of the oil and natural gas used*

> *annually by the forest products industry at a cost of $0.75 to $1.50/MM BTU ($4.50 to $9.00 per barrel of crude oil, 1976 dollars).*
>
> (MITRE 1979, pg. ix)

are unclear and require amplifying information. Which costs have been considered? If MITRE speaks only of the cost of energy in fuel, while ignoring the cost and efficiency of conversion, then its cost comparison is misleading.

Ethical arguments are advanced from some quarters to justify singular attention on residues as an energy source. Tillman (1978, pg. 198) adopts the principle laid down by Glesinger in 1949 that "no wood that can serve some other useful purpose should be burned,"[2] and eliminates from consideration as available supply the portion of the wood raw material that is forecast to be demanded by the fiber industries.

It is clear that rising fossil fuel prices will increase wood's value as a fuel and, in consequence, bring about increased demand for fuelwood. Even so, the price differential is widely regarded as being too great to allow users of wood for fuel to compete successfully for the same raw material with those who would use wood as a source of fiber. In addressing the question, "Will steadily rising energy costs have an effect on timber supply?", Wisdom (1978, pg. 78) notes that the maximum price that could be paid for fuelwood and still leave it competitive with fossil fuels is substantially below current market prices for pulpwood and sawlogs. He concludes that tomorrow's wood fuel supply will be derived from unutilized wood: that "efforts to increase the use of wood for fuel will have little, if any, impact on the timber supply."

The magnitude of this energy-fiber price differential in 1976 is illustrated by the following table:

Product	Relative Sales Price Index
Lumber	100
Pulpwood Chips	25
Sawdust and Shavings	5
Hogged Fuel	2-1/2

(Christensen in Forest Products Research Society 1976, pg. 41)

Such a relative price structure is purported to demonstrate the economic forces that work to persuade the rational sawmill operator to maximize his output of the higher-valued joint products of the wood raw material at the expense of the lower-valued ones. Sawmill efficiency is measured in terms of "solid wood recovery."

B. Forces Influencing the Supply of Wood Fuel

Three forces influencing wood fuel supply do not seem to be clearly understood.

1. Profit, Not Revenue, Guides Employment of Input Factors

In considering joint-product competition for raw materials, we must not look exclusively at the revenue that each product is expected to generate, but also at its production costs, for it is the *difference* between costs and revenues; i.e., profit, that guides allocation of input factors in our economy. Given some quantity of raw material, the rational sawmill operator should not harbor the objective of maximizing the output of high-valued products or the proportion of "solid wood recovery," but should, through his choice of the mix of joint-product outputs, attempt to maximize the excess of total revenues over total costs (or minimize the excess of total costs over total revenues in a loss situation). He accomplishes this feat by setting his level of output at the point where the additional revenue to be derived from the last unit of output is equal to the additional cost.

Given this overall objective, and given that the forest products industry does not deal with homogeneous input factors, what production decisions are relevant to each unit of input (e.g., each log)? That is, how should each unit be processed to enable the producer to achieve his goal of profit maximization? The answer is apparent to any sawmill operator. For each unit of input, the profit-maximizing producer should select his product mix so that the revenue to be derived from its sale exceeds the production costs by the greatest possible margin; that is, he should attempt to maximize the excess of marginal revenue over marginal cost[3] for each log. Quite obviously, no log promising conversion costs in excess of product revenues should be processed. Production proceeds to the point where no additional log can be found for which the marginal revenue to be derived from conversion to any feasible product mix exceeds the marginal cost. At this point, profit is maximized (or loss minimized).

2. Within Each Product Category are Grades of Marginal Profitability

The illusion is presented in Christensen's table that we deal with homogeneous products, each of which may be assigned a single relative value: that *all* lumber has a relative value of 100, for example. In fact, each product category contains a range of grades, each of which may have a different market value. The value given in the table merely represents the price of the average grade.

Within each product category are grades that are only marginally profitable to the producer. These grades are of comparatively low market value, while requiring essentially the same conversion costs to be incurred as the higher-valued grades within the product category. For example, pulpwood chips, by virtue of different degrees of contamination with bark and grit, more- or less-desirable species, more- or less-favorable economic location, time and circumstance of storage, physical dimensions, and so forth, have different value as a source of pulp fiber. There exists a grade of pulpwood chips for which the spread between revenue and production cost is only slightly greater than this spread would be if the raw material were produced and sold as wood fuel. Given slight improvement in the relative profitability of fuelwood, it will be in the economic interest of the producer to substitute wood fuel production for pulpwood production.

Once we accept the existence of the marginally-profitable grade within each product category, we find that joint-product substitution will occur at the boundary separating the products in response to changes in relative product prices or costs. Now, this is not to say that output of the product that has enjoyed an increase in relative profitability will be increased *only* at the expense of the higher-valued product. The margin shifts both ways. Higher relative profitability for chips will stimulate chip production: part of the increase will be derived from marginal sawlogs and part will come from marginal pulpwood.[4] But, lacking institutional constraints, the margin is just as likely to shift in one direction as the other: it follows the path of least cost-resistance.

What does all of this have to do with fuelwood supply? Quite simply this: Other things equal, if fuelwood's value and profitability improve relative to the other joint-products of the timber raw material, the market will respond by providing additional fuelwood. This added quantity will be derived not only from residue, but from raw material currently used as an input in production of other products, most notably, pulpwood. The diminished supply of pulpwood will work to drive up its price.

One caveat is required. The incentive always exists for the producer to modify his product output mix to increase profitability. For example, regardless of minor shifts in relative value among the joint-products of the log, it remains in the economic interest of the producer to find ways of reducing saw kerf, thereby increasing production of all lumber at the expense of all sawdust. This force is induced by the *existing* profitability structure among joint products and does not confine its effects to profitability margins. The force that we have been discussing, on the other hand, is induced by *changes* in the profitability structure that result in raw material substitution at the margins.

3. An Increase in the Profitability of One Joint-Product of the Log Will Result in Increased Supply of All

Rising fossil fuel costs increase wood's value as a source of energy. Accepting this contention, consider the marginal sawlog or pulpwood stick (or trees from which they are derived). This log, because of its form, size, species, or location, has a conversion-surplus value of zero. That is, its variable costs of conversion to final products are precisely the same as the incremental revenue that the products of this log will provide. Its conversion then becomes entirely a matter of indifference to the producer: the log is just as likely to be downgraded to forest residue as it is to be hauled to the mill and processed. Note that the revenue that this log provides is not restricted to the market value of the principal products of the log, but includes the aggregate values of all of them. Higher prices for fuelwood, other things equal, will increase the total revenue to be derived from the marginal log, cause its conversion-surplus value to become positive, and result in its transfer from the forest residue category to the pulpwood or sawtimber categories. Thus, the increasing value of wood fuel may work to *add to* quantities of pulpwood and sawtimber supplied.

The same phenomenon is evident in the case of wood chips produced by the sawmill. Formerly considered a waste byproduct of lumber production, the value of chips as a source of pulp fiber has increased to the point where some sawmill operators are heard to say, "Chips keep me in business." Revenue from chips not only provides the financial incentives necessary to bring about the supply of low-quality sawtimber, but also enables the marginally profitable sawmill to remain in operation. Thus, the quantity of sawtimber supplied is increased by higher prices for chips.

Note that the forces described in 2 and 3 above are activated simultaneously by shifts in relative profitability and, while both work to increase supplies of products enjoying higher relative profitability, they oppose one another in their effects on supplies of other joint products. Given an increase in the profitability of fuelwood relative to other joint products, for example, the substitution force (2 above) will cause raw materials at both the upper and lower fuelwood profitability margins to be diverted to fuelwood production. The complementary supply force (3 above), on the other hand, will result in an increased flow of raw materials at the lower profitability margins of all products having residue as a joint product (virtually all wood products). The effect of the substitution force will be to increase competition from fiber-wood and increase fiber-wood prices, while the complementary force will increase fiber-wood supplies and reduce fiber-wood prices.

C. Institutional Constraints Affecting Market Interaction

Institutional constraints are conventional practices or traditions in the forest products industry that impede market interaction. A policy of not accepting pulpwood sticks having a small-end diameter of less than 4 inches would be an example of such an institutional constraint. Given a relative increase in the profitability of pulpwood, such policy would tend to inhibit the response of producers to deliver marginal raw material. Any raw material differentiation or categorization based on physical characteristics alone - unyielding to shifts in relative profitability - would be an institutional constraint. Policies of maximizing solid wood recovery as opposed to profits would be an example of an institutional constraint in the sawmill, as would a policy of establishing an invariant mix of species for pulpwood in the pulpmill - regardless of relative costs.

These institutional barriers would tend to distort the margins that exist between grades and products, and hinder the market response of raw material substitution in response to shifts in relative profitability.

D. The Economic Supply of Fuel Wood

Wood fuel is defined here as wood for which the highest valued use at the moment of consumption is as a source of energy. This is strictly an economic definition, not a physical one. Thus, wood fuel is not, as contemporary literature sometimes infers, the physical supply of manufacturing residues or cull-hardwoods or some other such physical category. The highest valued use of a given wood category is reflected in the relative prices of the moment.

At this point, a discussion of the term "*value*" is in order. In Chapter 2 we spoke of *fuel value* as wood's physical properties that affect its utility as a source of energy. Fuel value is a major determinant of *market value* - the amount that consumers stand ready to sacrifice - but, certainly is not the only factor, and may not be the primary one. Other considerations that have been discussed include capital requirements for handling and energy conversion, combustion efficiency, and environmental constraints. *Conversion surplus* is a type of financial value that has been defined as value in production: the contribution to fixed costs and profits provided by a given unit of wood input. Generally, conversion surplus value exceeds market value. The firm cannot afford to pay conversion surplus value for its wood and remain a viable entity over the long term. There would be no return on invested capital.

Later, we will use "value" in yet another sense when we define *return-to-capital* and *relative fiber* values. Both will be indices of contribution to net revenue resulting from use of a given wood type, and both will attempt to account for differences in the permissible rate of wood input caused by wood's physical properties. These terms will be defined more fully in a later section.

Wood fuel, like the other products of the log, is non-homogeneous and comes in a wide variety of grades. Each grade may have different utility to consumers as a source of energy: utility based primarily, though not exclusively, upon wood's recoverable energy content. Recoverable energy varies with such factors as species, portion of the tree from which it is drawn, time and circumstance of storage, and so on; but most importantly from a practical sense, with moisture content. Some grades, particularly the dry ones, have higher utility and, in consequence, higher value as fuel than others.

1. The Nature of Wood Fuel

The fundamental problem that we face in addressing the question of wood fuel supply is that we deal with a commodity that is simultaneously product and residue. *Production* of the commodity that is sold and consumed as wood fuel is partly by design and partly by default: by design in response to price on the wood fuel market, and by default as the unavoidable result of the conversion of other timber products. If these woods and manufacturing byproducts were to have zero market value, some quantity would continue to be produced anyway.

As soon as a producer recognizes that his byproducts have market value, he will consciously take account of their potential revenue in (1) selecting the raw materials that he will process, and (2) determining the product mix that he will produce (the one that maximizes conversion surplus, if constant wood input is assumed). His "residue" acquires full status as a joint product of the log. The problem is that the residue's low value relative to the other products causes its price to be very much overshadowed by other factors in determining the quantity that he will supply per unit time.

To illustrate the problem, let us consider the production of manufacturing byproducts[5] the highest-valued use of which is as wood fuel. This source provides virtually all of the wood energy used in the forest products industry and roughly 70 percent of wood energy nationwide.[6]

The physical quantities of manufacturing byproducts that are produced over a given period will depend upon four factors: (1) the *output of wood products* that generates these byproducts, (2) the *technology* by which the process conversion is made, (3) the *quality* of the timber raw material, and (4) *price* on the byproduct market.

The effect of the first of these variables is self-evident: The output of byproducts is positively correlated to the output of products that generate them.

The technology variable describes the quantity of primary products that may be derived from timber raw material of given quality. It may be illustrated by saw kerf: the greater the saw kerf, other things equal, the greater the production of manufacturing byproducts (in this case, sawdust). This variable also deals with the *redefining* of primary timber products as a result of technological change in production processes for which these products are inputs. Thus, for example, the "upgrading" of whole-tree chips from wood fuel to pulpwood status by improve ments in pulpmill washing technology would be considered under this technological variable.

The timber quality variable influences byproduct production by describing, for a given technology, the proportion of raw material input suitable for conversion into a given primary product. In general, the lower the quality of the raw material input, the greater will be the output of wood byproducts. The combined effect of *both* the technology and quality variables can be measured as the ratio of primary product output to timber raw material input.

Finally, price in the byproduct market will affect the output of wood byproducts in two ways. First, price changes in the byproduct market determine the fate of the marginal log, thereby affecting the *quality* of the raw material delivered for conversion. As byproduct price goes up, wood quality goes down, and increased byproduct output results. Second, price changes on the byproduct market, *ceteris paribus*, increase or decrease the relative profitability of byproduct production *vis-a-vis* the other joint products of the log, and result in substitution of raw material input at both the upper and lower profitability margins. Both of these forces have been discussed at length.

Also discussed has been the force that ultimately allocates input factors to end products: this producer's desire to maximize profits or, disregarding fixed costs and revenues, and assuming a constant permissible rate of wood input, to maximize the raw material's conversion surplus value. This force is evident at each stage of the timber products conversion process at which production decisions are made.

Beginning with standing timber - stumpage - the producer, or his agent, sizes up conversion surplus potential as the difference between revenues to be derived and variable costs to be incurred from conversion of the raw material to the product mix promising highest profitability. If this differential proves to be both positive and sufficient to cover stumpage cost, then it is in the interest of the producer to buy and process the timber. Note that it is the *combined* revenue expected from sale of all products in the timber's optimal product mix that is used to overcome the variable costs of procurement and conversion. The producer considers joint-revenue and joint-cost possibilities. No one product must shoulder the entire production cost burden until such time as it becomes a separate entity in the process of manufacture. Thus, for example, if lumber and pulpwood chips are joint products, the one's costs of procurement and processing are partially subsidized by the other's.

The *degree* to which wood fuel's costs of procurement, processing, and energy conversion are shared by other products will greatly influence its variable cost and, in consequence, its market price. We can establish a continuum for various sources of wood fuel on the basis of this subsidy, or degree of cost-sharing, as shown in Figure 13.

To the left on the continuum, we deal with commodities displaying economic properties best described by the residue label. Levels of production and consumption of black liquor solids (dissolved organics produced as a by-product in the pulping process), for example, are little influenced by price on the wood fuel market. The costs of black liquor production, conversion to fuel form (accomplished through primary evaporation), and energy conversion are borne jointly with another joint product: wood pulp. Thus, the cost of black liquor *as an*

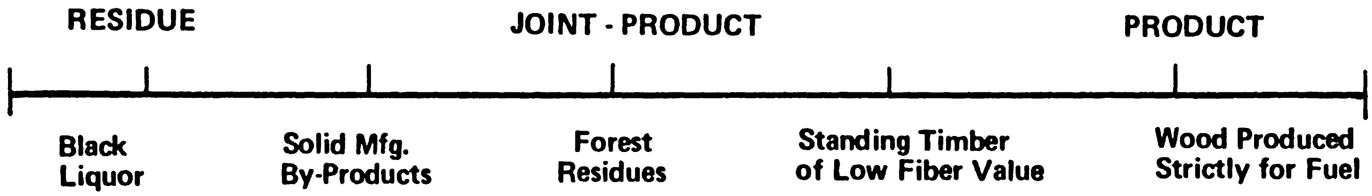


FIGURE 13

Wood-Form Categorization Based on the Degree to Which Production and Conversion Costs are Shared with Other Products *energy source* is low because its costs of production and conversion are subsidized by production of pulp and paper.

At the midpoint of the continuum, we find forest residue: a commodity labeled as a joint product. In this case, the costs of raw material procurement and separation from the other products of the log are borne jointly by all timber products. Additionally, costs of access roads, on-site labor and equipment, etc. are shared, such that only the scale of operation need be expanded for residue collection. However, as the potential wood fuel is separated earlier in the conversion process than, for example, manufacturing byproducts, greater wood fuel production costs must overcome. While manufacturing byproducts receive a subsidized ride to the mill on the backs of other products and are converted to fuel form largely by default in the process of other production operations, forest residue must pay its own way. The revenue derived from "forest residual fuel" must cover significantly greater costs of production, processing, and transportation than commodities to its left on the continuum, and, in consequence, one would expect its market price to be higher.

To the far right on the continuum, we find timber that is planted, managed, harvested, processed, delivered, and converted solely by virtue of wood's value as an energy source. There are no joint products to share the costs of production and energy conversion; there is no "subsidy" provided.

In general, production and conversion costs increase *relative to* fuel value as one moves to the right on the continuum; progressively more of these costs must be absorbed by the revenue provided by wood fuel. As one moves right, wood fuel's production and supply are found to respond more to price fluctuations on the wood fuel market and less to forces on other wood products markets.

2. The Economic Supply of Effective Energy Derived from Wood Fuel

We have noted that wood fuel is not a homogeneous commodity, but includes a number of different grades having varying levels of utility as energy feedstock. Such non-homogeneity poses a dilemma for supply theory development, for it implies that "wood fuels" cannot meaningfully be considered in the same supply relationship. Each grade should be considered as a separate commodity for which a separate supply function applies. Additionally, we already have discussed how wood's utility as a fuel differs depending on its physical properties. One dry ton of dissolved organic material in black liquor will have lower fuel value than one dry ton of forest residuals, for example, because the former has higher moisture.

This latter problem can be avoided by changing the label of the traditional "quantity" coordinates to "quantity of effective energy."[7] This allows us to compensate for differences in caloric value, energy conversion efficiency, and variable costs of energy conversion among the various grades of wood fuel, and to consider effective output energy as the production input factor for which the consumer expends his dollars. All grades of wood fuel are reduced to their *effective energy equivalence*. Points on the curves drawn in such a space correspond, not to quantity of wood fuel offered at a given price, but to the quantity of effective energy that a given firm can obtain from wood fuel for a given outlay. The curve is specific to a given wood fuel production and conversion situation; that is, production and conversion assets, as well as process technology, are assumed to be fixed. Thus, the curves represent a short-run relationship for a given consumer.

One possible set of supply relationships is illustrated in Figure 14. Each commodity has a supply function whose shape depends on the level of subsidy provided by the other joint products of the log. The greater the subsidy, the more price inelastic will be the supply curve. Note that progressively higher prices must be paid for effective energy derived from wood fuel commodities found to be right on the cost-sharing continuum of Figure 13. The order of market consumption corresponds to the level of cost-sharing, with the most heavily subsidized commodities having the lowest effective energy price and being consumed first. The Total Supply curve to the far right is the horizontal summation of the individual commodity curves. This total curve shows a highly price-elastic relationship for effective energy derived from all wood sources.

Each curve in Figure 14 represents the combined marginal costs of producing, delivering, and converting to usable energy the wood fuel category or commodity in question. The input factor whose supply we consider is not the nebulous "wood fuel," but, rather, the effective output energy that it can provide in a given production situation. Effective energy, in fact, is the commodity that must form the consumer's basis for evaluating *any* energy source. The variable costs that he considers should be the total of those required to derive usable energy from a given fuel.

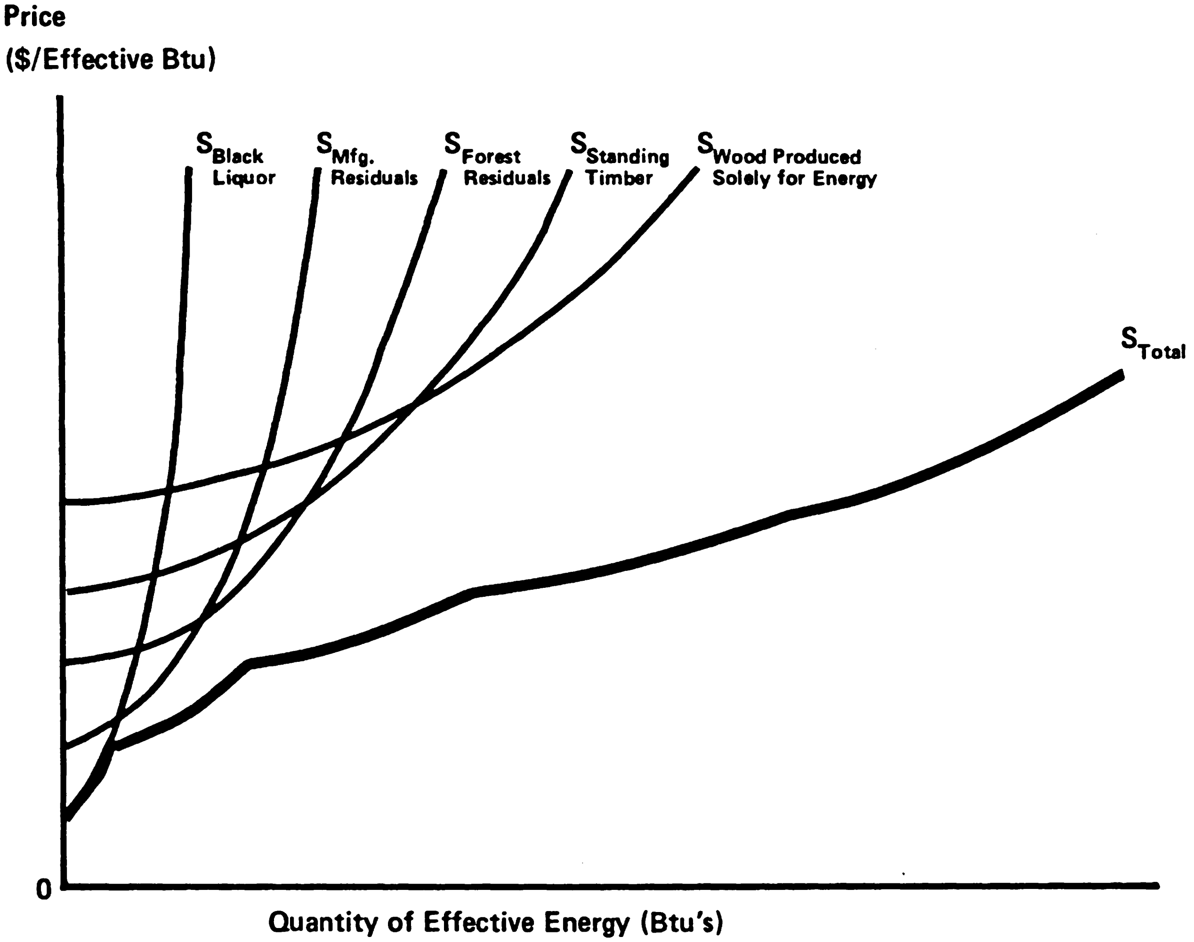


FIGURE 14

Supply of Effective Energy Derived from Wood Fuel

IV. CASE STUDY: THE HOPEWELL MILL

The case study that follows has two main objectives:

(1) To identify the principal energy conversion and consuming processes in a modern Kraft pulp-paper mill and to chart the energy flows between them.

(2) To develop a framework for analysis of a Kraft mill's energy substitution alternatives in the short-run, using the case study mill as a model.

The mill from which the data are taken is Continental Forest Industry's Kraft linerboard mill in Hopewell, Virginia. The Hopewell mill's production and consumption figures should be taken as illustrative of magnitude only. The short-run cost-minimization analysis is designed specifically for Hopewell's situation, and uses as input information that is readily available at this mill.

A. The Hopewell Mill

The Hopewell mill currently produces unbleached Kraft linerboard at a rate of 920 tons per day on its No. 2 Fourdrinier, and unbleached Kraft cylinderboard at a rate of 85 tons per day on its No. 3 cylinder machine. The former product is used in the manufacture of boxboard, and serves as the "liner" that encloses the corrugated medium of the standard corrugated container. The latter product is best described as heavy cardboard, and is used, at least by this mill, primarily in the manufacture of fiber drum ends for chemical transport and storage. Also included in the mill complex is the No. 1 Fourdrinier, which at one time produced corrugated medium from semichemical pulp. This machine and its semichemical pulping facility were closed several years ago due to low profitability, and are not expected to resume operation.

Steam and electrical energy required for mill operation are derived currently from six boilers (three oil-fired, one bark-fired, two black liquor) which, taken together, produce roughly 700,000 pounds of 435 pounds-per-square-inch steam per hour. A portion of this steam flows through two turbogenerators and produces 45 percent of the mill's electrical energy requirements. Unfortunately, these energy conversion assets are old, thermodynamically inefficient, and labor-intensive. The cost of the oil required annually to fuel the power boilers and lime kiln is becoming increasingly burdensome to mill profitability. Since 1972, the cost of No. 6 fuel oil delivered to the mill has increased seven-fold, while the value of the paper product has less than doubled. Almost as dramatic have been increases in the cost of purchased electricity. It became obvious by 1978 that changes were necessary if the mill was to remain profitable.

In that year, the decision was made to invest $138 million to renovate the Hopewell mill, the largest share of the investment to be made in power-recovery assets. The six boilers and two small turbogenerators are to be replaced by two efficient, high-pressure boilers (one "power" boiler for steam production and one recovery boiler used both for steam generation and for recovery and conversion of spent cooking chemicals) and one turbogenerator capable of satisfying the mill's entire electrical demand. The new power boiler is to be fueled with coal and wood, leaving oil to be burned only in the lime kiln. Improvements in No. 2 machine's "wet end" (the portion preceding the dryers) and the pulp mill's washing facility will increase No. 2's design capacity by 16 percent, to 1,000 tons per day.

B. Steam Production and Consumption

The 703,000 pounds per hour of 1,250 pounds-per-square-inch steam that the renovated mill will require for the "average annual day" will be produced in two large boilers, the general operating characteristics of which are summarized below:

	Recovery	Power
Fuel	48 tons black liquor dry solids per hour	10.5 tons pulverized coal and 30 tons bark and sawdust (M.C. = 50%) per hour
Efficiency	0.652	coal: 0.85 bark: 0.75
Steam Output (@ 1,250 pounds-per-square-inch)	366,000 pounds/hour	337,000 pounds/hour

Including the dissolved organic matter combusted in the recovery boiler, wood's contribution to energy requirements in the mill will be approximately 70 percent.

An energy balance for the renovated Hopewell mill is presented as Figure 15.[1] Operation of the mill requires an average hourly input in excess of one billion BTUs, derived from the following sources:

Black Liquor	49%
[2]Wood Fuel	22%
[2]Coal	22%
Oil	5%
Feedwater Makeup	2%

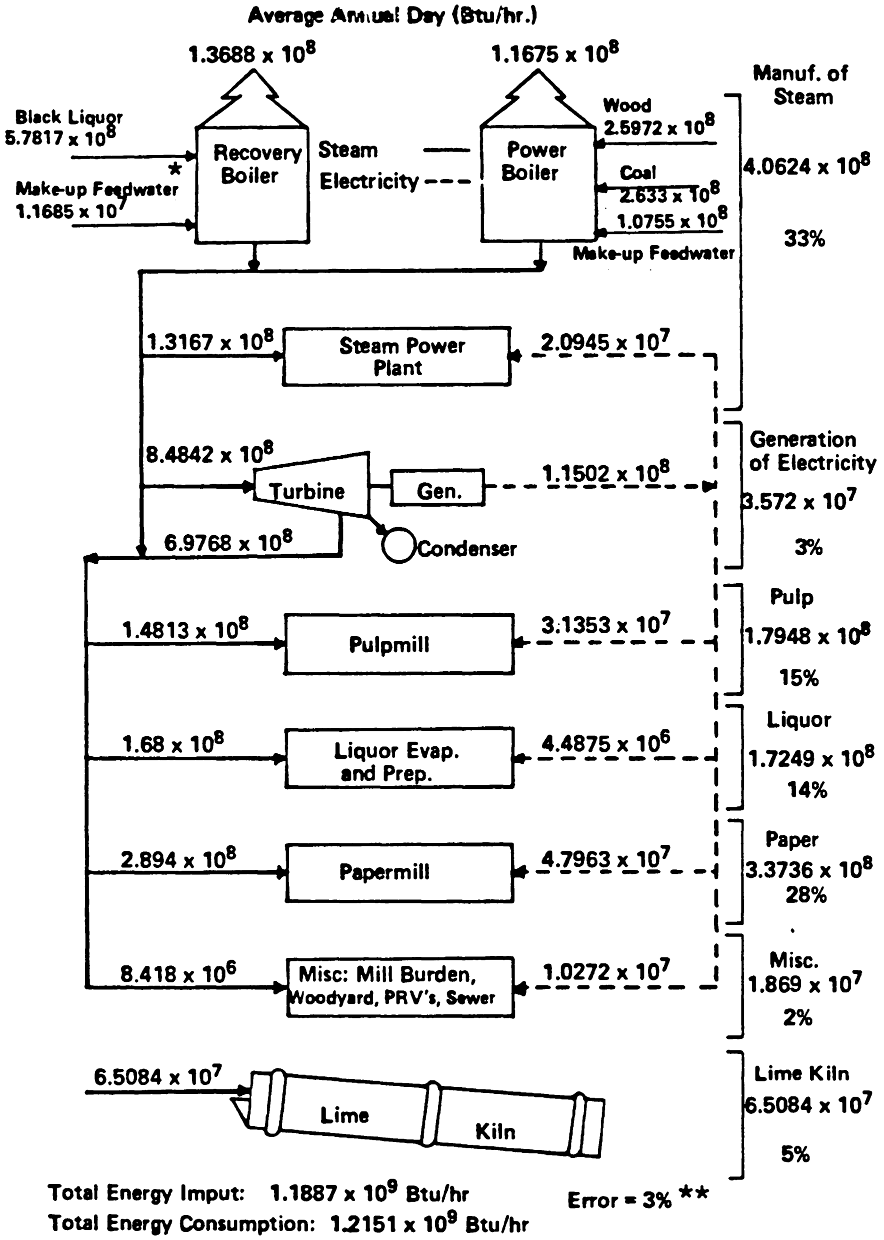


FIGURE 15

Energy Balance for Continental's Hopewell Mill

*This is energy contained in recycled steam condensate.
**Error results from inaccuracies in measurement.

Of the total energy consumed in the mill, one-third is used in the manufacture of steam. Most of this consumption (62 percent) may be attributed to inescapable boiler inefficiencies. The rest is expended in air and feedwater pre-heating and soot-blowing.

The magnitudes of other energy consuming activities in the mill are as shown. Note that the paper mill is the largest consumer, with roughly 80 percent of its demand going for the drying of paper.

Levels of steam production and consumption are calculated for the "annual average day." In fact, steam demand varies minute-by-minute, depending upon such variables as the number of digesters being heated, and seasonally, due to changes in ambient temperature. Expected seasonal demand by the renovated mill for process steam[3] is shown in Figure 16 as Curve A, which is based upon Hopewell's average process steam demand over a five-year period. During the cooler months of the year, the mill's demand for process steam is sufficient to provide generation of the mill's entire electrical demand as a byproduct. During the summer months, however, there is insufficient demand for process steam to allow the turbogenerator to meet the full electrical demand. Thus, during these warmer months, additional high-pressure steam must be produced by the boilers for the sole purpose of generating electricity. This quantity is represented by the vertical distance between Curves A and A'.[4] Thus, total steam demand is represented by segments A A' A.

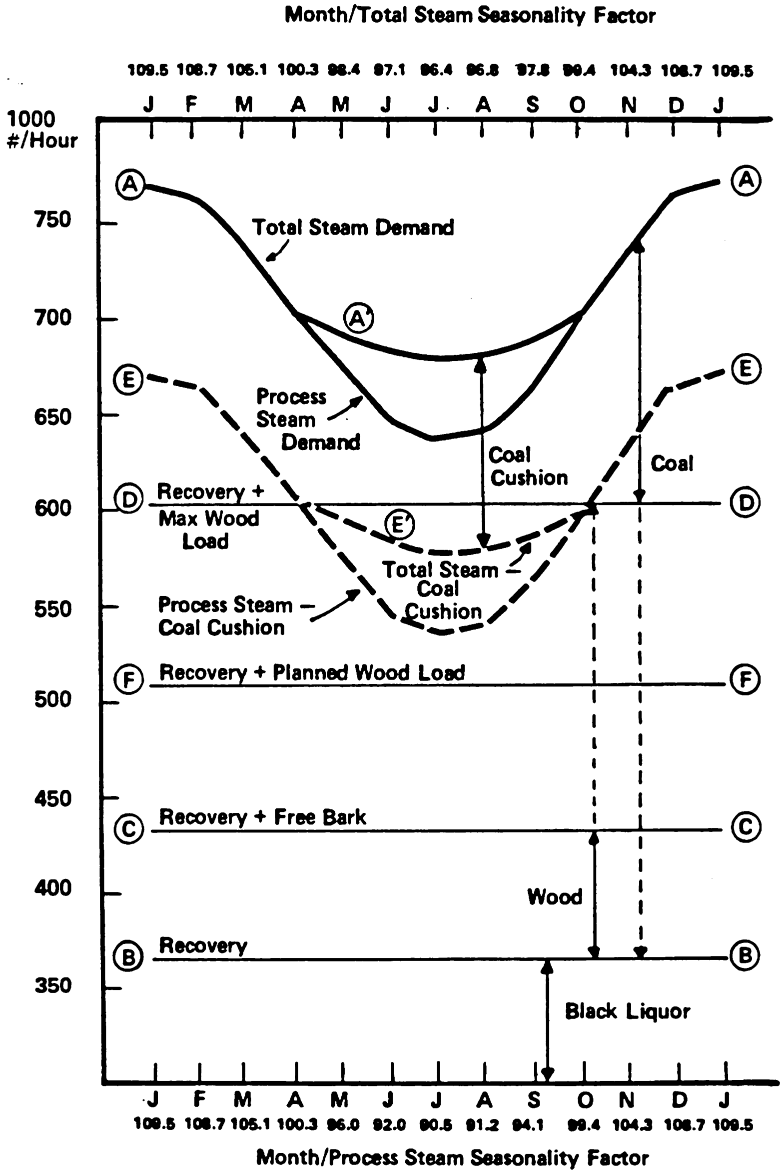


FIGURE 16

Seasonal Steam Demand at the Hopewell Mill

The lower horizontal line, Curve B, shows that portion of the total steam demand that will be satisfied by the recovery boiler through combustion of black liquor. Given a constant rate of pulp production, the steam output from the recovery boiler will remain relatively stable over time. Seasonal and minute-by-minute "swings" in steam demand, therefore, will be absorbed entirely in the power boiler.

In the power boiler - or combination boiler, as it is commonly known - wood in varying sized chunks is burned on a traveling grate, while pulverized coal is sprayed through nozzles into the combustion chamber, where it burns almost instantly. The adjustment of steam supply to demand is made automatically through regulation of the rate by which coal is injected. Wood fuel, by virtue of its high variability in size and combustion characteristics, is loaded into the boiler at a relatively constant rate, insensitive to swings in demand. The vertical distance between Curves B and C represents that portion of total steam demand that is expected to be satisfied by "free" bark and sawdust generated in the mill. Curve C, therefore, represents the minimum wood load in the short run. The vertical distance between Curves B and F represent the planned wood load. Its level was established by supply projections that indicated a stable flow of wood residue from other timber conversion operations in the Hopewell timbershed. In fact, the combination boiler is designed to burn up to 100,000 pounds per hour of hogged fuel (Curve D), or 66 percent more than the expected base load. Note in Figure 16 that fuel for the boiler may be comprised entirely of coal, or some mixture of wood and coal, up to wood's limit of 100,000 pounds per hour. Beyond this 100,000 pound limit, the traveling grate upon which the majority of the wood is burned[5] becomes overloaded, air circulation required for efficient combustion becomes inadequate, and thermal efficiency falls below an acceptable level.

A requirement exists for a "coal cushion," or minimum charge of coal that is necessary to absorb instantaneous swings in steam demand. A representative cushion of 100,000 pounds per hour is depicted as the vertical distance between Curves A A' A and E E' E in Figure 16. The precise size of this cushion will be dependent upon such variables as the size of the anticipated swings in short-term demand, the time required to adjust to changing demand with hogged fuel, and boiler design characteristics requiring some minimum rate of coal loading. In theory, its size also should be dependent upon relative fuel prices: a higher cost of coal relative to wood fuel would call for a smaller cushion - providing a greater possibility of steam loss while adjusting to swings. In other words, there is an economic trade-off between the added cost of coal-cushion steam and the cost of wasted steam should instantaneous demand fall below the lower boundary of the cushion. The objective should be minimization of the sum of these costs. A procedure for determining the optimal size for this cushion will be investigated in the next section.

To summarize: Wood fuel may be used in the combination boiler to produce the quantity of steam represented in Figure 16 by the vertical distance between Curve B at the lower extreme and Curve D and/or Curve E E' E at the upper extreme. Given these limits, the optimal mix of wood and coal is dependent upon the relative costs of producing steam using the two fuels.

Note that there are two adjustments that can be made to alter the fuel mix in the boiler and thereby influence the cost of producing steam. The first involves adjustment of the wood input between its upper and lower limits, and the second involves adjustment of the upper limit by changing the size of the coal cushion. The second alternative becomes a viable means of cost adjustment only if:

(1) The optimal fuel mix falls within the region bounded by Curve D above and Curve E E' E below.

(2) The cost of steam derived from wood is less than the cost of steam derived from coal.

C. Short-Run Fuel Cost Minimization Model for the Hopewell Mill

Given Hopewell's energy conversion assets following renovation in 1981, the firm's objective becomes one of choosing the mix of coal and wood fuel that will minimize costs, while staying within physical boiler constraints and continuing to satisfy the mill's demand for steam. The costs of coal and wood fuel are not directly comparable, due to the different heating values of the two fuels and different fuel handling costs. Coal provides roughly three times the caloric value of green wood per unit weight, and its combustion results in increased boiler efficiency as well. Additionally, the fuels are processed and handled by entirely different systems of men and machinery: imposing different variable costs. The problem comes in identifying these variable costs and describing how they change with the fuel mix. The optimal mix is found where the marginal costs of steam derived from the two fuels are equal.

In this section, a procedure for determining this optimal fuel mix in the short run[6] is developed. The renovated Hopewell mill serves as the model, though the principles used here would apply to any industrial boiler capable of burning two or more fuels. In essence, the procedure involves stating the cost-minimization objective, system constraints, and variable cost relationships as linear functions of fuel quantity, and then applying linear programming techniques to arrive at the optimal solution. Solving the problem after all relationships have been described mathematically is relatively easy; the difficulty lies in problem formulation.

1. Objective

The objective may be stated as minimization of the cost of steam production in Hopewell's combination boiler per month,[7] subject to certain constraints. The model will be concerned exclusively with variation in the boiler's fuel mix, and the impact of this variation on all other inputs and, hence, the cost of making steam. The decision variables, therefore, will be defined as wood fuel tonnage burned in the combination boiler during a given month, denoted by x, and coal tonnage burned in the boiler during the same month, denoted by y.

The variable cost[8] of steam production may be classified as arising either from the coal or wood component, where these component costs include all variable costs of fuel purchase, handling and processing, combustion, and ash disposal. We omit from analysis those costs that are invariant with the fuel mix chosen.

Mathematically, the objective function may be written as:

Minimize $Z = c + w$

where c = coal component cost, w = wood component cost, and all costs are written as linear functions of the decision variables.

2. Constraints

(a) The first constraint that must be imposed is that steam supply equal steam demand. Given a fixed rate of steam production in the recovery boiler, variable steam demand must be satisfied by the combination boiler. For a given month, this demand may be expressed as:

Variable Steam Demand = ab(T.S.F.)

where a = estimated annual average demand per hour, b = expected operating hours per month, and T.S.F. = total steam seasonality factor for the month being considered. For the Hopewell mill, this expression simplifies to:

Variable Steam Demand = (337,000 lb/hour)
(720 hours/month)(T.S.F.) = (2.4264×10^8)(T.S.F.) lb/month

This variable demand is satisfied through combustion of coal and wood fuel. In general, the steam produced from a given fuel may be determined from the following formula:

Steam Supplied = [(Fuel Quantity)(Fuel's Caloric Value per Unit of Input)(Boiler Efficiency)] ÷ Energy Input Required per Pound of Boiler Steam

The figures used in planning Hopewell's expansion yield these steam supply expressions:

$$\text{Wood Steam (lbs/1250 psi steam)} = \frac{x\,(8.6 \times 10^6\ \text{BTU/ton})(.75)}{1{,}438\ \text{BTUs/lb} - 243\ \text{BTUs/lb}}$$

$$= (5.397 \times 10^3)\,x\ \text{lb/month}$$

$$\text{Coal Steam (lbs/1250 psi steam)} = \frac{y\,(2.5 \times 10^7\ \text{BTU/ton})(.85)}{1{,}438\ \text{BTUs/lb} - 243\ \text{BTUs/lb}}$$

$$= 1.778 \times 10^4\ y\ \text{lb/month}$$

Thus, for any given month, Constraint 1 becomes:

$$(5.397 \times 10^3)\,x + (1.778 \times 10^4)\,y = (2.4264 \times 10^8)(\text{T.S.F.})$$

(b) Next, we must require that the quantity of coal combusted must produce sufficient steam to satisfy the minimum coal cushion requirement. The optimum-sized coal cushion has yet to be determined, so, for the moment, let us write a general expression as:

$$y \geqq \frac{[\text{Coal Cushion (in lb/hour)}]\ [\text{Expected Operating Hours per Month}]\ [\text{Energy Input Required per Pound of Boiler Steam}]}{[\text{Coal's Caloric Value per Ton}]\ [\text{Boiler's Coal-Firing Efficiency}]}$$

For the Hopewell mill, this constraint becomes:

$$y \geqq \frac{[1{,}438 \text{ BTU/lb} - 243 \text{ BTU/lb}]\ [720 \text{ hours/month}]\ [\text{C.C. (in lb/hour)}]}{[2.5 \times 10^7 \text{ BTU/ton}]\ [.85]}$$

and, simplifying:

$$y \geqq (4.0489 \times 10^{-2})(\text{C.C.}) \text{ tons/month}$$

(c) The final constraint deals with wood tonnage and imposes a maximum limit on the boiler's wood-burning capacity, and a minimum on the quantity of "free bark" generated from the pulping process. This latter condition is imposed because, in the short run, no method of free bark disposal other than burning is contemplated. For the Hopewell mill, this constraint may be written:

$$\frac{89{,}849 \text{ tons/year}}{12 \text{ months/year}} \leqq x \leqq \frac{(100{,}000 \text{ lb/hour})(720 \text{ hours/month})}{2{,}000 \text{ lb/ton}}$$

which reduces to:

$$7.487 \times 10^3 \text{ tons/month} \leqq x \leqq 3.6 \times 10^4 \text{ tons/month}$$

3. Cost Relationships

The total variable cost of producing steam in the combination boiler is defined as the sum of the coal component cost and the wood component cost. Each of these costs may be written as a function of the variable costs comprising it.

Fuel Component Cost = Fuel Cost + Fuel Handling Cost + Labor Cost + Demurrage Cost + Ash-Handling Cost + Fuel Inventory Cost

One such equation may be derived for each component fuel.

a. Fuel Cost

1. Coal

Coal is purchased on long-term contract that specifies its price per ton FOB Hopewell. For short-run analysis, we may assume that this contract has been negotiated. Over the life of the contract, the firm may place monthly orders for any quantity of coal desired (within limits) at price P per ton (see Figure 17A). Thus, for the short run and over the range of relevant tonnages, the coal supply function facing the firm is a perfectly elastic one. The variable cost of coal may be written as:

$$\text{Coal Cost} = Py \tag{4}$$

2. Wood

Wood fuel supply is more complex, with the firm facing steadily increasing prices per ton for additional tonnage (see Figure 17B). An initial increment, which is expected to amount to roughly 3,000 tons per month at the Hopewell mill, is provided as a byproduct of the pulping operation. There are no short-run opportunities for sale of this material, and its cost will be assumed to equal zero.

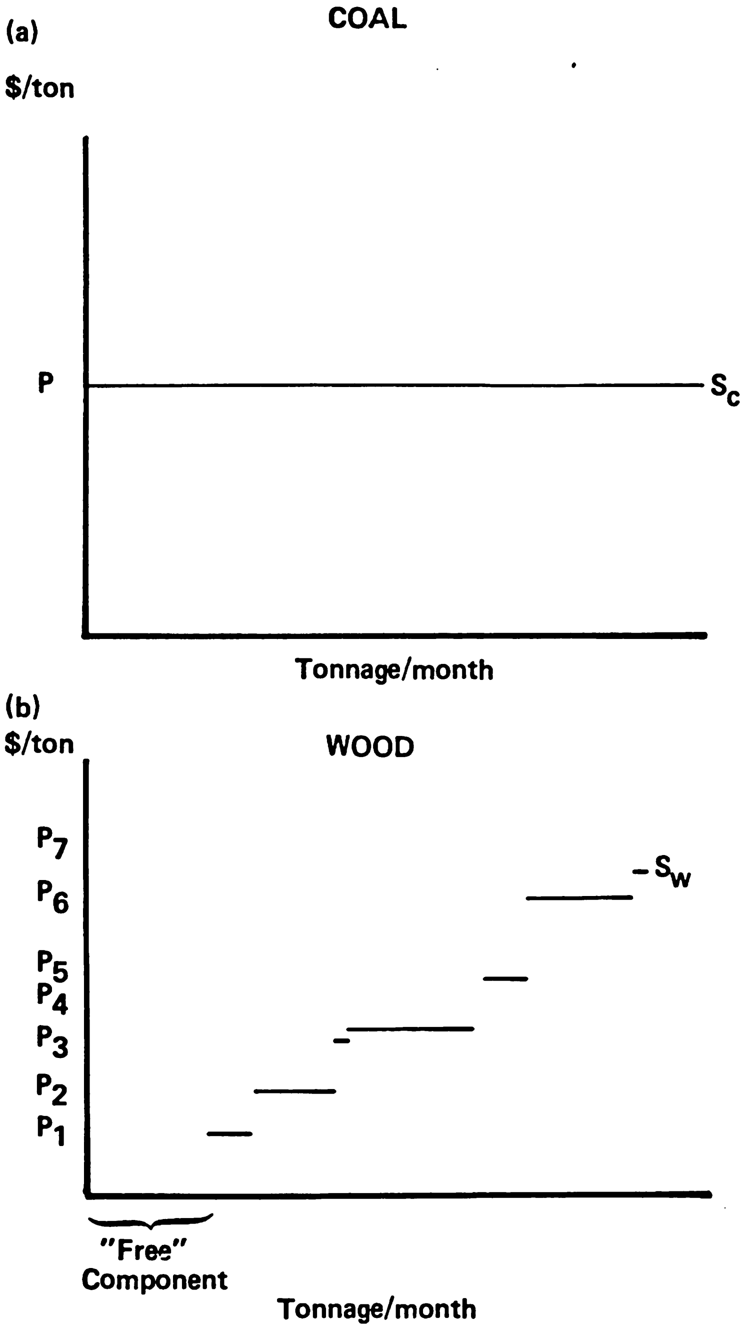


FIGURE 17

Short-Run Fuel Supply Functions

Higher prices per ton for incremental quantities result primarily from increased hauling costs as the company must subsidize the fuel's transport from increasingly more distant suppliers. Thus, the cost of wood fuel becomes:

$$\text{Wood Fuel Cost} = P_1q_1 + P_2q_2 + \ldots + P_nq_n = \sum_{i=1}^{n} P_iq_i \qquad (5)$$

where n = number of shipments per month, and $\sum q_i = x$

b. Fuel Handling Cost

Hopewell's planned coal and wood fuel handling systems are separate entities. The variable costs associated with operation of these systems are the electrical cost, mobile equipment operating cost, labor cost, and maintenance cost.

1. Electrical Cost

a. Electrical Draw

Conveyors, compressors, and pumps are used by each system in various capacities to unload, process, store, and deliver fuel to the combination boiler. These devices are powered by electric motors that draw on mill-generated electricity. Since the systems are not yet operational, the electrical draw for each may be estimated as follows:

Electrical Draw (in kilowatts) = (Horsepower Load)(Load Factor)
(Kilowatt Conversion Factor)

For the system under construction at the Hopewell mill, the estimated electrical draws are:

$$\text{Coal System Electrical Draw} = (695.33 \text{ hp})(0.7)(0.746 \text{ kw/hp}) = 363 \text{ kw} \tag{6}$$

$$\text{Wood System Electrical Draw} = (614.5 \text{ hp})(0.7)(0.746 \text{ kw/hp}) = 321 \text{ kw} \tag{7}$$

These electrical draws are imposed only when the system is operating, and operating time may be expressed as a linear function of the fuel quantity to be handled. No assertion is made that the total system must operate simultaneously or that it must process the same quantity of fuel per unit time all the while. Over time and on average, a given quantity of fuel burned in the combination boiler will result in operation of its fuel handling system for a definite period of time. This relationship between the quantity of fuel handled and system operating time may be estimated by simple linear regression after the system has become operational and sufficient data has been compiled. This equation will take the following form:

Hours of Fuel System Operation = (Some Constant)(Fuel Quantity
Processed)

For coal, we may write:

$$\text{Hours of Coal System Operation} = ey \qquad (8)$$

and for wood, the expression is:

$$\text{Hours of Wood Fuel System Operation} = fx \qquad (9)$$

where e and f are the slope coefficients of the respective regression equations.

The similarity in kilowatt draws for the two systems may belie the true cost in terms of steam productivity. One kilowatt-hour of electrical energy expended in the wood fuel handling system may be much less productive in terms of steam output than one kilowatt-hour expended in the coal handling system. Since our model uses the cost of steam output as its measure of efficiency, such factors will be taken into account.

From the foregoing relationships, we may associate an expected draw of electricity in kilowatt-hours with a given fuel quantity to be processed. The electrical component of the fuel handling system cost may be determined by multiplying the fuel quantity for the expected hours of system operation per ton by the kilowatt draw per hour by the variable cost of electricity.

b. The Variable Cost of Electricity

Electricity in the renovated mill, we recall, is produced primarily as a byproduct of process steam. Only during the warm summer months when process steam demand is low will fuel be expended solely to produce high-pressure boiler steam for electrical generation. Given the accounting figures available at the Hopewell mill, it is impossible to identify electrical production costs that truly are variable with output - with the exception of the cost of fuel used to produce the increment of boiler steam generated solely to satisfy electrical demand. Undeniably, variable costs in addition to this steam increment are imposed by the production of electricity (e.g., turbogenerator maintenance and some labor costs); however, only the steam costs are identifiable, and only they will be considered. In any case, non-steam variable costs are miniscule.

For a given month, the quantity of steam produced solely for use in electrical generation may be found as:

Electrical Steam = (Annual Average Steam Load per Hour)(Expected Operating Hours per Month)(Total Steam Seasonality Factor - Process Steam Seasonality Factor)

For the Hopewell mill, this quantity is:

$$\text{Electrical Steam} = (703{,}000 \text{ lb/hour})(720 \text{ hours/month})(\text{T.S.F.} - \text{P.S.F.}) = 5.0616 \times 10^{8} (\text{T.S.F.} - \text{P.S.F.}) \text{ lb/month} \qquad (10)$$

The cost of this steam is a function of our decision variables. Only after solving the model for the optimal fuel mix could we determine the cost of this electrical steam component. For purposes of model formulation, a budgeted average variable cost of steam production, which is determined regularly by the Accounting Department, will be used. It will take the following form:

$$\text{Average Variable Cost of Steam} = \$g/\text{lb} \tag{11}$$

where g = an accounting number.

To determine the variable cost of electrical steam produced during a given month, we combined equations (10) and (11) to get:

$$\text{Cost of Electrical Steam} = [5.0616 \times 10^{8}\ (\text{T.S.F.} - \text{P.S.F.})\ \text{lb}/\text{month}]\ [\$g/\text{lb}] \tag{12}$$

and the cost per kilowatt-hour becomes:

$$\text{Cost of Electrical Steam} = \frac{5.0616 \times 10^{8}(\text{T.S.F.} - \text{P.S.F.})(\$/g)}{\text{Average Electrical Draw}}$$

$$= \frac{5.0616 \times 10^{8}(\text{T.S.F.} - \text{P.S.F.})(\$/g)}{(33{,}700\ \text{kw-hours/hour})\ 720\ \text{hours/month}}$$

$$\text{Cost of Electrical Steam} = 20.8605\ (\text{T.S.F.} - \text{P.S.F.})(\$g/\text{kw-hour}) \tag{13}$$

The electrical cost for each fuel handling system now may be determined by multiplying the kilowatt draw found in equations (6) and (7) by the hours of system operation per month found in equations (8) and (9) by the cost of electrical steam per kilowatt-hour found in equation (13).

The cost functions for each system are:

$$\text{Coal System Electrical Cost} = (363\ \text{kw})(ey\ \text{hours})\ [20.8605\ (\text{T.S.F.} - \text{P.S.F.})]\ (\$g/\text{hw-hour}) = \$7.5724 \times 10^3\ (\text{T.S.F.} - \text{P.S.F.})\ (gey) \tag{14}$$

$$\text{Wood Fuel System Electrical Cost} = (321\ \text{kw})(fx\ \text{hours})\ [20.8605\ (\text{T.S.F.} - \text{P.S.F.})]\ (\$g/\text{hw-hour}) = \$6.6962 \times 10^3\ (\text{T.S.F.} - \text{P.S.F.})(gfx) \tag{15}$$

2. Maintenance Cost

The cost of maintaining a given system, to include the cost of labor, repair parts, and supplies (such as lubricants) may be visualized as shown in Figure 18. Cost OA represents the cost of periodic or "preventative" maintenance undertaken by the firm, irrespective of operating time. Also included in this increment is the cost of replacing system components, the lives of which are independent of operating time. The curve AB depicts the most likely variable-cost relationship: the longer the system operates, the more likely it becomes to incur maintenance cost, but at a declining rate. Thus, if the system operates for 2,000 hours, it will impose a higher maintenance cost than if it were to operate only for 1,000 hours, but the cost likely will not be twice as much. The problem comes in describing such a relationship mathematically: a feat that could be performed only by monitoring the performance of a significant number of comparable systems over a long period of time. Although annual maintenance budgets are compiled by each operating department in the mill, and these estimates prove to be reasonably

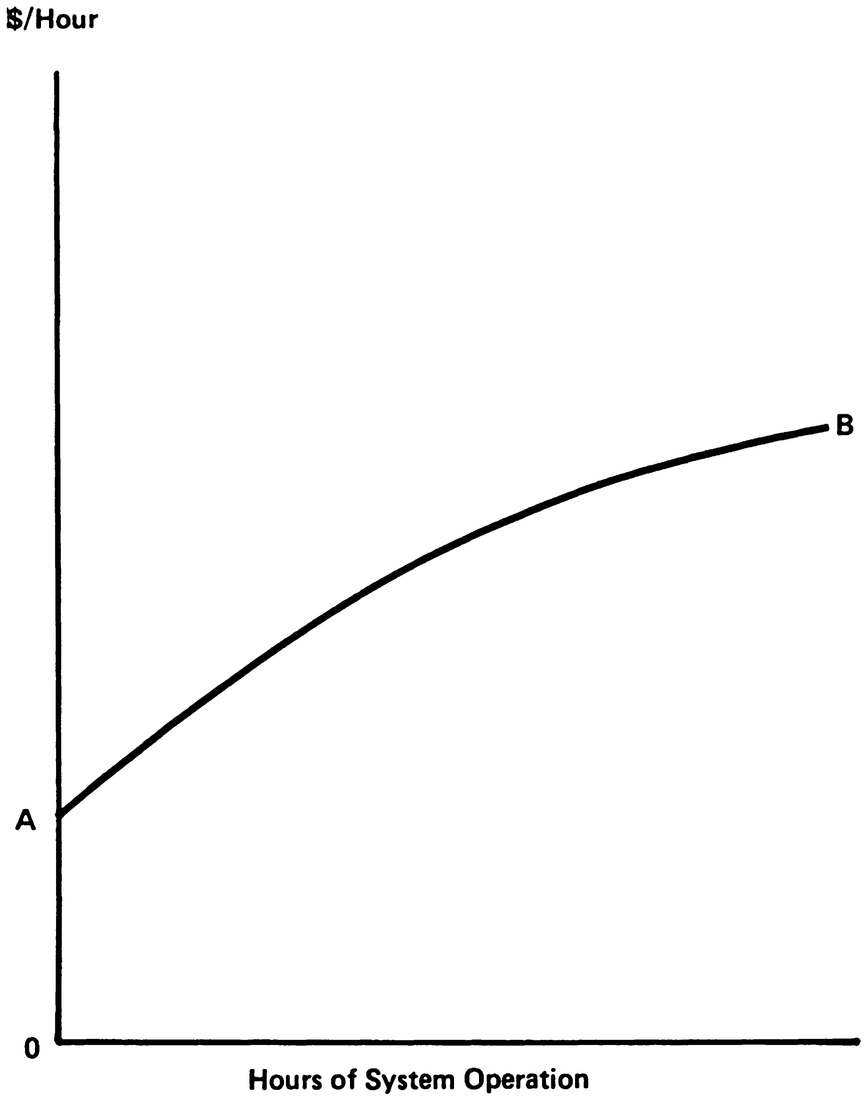


FIGURE 18

Total Cost of System Maintenance

accurate, we have no means of separating the fixed from the variable components. Even time-series regression analysis of system maintenance cost over varying hours of operation would fail to account for advancing age, and, thus, increased likelihood of breakdown of system components. Thus, for this analysis, within production ranges contemplated, the cost of maintenance will be assumed invariant with the quantity of fuel processed: we will ignore it.

3. Mobile Equipment Operating Cost

Fuel handling and processing requires operation of supporting mobile equipment. Just as we can establish a relationship between hours of fuel handling system operation and fuel tonnage processed, so, too, can we establish such a relationship for supporting mobile equipment. The equation would take the following form:

$$\text{Hours of Mobile Equipment Operation} = k\,(\text{Fuel Quantity Processed}) \qquad (16)$$

where k is a slope coefficient determined through regression analysis.

The variable cost of operating a given piece of heavy equipment may be determined from estimates provided by the manufacturer or from data compiled by the firm. The cost of the operator and fixed costs, such as depreciation, should be ignored. The variable cost of equipment operation may be expressed as:

$$\text{Mobile Equipment Operating Cost} = l\ (\text{Hours of Equipment Operation}) \qquad (17)$$

where l = variable cost per hour.

Combining equations (16) and (17), we may write expressions for both coal and wood fuel-handling systems:

$$\text{Cost of Coal System Mobile Equipment} = kly \qquad (18)$$

$$\text{Cost of Wood Fuel System Mobile Equipment} = k'l'x \qquad (19)$$

c. Labor Cost

Given the requirement that "coal cushion" coal and "free" bark be processed regardless of relative fuel component prices, both coal and wood fuel handling systems must operate for some portion of the day. For each system during the daylight shift, personnel assigned are capable of operating the system at its maximum capacity or any reduced capacity desired. Within broad ranges, workers assigned to the coal and wood fuel handling systems are able to process variable quantities of fuel. That is, up to each system's physical capacity,[9] a wide variation in the quantity of fuel handled by a fixed number of workers is possible. The cost of short-term surges in the rate of fuel arrival would be felt, initially, as demurrage costs rather than increased labor costs, as the carriers simply would be queued until the system was capable of handling them. The existence of labor contracts that discourage worker lay-offs,[10] and the ability of the woodyard foreman to shift workers from task to task as the occasion demands each tend to fix the existing manning level in the short run.

Given these factors, and considering the probability of a rather narrow variance in coal and wood tonnages processed after the system becomes operational, the short-run cost of labor will be assumed invariant with fuel quantities.

d. Ash-Handling Cost

Ash is deposited in the combination boiler in the form of fly ash and bottom ash, each necessitating a separate disposal system. Coal and wood yield different portions of their input weight as ash, and different portions of this total in the form of fly ash and bottom ash. Thus, depending upon the fuel mix used, ash quantities, their form, and resulting disposal costs are variable and must be considered in our analysis.

Fly ash will be collected in an electrostatic precipitator and removed by means of a flow of water that will deposit the ash in one of two settling ponds. There, the ash slurry dewaters to a consistency allowing it to be dredged and hauled to a disposal site. The dredging and hauling operations will be performed by independent contractors at an expected frequency of once in six months. Contractor cost is expected to be some linear function of ash tonnage.

Bottom ash is to be removed from the boiler daily and hauled to the same disposal site several times a week. This function, too, will be contracted outside the company, and its cost will be some linear function of ash quantity.

The following figures are the firm's estimates of quantities of fly and bottom ash that will be generated by the two fuels:

Fuel	Percentage of Fuel Remaining as Ash, by Weight	Of Total Ash Deposited, Percentage in the Form of: Fly Ash	Bottom Ash
Bark and Wood Residue	6	60	40
Coal	15	85	15

Thus, ash deposition can be written for each fuel as:

$$\text{Wood Fly Ash} = x(.06)(.6) = .036x$$

$$\text{Wood Bottom Ash} = x(.06)(.4) = .024x$$

$$\text{Coal Fly Ash} = y(.15)(.85) = .1275y$$

$$\text{Coal Bottom Ash} = y(.15)(.15) = .0225y$$

The variable cost of bottom ash disposal can be calculated strictly as a function of the number of trips the contractor must make to haul it to the disposal site.

$$\text{Bottom Ash Disposal Cost} = \frac{\text{Ash Tonnage}}{q} \quad r$$

where q = contractor's capacity per haul in tons and r = contractor's price per haul.

Disregarding the costs of precipitator operation and fly ash transport to the settling ponds, both of which are expected to be invariant with ash quantity, the variable cost of fly ash disposal consists of the price bid by contractors to dredge ash from the ponds and haul it to the disposal site. This cost can be expected to be a linear function of ash tonnage, and can be written as:

$$\text{Fly Ash Disposal Cost} = (\text{Ash Tonnage})s$$

where s = contractor's fee per ton.

Thus, we may express the variable ash handling costs for each fuel as follows:

$$\text{Wood Ash Disposal Cost} = \frac{.024rx}{q} + .036sx \qquad (20)$$

$$\text{Coal Ash Disposal Cost} = \frac{.0225ry}{q} + .1275sy \qquad (21)$$

e. Demurrage Cost

If the mill takes an excessive amount of time to unload rail cars or trucks "placed" at the mill, shipping firms impose a periodic fee in compensation for the loss of their carriers. A sample demurrage schedule for rail cars is shown as Table 5. Based upon experience at the Hopewell mill, this penalty is much more likely to be imposed by rail companies, since rail shipments are more likely to arrive en masse and experience delays in unloading. Demurrage fees imposed by trucking firms are inconsequential. Coal will be delivered to the Hopewell mill exclusively by rail; wood fuel will be delivered almost exclusively by truck. Thus, a shift toward use of coal would increase the likelihood of demurrage fees being imposed.

TABLE 5

Hopewell Demurrage Schedule per Car for Rail Shipments
(Effective 7:00 a.m., February 1, 1979)

Placed For	Mon.	Tues.	Wed.	Thur.	Fri.	Sat.	Sun.	Mon.	Tues.	Wed.	Thur.
Loading	Placed	Free	$20	$20	$20	$20	$30	$30	$60	$60	$60
Unloading	Placed	Free	Free	$20	$20	$20	$20	$30	$30	$60	$60
Loading		Placed	Free	$20	$20	$20	$20	$30	$30	$60	$60
Unloading		Placed	Free	Free	$20	$20	$20	$20	$30	$30	$60
Loading			Placed	Free	$20	$20	$20	$20	$30	$30	$60
Unloading			Placed	Free	Free	Free	Free	$20	$20	$20	$20
Loading				Placed	Free	Free	Free	$20	$20	$20	$20
Unloading				Placed	Free	Free	Free	Free	$20	$20	$20
Loading					Placed	Free	Free	Free	$20	$20	$20
Loading					Placed	Free	Free	Free	Free	$20	$20
Loading						Placed	Free	Free	$20	$20	$20
Unloading						Placed	Free	Free	Free	$20	$20
Unloading							Placed	Free	$20	$20	$20
Unloading							Placed	Free	Free	$20	$20

Rail demurrage fees are a function of arrival rate versus unloading rate and time of placement (hour and day of the week). To simplify calculation of variable demurrage cost, it is suggested that historical data plotting demurrage fees as a function of monthly coal tonnage arrivals be amassed. The linear regression line derived from such data could them be used to estimate demurrage fees as a function of coal tonnage arrivals expected during a given month. This cost may be expressed as:

$$\text{Coal Demurrage Cost} = my$$

where m = the slope coefficient of the regression equation.

This linear equation would require updating in the event of changes in the demurrage fee schedule.

f. Inventory Cost

Fuel inventories will be maintained as the quantity corresponding to a certain number of days' supply. Thus, if usage of a fuel is increased or decreased, so, too, will the size of its inventory. The cost imposed by an inventory is found by multiplying its value by the firm's opportunity cost of capital. Thus, for our component fuels, and assuming a 30-day inventory as currently planned, the inventory costs may be written as:

$$\text{Wood Inventory Cost} = \left[\sum_{i=1}^{n} P_i x_i\right] w$$

Coal Inventory Cost = Pyw

where w = the firm's monthly opportunity cost of capital.

4. Linear Programming Model

Given all variable costs expressed as linear functions of coal and wood quantity, the linear programming model may be written as follows:

$$\underline{\text{Minimize}}\ Z = Py + \sum_{i=1}^{n} P_i q_i + 7.5724 \times 10^3\ (\text{T.S.F.} - \text{P.S.F.})(gey) + 6.6962 \times 10^6\ (\text{T.S.F.} - \text{P.S.F.})(gfx) + kly + k'l'x + \frac{.024rx}{q} + .1275sy + my + \left[\sum_{i=1}^{n} P_i q_i\right] w + Pyw + .036sx + \frac{.0225ry}{q}$$

Subject to:

(1) $(5.397 \times 10^3)x + (1.778 \times 10^4)y = (2.4264 \times 10^8)(\text{T.S.F.})$

(2) $y \geqq (4.0489 \times 10^{-2})(\text{C.C.})$

(3) $7.487 \times 10^3 \leqq x \leqq 3.6 \times 10^4$

where:

y = tons of coal purchased for a given month

x = tons of wood fuel purchased for a given month

P = price of coal per ton

$P_i q_i$ = quantity and price per ton of i'th wood fuel shipment

T.S.F. = total steam seasonality factor

P.S.F. = process steam seasonality factor

g = budgeted variable cost of steam/lb

e = regression slope coefficient for relationship between hours of coal system operation and tons of coal handled per month

f = regression slope coefficient for relationship between hours of wood system operation and tons of wood fuel handled per month

k = regression slope coefficient relating hours of mobile equipment operation to coal tonnage processed per month

k' = regression slope coefficient relating hours of mobile equipment operation to wood fuel tonnage processed per month

l = variable cost per hour of operating coal system mobile equpiment

l' = variable cost per hour of operating wood fuel system mobile equipment

q = contractor's bottom ash capacity per haul, in tons

r = contractor's price per haul

s = contractor's fly-ash disposal fee per ton

m = slope coefficient of regression equation relating demurrage cost to coal tonnage

w = firm's monthly opportunity cost of capital; i.e., the "cost of money"

D. The Optimum Coal Cushion

The coal cushion described in previous sections may be separated into two components: (1) a fixed component the size of which is established by "system operability,"[11] and (2) a variable component established for the purpose of absorbing downward swings in steam demand. Because the coal cushion may act as an upper limit to the quantity of wood that may be fired in the boiler, thereby affecting the location of the cost-minimizing fuel mix determined in the linear-programming model, the decision regarding the size of its variable component must be made with care.

Referring to Figure 19, we see a hypothetical probability distribution for average hourly steam demand during a given month. The expected value of 600,000 pounds/hour is the same figure that would be determined by multiplying the annual average steam demand expected for the system by the total steam seasonality factor for the month under consideration. A hypothetical coal cushion of 100,000 pounds/hour is shown for illustrative purposes. Now, *if* the coal cushion acts as the upper boundary to wood firing (most likely during summer months), and *if* the linear-programming model places the least-cost mix of fuels above this boundary, then maintenance of the coal cushion imposes a cost that may be expressed as:

> Cost of Coal Cushion = (Quantity of Wood Steam Displaced by Coal Cushion Steam)(Marginal Cost of Coal Steam - Marginal Cost of Wood Steam)

While average monthly demand is represented by curve AA'A, "instantaneous" swings in demand occur each time some piece of steam-consuming machinery is turned on or off in the mill (e.g., a digester is emptied). If this instantaneous swing causes total demand to fall below the coal cushion's lower boundary (line EE'E[12]), a separate cost is imposed because the fuel input system is no longer able to adjust automatically to the reduced steam load. In such cases steam is "blown," or wasted, while manual adjustments are made to the rate of wood input and the boiler burns the wood already present in its combustion chamber. Blown steam imposes a cost that can be written as:

> Cost of Blown Steam = (Quantity of Steam Blown)(Marginal Cost of Wood Steam)

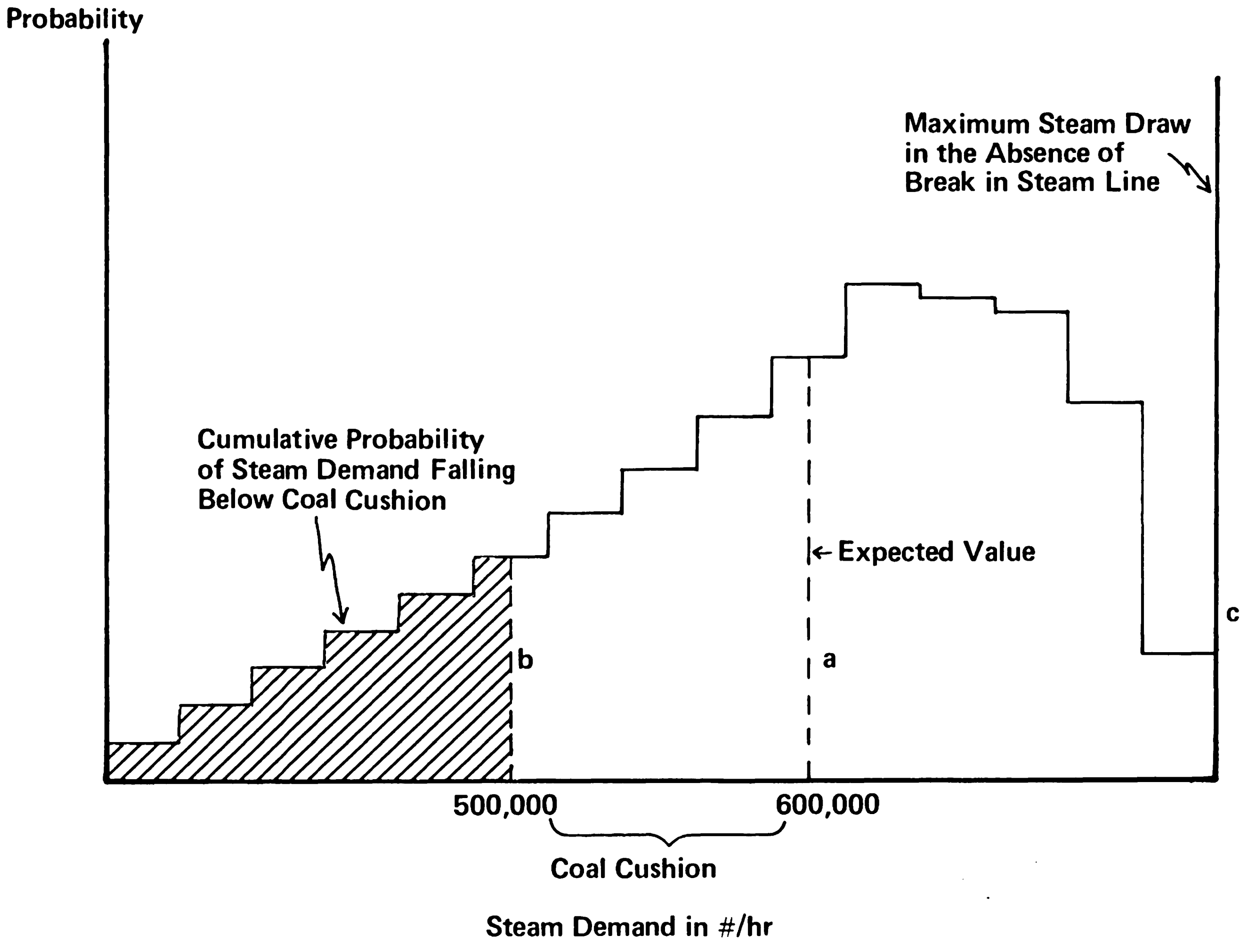


FIGURE 19

Hypothetical Steam Demand Probabilities for a Given Month

The quantity of steam that is wasted is a function of a number of probabilitistic elements, to include: duration of the negative swing, magnitude of the swing relative to the coal cushion boundary, time required to adjust wood input manually, and so on. Note in Figure 19 that by increasing the size of the coal cushion (moving Line b to the left), we reduce the probability that negative swings in steam demand will fall outside the boundary of the coal cushion and that steam will be blown to the atmosphere. At the same time, we may impose added constraints upon the optimal fuel mix by further limiting the quantity of wood that may be fired. Thus, movement of Line b in either direction - that is, increasing or decreasing the size of the coal cushion - may impose costs. This cost relationship is depicted graphically in Figure 20. The optimal coal cushion is found where the sum of costs C_1 and C_2 is minimized.

The problem comes in determining these costs. The cost of maintaining the coal cushion depends upon the optimal fuel mix identified in the linear programming model. The probability of wasting steam and, hence, the cost of wasted steam, depends upon the size of the coal cushion. And the optimal fuel mix chosen in the linear programing model depends upon the size of the coal cushion. Thus, costs C_1 and C_2 are interdependent: each must be solved before the other may be determined. It is precisely <u>because</u> costs C_1 and C_2 are interdependent that separate models for solution of the optimal coal cushion and the optimal fuel mix are infeasible. Our model must solve both problems simultaneously.

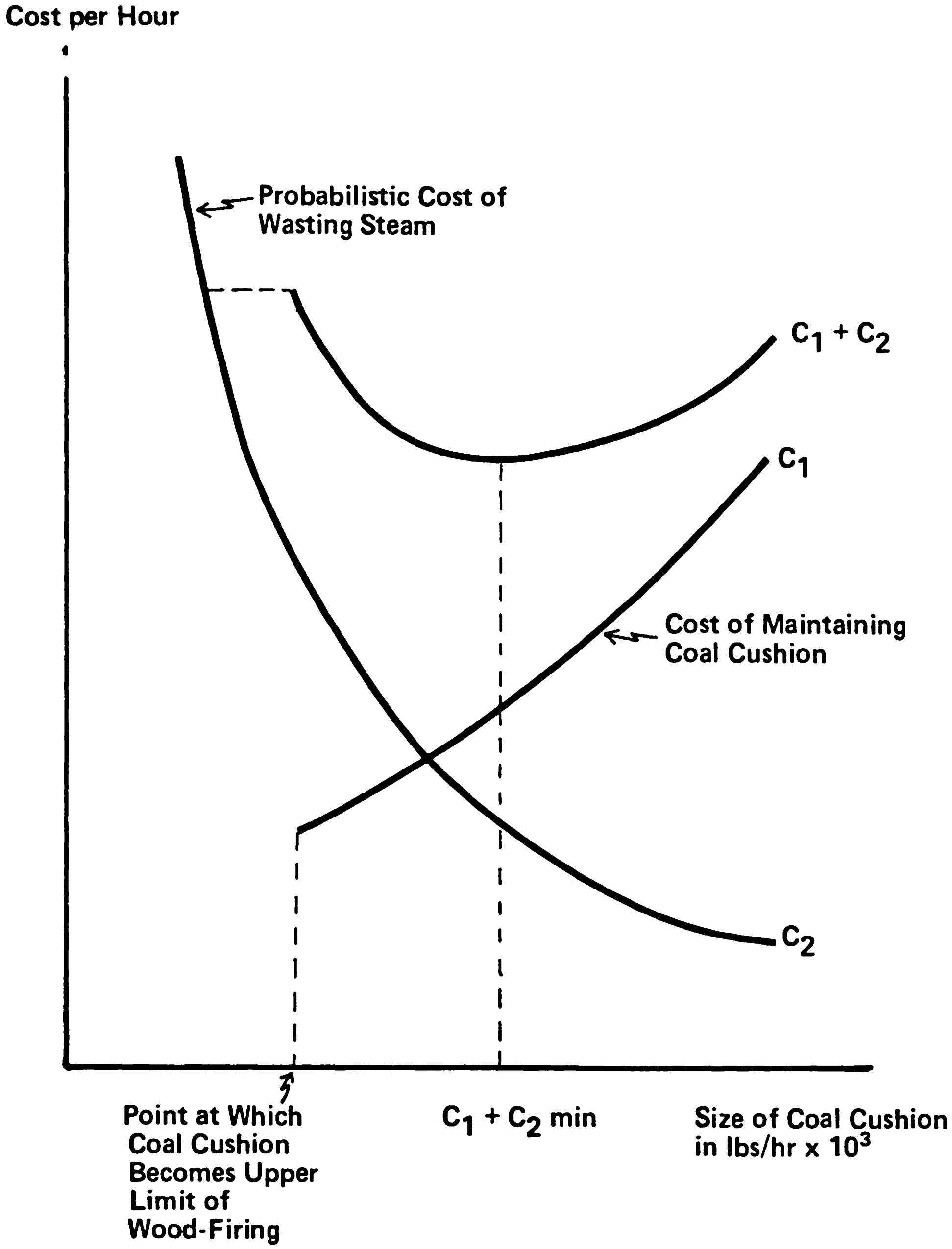


FIGURE 20

Coal Cushion Cost

A simulation approach is proposed. Given a coal cushion, we may solve the linear programming model and identify the optimal fuel mix. Given a coal cushion and this optimal fuel mix, we may solve for costs C_1 and C_2 and find their minimum point. Our task is one of calculating the total variable cost of steam for a range of coal cushions and selecting the size that minimizes cost. The following data is required for such analysis:

For a Given Month		For a Coal Cushion of Size w (in 1,000 lb/hour)	
Average Steam Demand per Hour	Probability of Occurrence	Steam Produced - Steam Consumed	Cost of Wasted Steam
(1)	(2)	(3)	(4)

where w ranges from 0 to (total steam demand - free bark increment) in feasible increments.

Values for Columns (1), (2) and (3) will become available from records kept in the Power-Recovery Department after the boiler becomes operational. Values for Column (4) may be calculated as the cost of wood steam that is wasted[13] (Column (3)) by using the following procedure:

(a) Determine the quantity of wood fuel that must be fired to produce the steam quantity given in Column (3):

$$\text{Wood Fuel Tonnage} = \frac{(\text{Wood Steam Quantity})(1{,}436\ \text{BTUs/lb} - 243\ \text{BTUs/lb})}{(8.6 \times 10^{6}\ \text{BTUs/ton})(.75)}$$

(b) Determine the variable cost of producing steam from this wood tonnage:

$$\text{Variable Cost of Wasted Steam} = x' \sum_{i=a}^{n} P_i q_i + 7.5724 \times 10^3 \, (\text{T.S.F.} - \text{P.S.F.})$$
$$(gf) + k'l' + \frac{.024r}{q} + .036s + \sum_{i=a}^{n} P_i q_i$$

where $\sum_{i=a}^{n} q_i = x'$ = wood fuel tonnage determined in (a) above.

The variable cost calculated in (b) becomes the value entered in Column (4) of the table. The expected cost of steam wasted while maintaining a specified coal cushion is simply the cumulative total of Column (2) multiplied by Column (4).

Now, over the same range of coal cushions considered above, the linear programming model may be solved to determine a range of optimal fuel mixes. Corresponding to each mix will be a total variable cost of producing steam: $Z = c + w$, the value of our original function. To this cost, for each coal cushion considered, we must add the expected cost of wasted steam determined above to form a new objective function:

$$Z' = c + w + v$$

where c = coal component cost of steam, w = wood fuel component cost of steam, and v = probabilistic cost of wasted steam.

Values for Z' may then be plotted over the range of possible coal cushions. The minimum value of Z' identifies both the optimal coal cushion and the optimal fuel mix to minimize the cost of steam produced in the combination boiler.

I. Overview

We may view the problem of determining the least-cost fuel mix for the combination boiler from a slightly different perspective to ensure that the theory has not been obscured by mathematics. Assuming for the moment that all constraints have been relaxed save the one requiring steam supply to equal steam demand, Figure 21 shows the marginal costs of steam production using coal and wood fuel as MC_{cs} and MC_{ws}, respectively. Given the assumptions used in development of the linear programming model, the marginal cost of steam derived from coal is invariant over relevant, short-run quantities. The marginal cost of steam derived from wood rises steadily after "free bark" has been combusted, reflecting the slope of the wood fuel supply function. The precise shape of the wood fuel supply curve remains to be determined, but the function definitely will be a monotonically increasing one. The curves MC_w and MC_c represent the marginal costs of the component fuel alone, neglecting such variable costs as fuel handling and ash disposal. The constant increments Δc and Δw represent these additional variable costs for coal component steam and wood component steam, respectively.

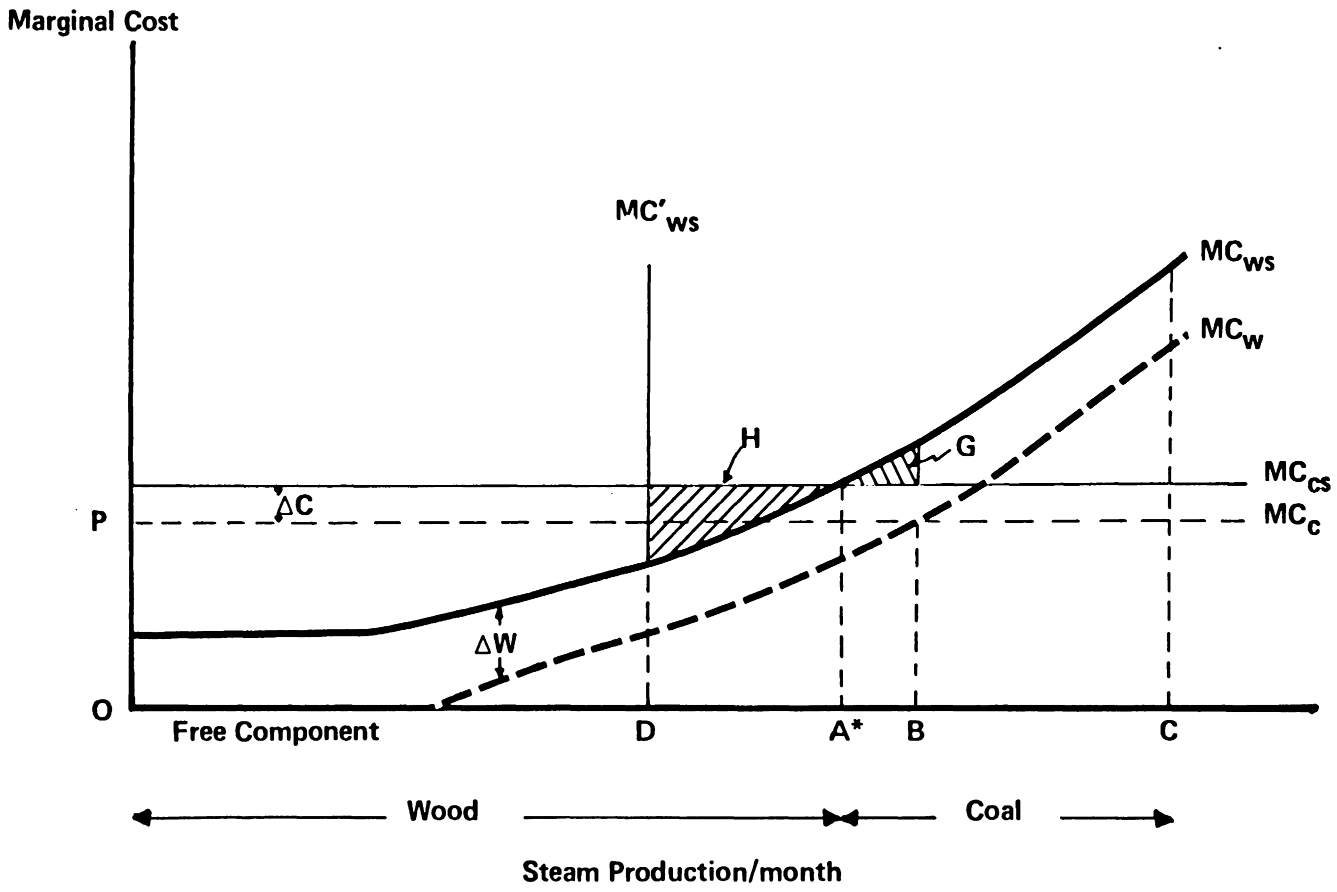


FIGURE 21

Marginal Cost of Steam

The point at which the marginal cost of steam produced from coal equals the marginal cost of steam produced from wood fuel is denoted A*. To the left of A*, the cost of an additional pound of steam derived from wood is less than the cost of an additional pound of steam derived from coal. To the right of A*, the situation is reversed, with the cost of incremental steam being less when coal is used as fuel. Given level of steam production C as the average steam demand for the month being considered, it is clear that wood fuel should be used to produce steam increment OA* and coal should be used to produce increment A*C, as this fuel mix minimizes costs.[14] Note that if only fuel costs and steam producing efficiencies are considered, the optimal fuel mix is determined incorrectly at Point B, and an unnecessary monthly cost, represented by Area G, is imposed upon the firm.

Let us now impose a constraint in the form of a maximum limit on the quantity of wood fuel that may be fired in the boiler at Point D. Given this constraint, the marginal cost of wood steam function, now given by MC'_{ws}, rises to infinity at Point D, and the new optimal mix is described here. The monthly cost of this constraint is shown as Area H. This constraint may be visualized as being imposed either by the boiler's physical wood-firing capacity (producing a maximum wood steam output of OD), or by the requirement for a minimum coal cushion of DC. In each case, cost H is imposed, but in the former case the cost is fixed by physical limitations that cannot be altered in the short run. In the latter case, cost H = cost C_1, where C_1 has been defined previously as the cost of maintaining the coal cushion, and wood-firing limit D may be adjusted to minimize the sum of costs C_1 and C_2, where C_2 is the probabilitistic cost of wasting steam (cost C_2 is not depicted in Figure 25).

It is the existence of these constraints that led to adoption of the model developed in the previous section. Linear programming provides the tools for handling the types of constraints involved in this problem quite easily, and simulation offers the advantage of simultaneous solution of interdependent decision variables. The model, quite obviously, will require the aid of a computer for solution, but such a task will be simplified by the availability of a number of software programs designed for linear programming. Once the model has been coded and entered into the computer, monthly input would consist only of price changes.

II. System Start-Up

A significant portion of the data required for solution of the model must be collected after the new system becomes operational. There is no method of accurately forecasting such variables as monthly steam demand probabilities, blown steam for a given average hourly demand, fuel handling system hours of operation for a given quantity of fuel processed, etc. In the interim, the following course is recommended:

(1) The size of the coal cushion should be established initially on the basis of the experience of others who fire similar boilers. The manufacturer doubtless can provide such information.

(2) The optimal fuel mix should be determined on the basis of variable fuel costs alone: the intersection of curves MC_c and MC_w in Figure 21 should be identified. This point will provide a "break-even price" for coal and wood steam

that will approximate point A*. For example, assuming a hypothetical 1981 price of delivered coal to be \$60.00/ton, the break-even price for wood fuel may be determined as follows:

(a) Each ton of wood fuel provides the following useful energy:

Effective BTUs Derived from Wood = (8.6) x 10^6 BTUs/ton)(.75 conversion efficiency) = 6.45 x 10^6 effective BTUs

(b) Each ton of coal provides:

Effective BTUs Derived from Coal = (2.5 x 10^7 BTUs/ton)(.85 conversion efficiency) = 2.125 x 10^7 effective BTUs

(c) The break-even price, P, where $MC_w = MC_c$ becomes:

$$\frac{2.125 \times 10^7 \text{BTUs}}{\$60.00/\text{ton}} = \frac{6.45 \times 10^6 \text{BTUs}}{P}$$

$$P = \$18.00/\text{ton}$$

Thus, in the absence of wood-firing constraints, the firm should buy all of the wood fuel possible at a delivered price of \$18.00/ton or less, and make up the remainder of its steam demand with coal. If wood fuel quantities availble at these prices exceed wood-firing constraints imposed either by the boiler's physical limitations or the coal cushion established in (1) above, then wood fuel purchases should be held to the level of the most limiting constraint.

This preliminary coal cushion and fuel mix should be used until sufficient cost data becomes available for a lower cost solution to be determined via the model.

III. Conclusion

It may be argued that the variable costs of the fuels make up the vast majority of the total variable cost of steam production and that the other costs, which are exceedingly difficult to describe mathematically, may be ignored with little effect on the final outcome. In effect, this argument asserts that cost G in Figure 21 is insignificant. Perhaps, but this remains to be seen. Even if the non-fuel variable costs ($\Delta c + \Delta w$) amount to 10 percent of the total variable cost of making steam, their impact may prove highly significant over the 30-year life of the boiler system. And these costs may be avoided *merely by changing the fuel mix*. Clearly, these costs should not be overlooked. Before embarking upon a fuel-firing policy that may well become institutionalized, mill management should expend its best intellectual efforts toward finding the optimal fuel mix.

The same arguments may be advanced toward determining the optimal coal cushion. If its size becomes an engineering decision, based upon system operability and minimization of blown steam, the cushion probably will be made too large. The cost of wasted steam is obvious. The cost of a coal cushion that is made too large is more insidious.

Only by use of some marginal analysis procedure, such as the one developed here, will the true costs of fuel-input decisions become apparent.

V. GUIDES TO THE USE OF WOOD AS FUEL

We have discussed in some detail the economic forces that combine to determine the price and quantity of energy that will be derived from wood in a given production situation. The quantity of energy supplied was found to depend on the degree to which costs are shared with costs of producing other joint products of the log, such as wood pulp. For the "residual" wood fuels, the degree of subsidy may be more important than price in determining the quantity of energy that will be produced from wood.

The Hopewell case study considered the trade-off between wood and coal, assuming wood to be a homogeneous fuel with fixed properties. No competing demands for wood fuel were considered, and the mill was assumed able to buy all that it needed, although at an increasing price per ton. The analysis was strictly short-term, in that all required fuel handling and conversion assets were assumed to be in place, and all inputs were assumed fixed, with the exception of the fuel mix and the inputs whose cost varied directly with this mix.

Thus far we have ignored the following practical questions:

- Given existing assets, *which* fuelwood sources should be tapped to supply a given facility?

- How should competing demands for the same wood from the firm's other energy and fiber converting facilities be resolved?

- How should wood fuel be evaluated against the alternatives for future production?

They arrange themselves logically into questions of source, allocation, and capital budgeting, all of which will be addressed in this section. Our objective is to provide useful guides to industry managers that will enable them to better assess wood's fuel potential.

The assumption is made that we address managers who have as their goal the maximization of the firm's net worth, as reflected in the market value of its common stock. Such a goal implies consideration of long-term consequences of short-term actions: that each production and investment decision be made with an eye toward maximizing the present value of a future stream of net income, with due account made for the risk that accompanies this benefits stream. To achieve this objective, the firm's managers control some array of productive factors - land, labor, and capital - that can be manipulated to produce a product or products of value. The challenge comes in selecting and employing these assets to greatest advantage. In this section, we consider wood fuel's position as a potential input factor for short- and long-run production of Kraft pulp-paper.

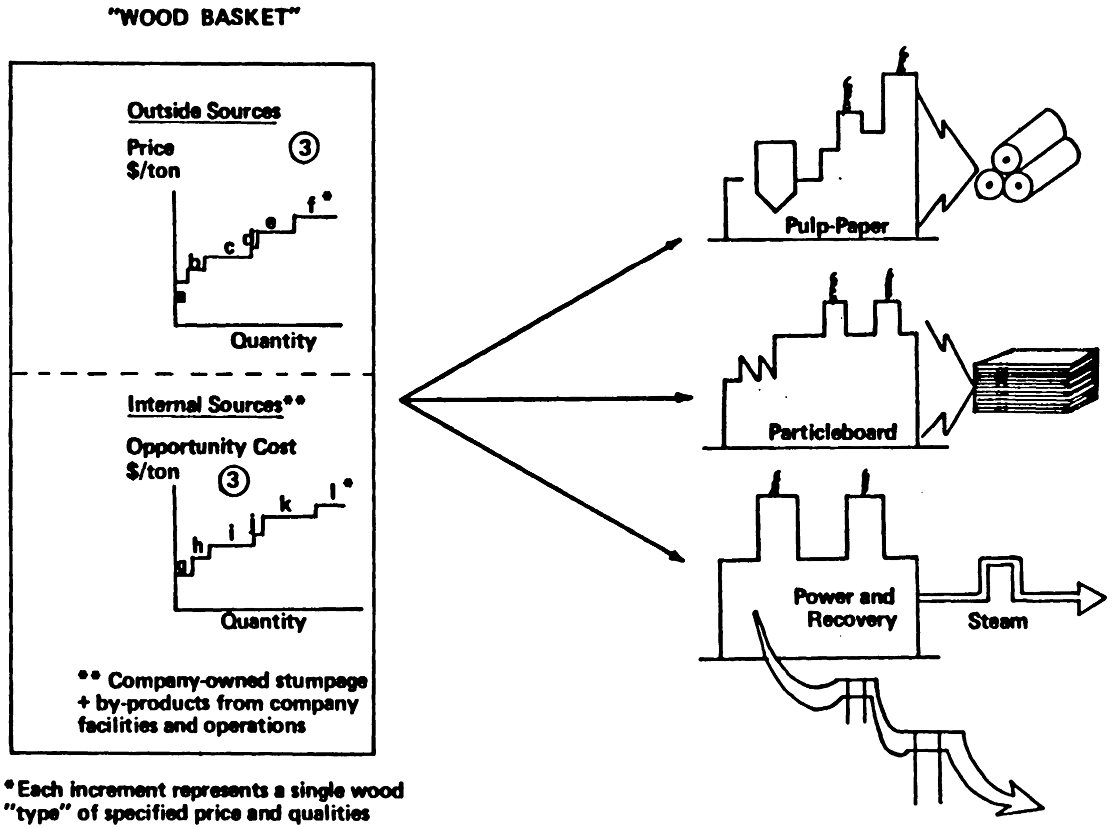
A. Short-Run Analysis

1. The Wood Source and Allocation Problem

Consider the plight of the raw material procurement and allocation manager, who must decide which wood to buy in what quantities, and how to distribute this wood among the firm's competing demand centers. If meeting the firm's objective demands simultaneous employment of all factors in a manner that maximizes their aggregate, net value over time, such words offer little in the way of practical guidance to the fiber manager. He controls but one input factor and wishes to purchase and distribute it among his facilities in the best way, subject to his position in the firm and degree of control over the production process. What does he do? Typically, he adopts some variant of the principle of "least-cost sourcing," and allocates wood so as to remain within quality guidelines that have been established for each facility. For fuelwood, such guidelines might address particle size, moisture level, or degree of contamination with sand and grit. Unfortunately, least-cost sourcing and allocation within quality guidelines will produce a sub-optimal solution. In the succeeding pages of this section, we will demonstrate why this is true and, at the same time, propose an alternative approach that is superior.

Consider the example illustrated by Figure 22. The fiber manager sees three wood-using facilities that must be supplied[1] with wood over the planning period. He has these pieces of information at his disposal:

(1) An estimate of wood demand at each facility;



*Each increment represents a single wood "type" of specified price and qualities

FIGURE 22

Region Sourcing and Allocation Problem

(2) Wood type and quality guidelines for wood delivered to each facility;

(3) Prices and quantities of wood available from each alternative source;

(4) Some knowledge of wood characteristics and quality of each source;

(5) Raw material inventory at each facility of known size, quality (e.g., degree of deterioration), and cost.

The vital piece of information that is missing from this list is a measure of value: one for each raw material type at each facility where it could be considered to be a potential input. This value should express the effects of raw material properties on production costs and revenues. Without this information, any savings in purchase price or opportunity cost may be illusionary: more than overcome by higher processing costs or lower product revenue. While quality guidelines attempt to account for wood's value, they do a poor job of it. A maximum acceptable moisture level of 55 percent for wood fed to the boiler, for example, implies that all levels less than 55 percent are equally acceptable. We are given no index with which to measure the increasing desirabilty of drier wood. All moisture levels above 55 percent are assumed equally unacceptable, regardless of delivered price.

2. <u>Conversion Surplus</u>

Conversion surplus, which we defined previously as the excess of marginal revenue over marginal cost per unit input, would seem to be the logical evaluation tool. Could we not simply calculate a conversion surplus value for a given wood type at each potential consuming facility and allocate the wood to the place where its value is highest? A purchase and allocation scheme could be devised to select wood sources and destinations to maximize the spread between fiber cost and value for the region. Linear programming techniques would be ideally suited for this purpose. Unfortunately, while this approach would succeed in providing the wood mix having the greatest net value, it would fail dismally in meeting the firm's objective of maximizing profits. The reason, simply, is that wood's input into each of the production processes being considered is variable: it varies as a function of wood type and quality. Maximizing the net revenue from a single input factor maximizes region contribution to fixed costs and profits only so long as the quantity that may be added per unit time is fixed (see Duerr 1960, pg. 55).

It is extremely important that this concept be understood, so I provide a simple example. Say that we have two wood types, A and B, that are potential input to a Kraft mill's batch digesters. Assume that in this particular mill, the digesters are the "bottleneck" and operate at their volumetric capacity. Increased production from the digesters results in increased production of the mill's products. Wood type A has an effective yield of .50, meaning that half of its dry weight can be converted to usable fiber, and produces linerboard of high bursting strength and relatively high market value. Type A's conversion surplus calculates to be, say, $100 per dry ton. While type B has the same yield as type A, its fiber strength is lower and it produces a weak sheet of low market value. Because of the lower revenue that can be assigned to each ton of B that is pulped, B's conversion surplus is found to equal only $95 per dry ton.

But type B has one advantage that is not captured in the conversion surplus calculation. Its higher specific gravity allows more tons of wood to be packed into each digester load and, given the mill's bottleneck, provides for a greater rate of production. So long as our measure of value expresses mill contribution on a dollar per unit of input basis, the value of this increased productivity is not reflected. The computations in Table 6 will help to illustrate the problem.[2]

Conversion surplus is calculated as revenue minus processing cost divided by wood tonnage for each wood type. It is defined simply as mill contribution per unit of wood input: a measure of the wood's value in production.

TABLE 6

Conversion Surplus Computations

	Wood Type A	Wood Type B
Total Revenue ($1,000/day)	300*	319**
Variable Costs ($1,000/day)		
Chemicals @ $25/ton, wood	(50)	(55)
Energy @ $40/ton, finished	(40)	(44)
Packaging @ $10/ton, finished	(10)	(11)
Contribution Minus Wood Costs ($1,000/day)	200	209
Wood Input (tons/day)	2,000	2,200
Conversion Surplus ($/ton)	100	95

* 1,000 tons linerboard @ $300/ton
** 1,100 tons linerboard @ $290/ton

From Table 6 we see that although B's conversion surplus value per ton is less than A's, use of B provides a mill contribution (disregarding wood costs) that is higher. The question of whether type B is preferred to A depends on their relative prices. Assuming for a moment that both types can be delivered to the mill gate for $40/ton and leaving all other revenues and costs the same, we get the profit statement shown in Table 7. At a price of $40/ton, type B is preferred because it provides $1,000/day more in contribution than type A.

If asked the question, "What contribution to fixed cost and profit will result from processing one ton of each wood type in the facility?" we are able to provide an answer: conversion surplus. If asked instead, "Which type is preferred?" we cannot find the answer in conversion surplus, *unless wood input is held constant.* In the real world, it is more often the case that wood input will vary as a function of wood properties. Three examples are offered:

. A hogged fuel boiler operates at its maximum allowable emissions level: a level that is affected by fuel particle size and moisture content. The substitution of fine particles having higher moisture content (e.g., green sawdust for drier hog fuel) will result in higher emissions per dry ton fired. The larger the sawdust fraction in the fuel blend, the fewer the tons that can be combusted.

TABLE 7

Contribution Margin Computations

	Wood Type A	Wood Type B
Total Revenue ($1,000/day)	300	319
Variable Costs ($1,000/day)		
Chemicals	(50)	(55)
Energy	(40)	(44)
Packaging	(10)	(11)
Wood	(80)	(88)
Contribution ($1,000/day)	120	121

. A hogged fuel boiler is limited by the capacity of its fans to provide air for combustion. The higher the fuel moisture, the greater the requirement for excess air and the fewer the tons of wood that may be fired before the fans' limit is reached.

. A pulp mill operates at the capacity of its recovery boiler, which is limited in the amount of total dissolved solids that can be processed per unit time. Pulpwood having lower yield or higher cooking chemical demand will increase the boiler's total dissolved solids loading per dry ton pulped. Thus, both the mill's production rate and its rate of wood input are affected directly by wood properties.

Given that the wood's physical properties affect its rate of input into most production processes and, therefore, that conversion surplus fails us as an evaluation tool, how then do we proceed? By what criteria do we judge the desirability of a given wood type being considered for use in a particular facility? Clearly, we must use some index of wood's contribution to net revenue, not its value per ton. We must account for differences in revenues and costs that result from differences in the permissible rate of wood input.

3. Relative Fiber Value

Let us return to the example illustrated by the value and contribution calculations of Tables 6 and 7. From Table 6 we see that use of type B provides a mill contribution that is $9,000/day higher than would be earned if type A were used instead. But B's full benefit requires input of 10 percent more wood. Clearly, type B is preferred so long as its total cost does not exceed that of type A by \$9,000/day. Mathematically,

$$2{,}200\ (\text{Price B}) - 2{,}000\ (\text{Price A}) < 9{,}000$$

$$\text{Price B} < \frac{9{,}000 + 2{,}000\ (\text{Price A})}{2{,}200}$$

This relationship is graphed in Figure 23. If the price of type A is \$40/dry ton, as assumed in Table 7, then we can pay any price less than \$40.45/dry ton for type B and improve region contribution. If A's price increases to \$60/dry ton, however, we can pay only \$58.63/dry ton for B and break even. The *relative value* of B to A is not static; it varies with the price of A. This relationship is illustrated in Figure 24. Given a price for A, the graph shows how much more, or less, the firm can spend for B and leave region contribution unchanged.

If the Relative Fiber Value approach is to be used, alternate wood types being considered for addition to a facility must be evaluated against the specific wood type for which they would be substituted. They may not meaningfully be evaluated against a "base case" blend of wood types (the present mill furnish) and an average wood cost. The error in this approach is illustrated in Figure 25.

Assume that a wood-using facility presently receives a blend of three wood types: x, y and z. At price P(b), the wood types have relative values given by V(x), V(y), and V(z). (Notice that at price P(b') the relative values have reversed themselves, with type z now having the highest value relative to the blend.) These values have validity only if the wood type being evaluated is substituted for the

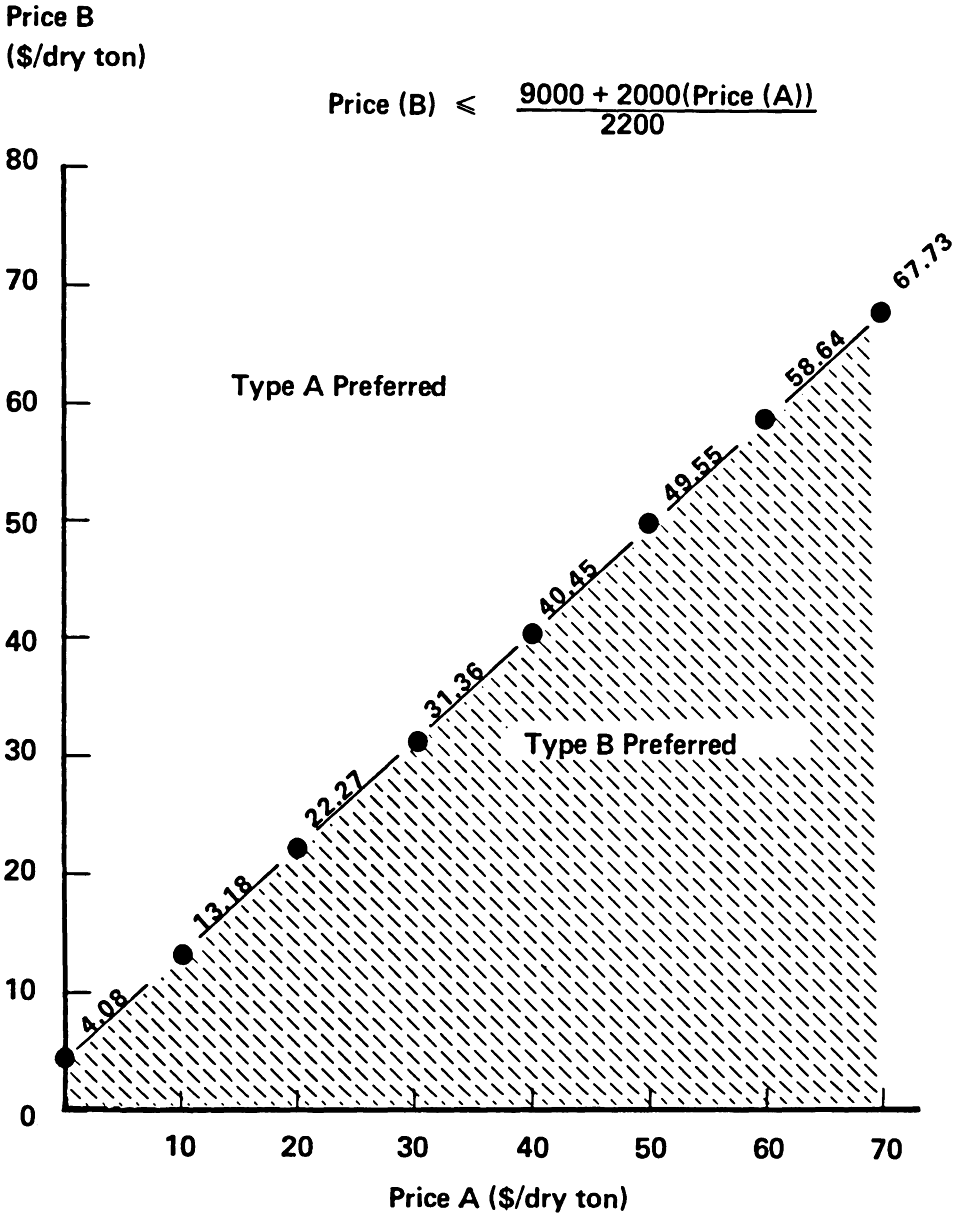


FIGURE 23

Breakeven Prices
Wood Types A and B

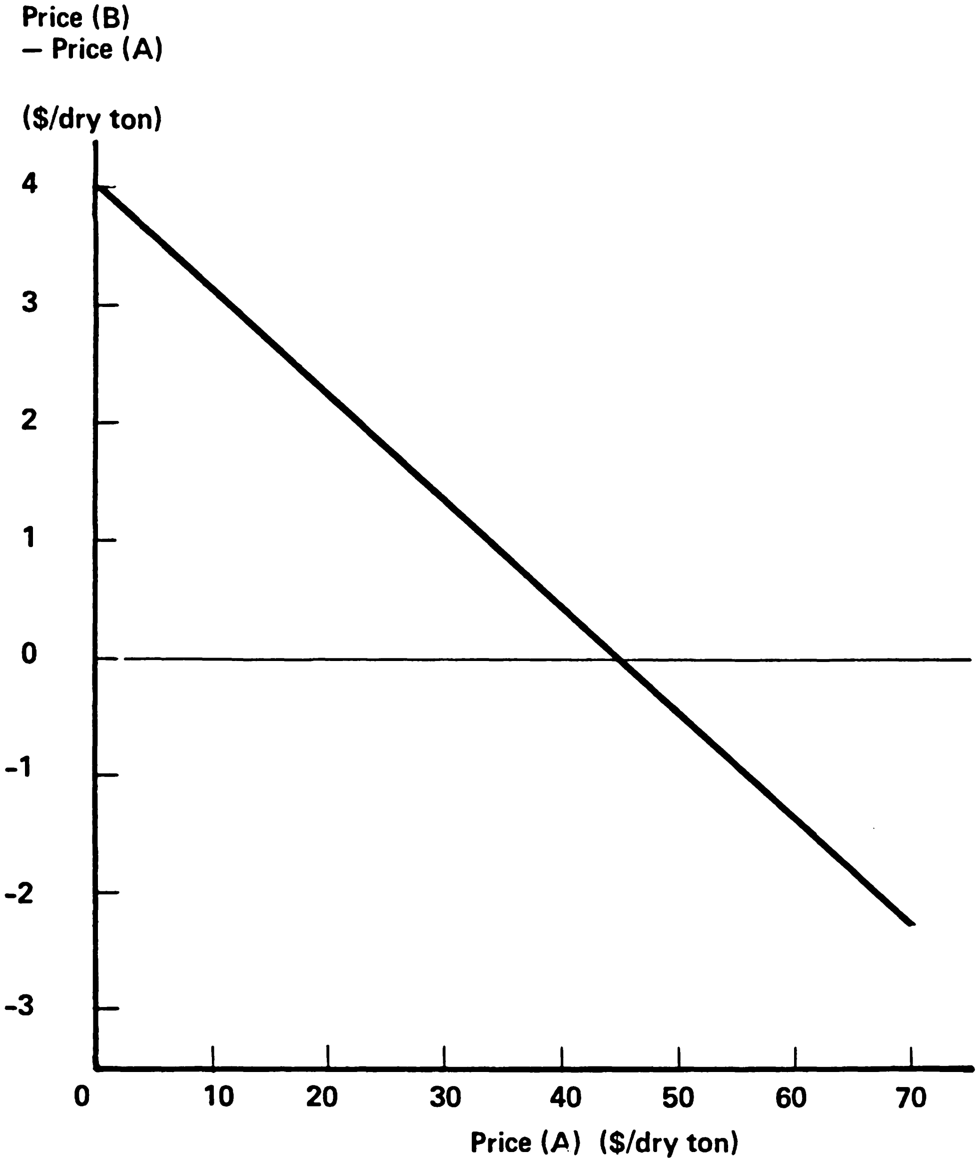


FIGURE 24

Relative Fiber Value
Type B to Type A

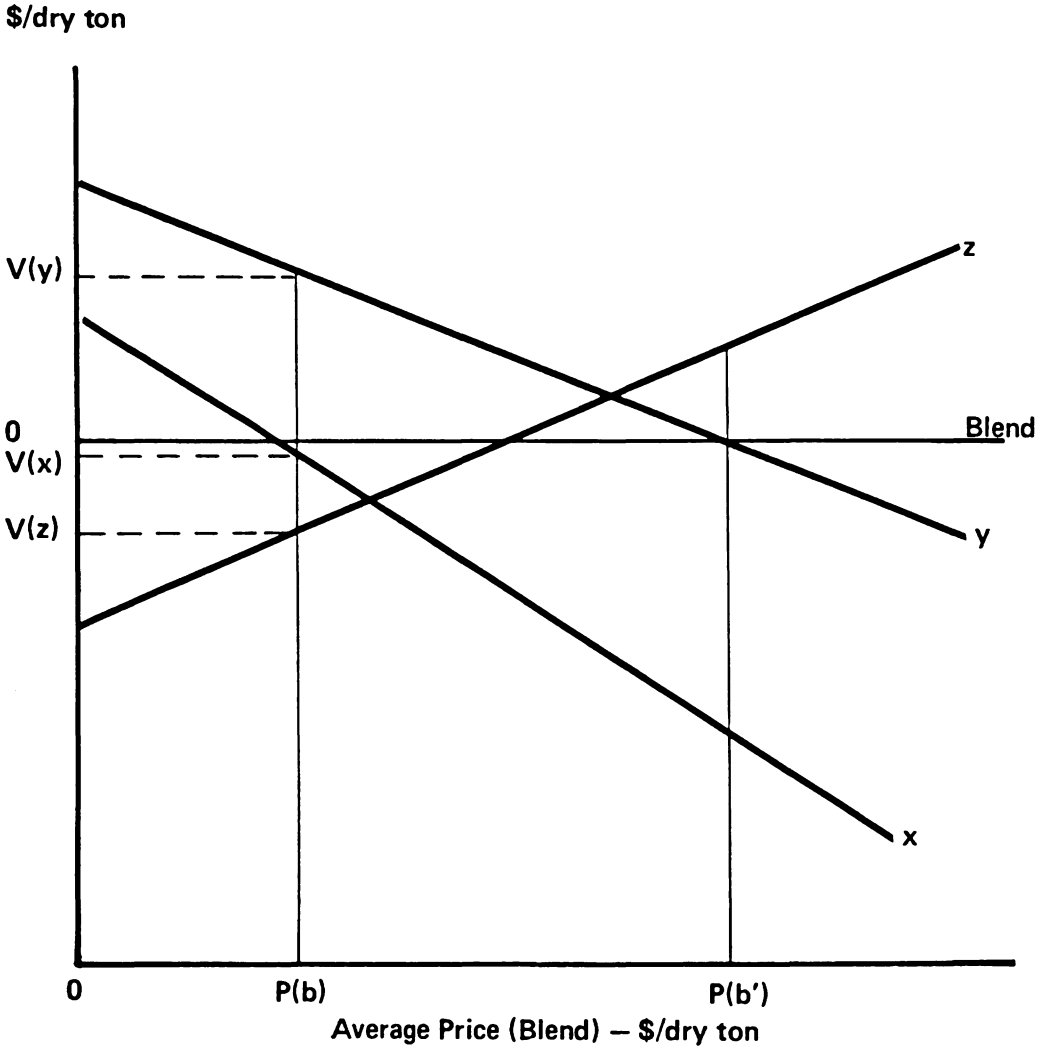


FIGURE 25

Relative Fiber Value
Wood Types x, y and z Relative to the Blend

wood types that comprise the blend in their correct proportions and at the average wood cost used in the relative value calculations. Far more interesting - and more likely - is the substitution of one wood type for another where the price of the wood type being replaced does *not* equal the average wood cost. But here the relative values plotted in Figure 25 are of no help. We cannot say, for example, that at price P(b), type y should be substituted for type z because its value is higher by an amount V(y) - V(z). We know only that if type y were used to replace wood of the proportional types and average cost of the blend, its value would exceed that of the wood it displaced by an amount V(y). The relative value of y to z depends upon z's price, not the price of the blend.

To correctly identify the collection of wood types that maximize region contribution, we must formulate a Relative Fiber Value equation like the one shown in Figure 24 for each raw material alternative relative to every other one over the conceivable range of prices. Then, for a given set of prices, we could (with some effort) select the set of wood types having the greatest value relative to one another and use them to maximize region contribution. Let the price of just one of them change, however, and the relative values change as well, necessitating a new analysis and, quite possibly, a new optimal assortment of wood types. This approach has little practical appeal.

4. Return to Capital

The objective is to maximize region contribution through our choice of wood types. Each wood type has the potential to affect both the maximum permissible wood input and production output at each wood-using facility. *Each has the* *potential to* shift *the firm's total cost and total revenue functions because "wood" is not a homogeneous input factor.* Given this situation, the firm should attempt to maximize contribution neither per unit input nor per unit output. We can demonstrate the validity of this statement with the help of data from Table 7.

	Wood Type A	Wood Type B
Contribution/Unit Input ($/dry ton)	60	55
Contribution/Unit Output ($/dry ton)	120	110

Both methods identify A as the wood type with the highest value, but we already have shown B to provide the greatest contribution.

In the final analysis, the firm cares little about quantities in and out, only about total contribution. It should maximize contribution relative to the only factor of production that definitely remains fixed in the short-run: the physcial plant. The facility manager should ask, "If I devote 5 percent of my plant's capacity to processing wood type B as opposed to A, what difference will it make to my mill's contribution?" This is the key question.

The question can be answered by calculating a return-to-capital value for each wood type being considered, where return-to-capital is defined as contribution per percent of facility capacity expended. We simply divide the mill contribution resulting from use of a given wood type and volume by the percentage of mill capacity devoted to its processing, as shown in Table 8.

TABLE 8

Return to Capital Calculations

	Wood Type A	Wood Type B
Total Revenue ($1,000/day)	300	319
Variable Cost ($1,000/day)		
Chemicals	(50)	(55)
Energy	(40)	(44)
Packaging	(10)	(11)
Wood	(80)	(88)
Contribution ($1,000/day)	120	121
Percent Mill Capacity Expended	100	100
Return to Capital ($/percent mill capacity expended)	1,200	1,210

These figures show that for each percent of mill capacity devoted to processing wood type B, the mill earns $10/day more in contribution than would be the case if A were processed instead. Expended capacity should be calculated at the mill bottleneck as the flow at this stage of processing that results from the wood type and volume being evaluated divided by the total allowable flow. The wood type need not "consume" 100 percent of facility capacity, as shown here. This certainly will not be the case in practice. So long as the values are expressed per unit of facility capacity, any volumes are comparable.

Note carefully that wood price is a component of return-to-capital. As the price of a wood type changes, so, too, does its return-to-capital. Indeed, return-to-capital for a given wood type may be plotted as a function of its price as shown in Figure 26 for wood type B. B's return-to-capital equals zero at the point where its price equals $95/dry ton: its conversion surplus value (see Table 6). At this point, mill contribution equals zero: all potential earnings have been expended for wood.

To maximize mill contribution, all the fiber manager need do is select wood sources that maximize return-to-capital for the fraction of mill capacity that the firm elects to operate. These sources are those appearing to the left of the 100 percent line in Figure 27. The area under the full curve (from 0 to 100 percent) shows the total contribution that would result from conversion of these sources to final product. Small rectangles under each "step" of the function show mill contribution attributable to each source or supplier. Numbers above the return-to-capital curve are supplier designations assigned on the basis of delivered price, with low numbers indicating the cheapest sources (see Figure 28).

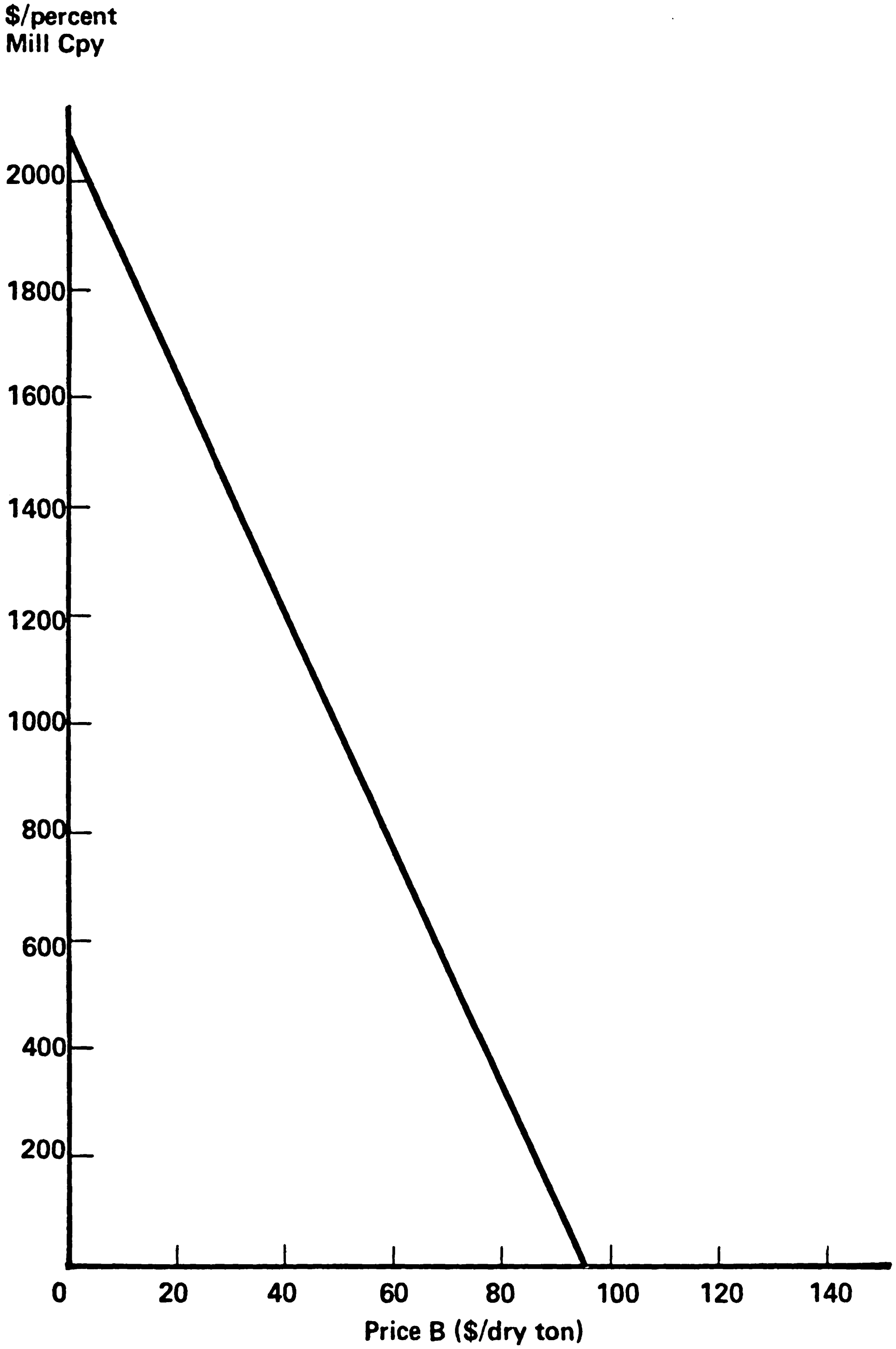


FIGURE 26

Return-to-Capital
Wood Type B

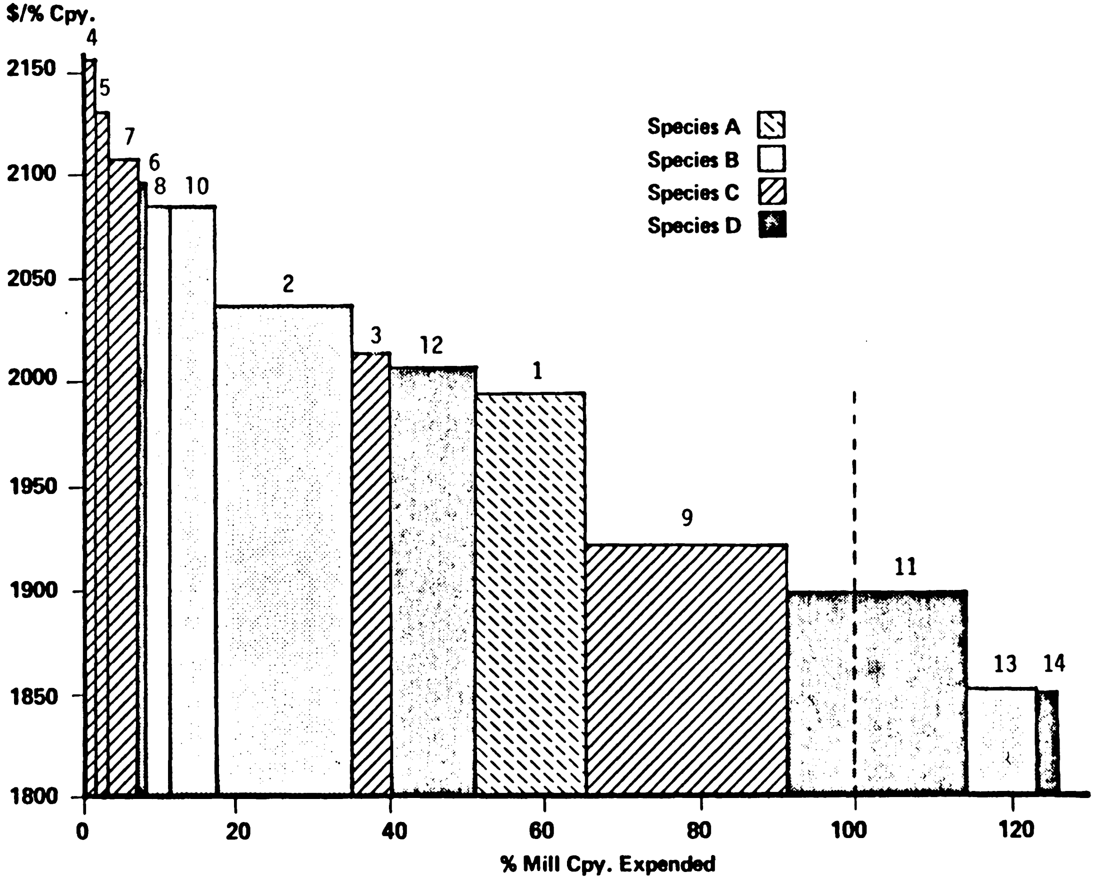


FIGURE 27
Return-to-Capital as a Function of Facility Capacity Expended in Processing

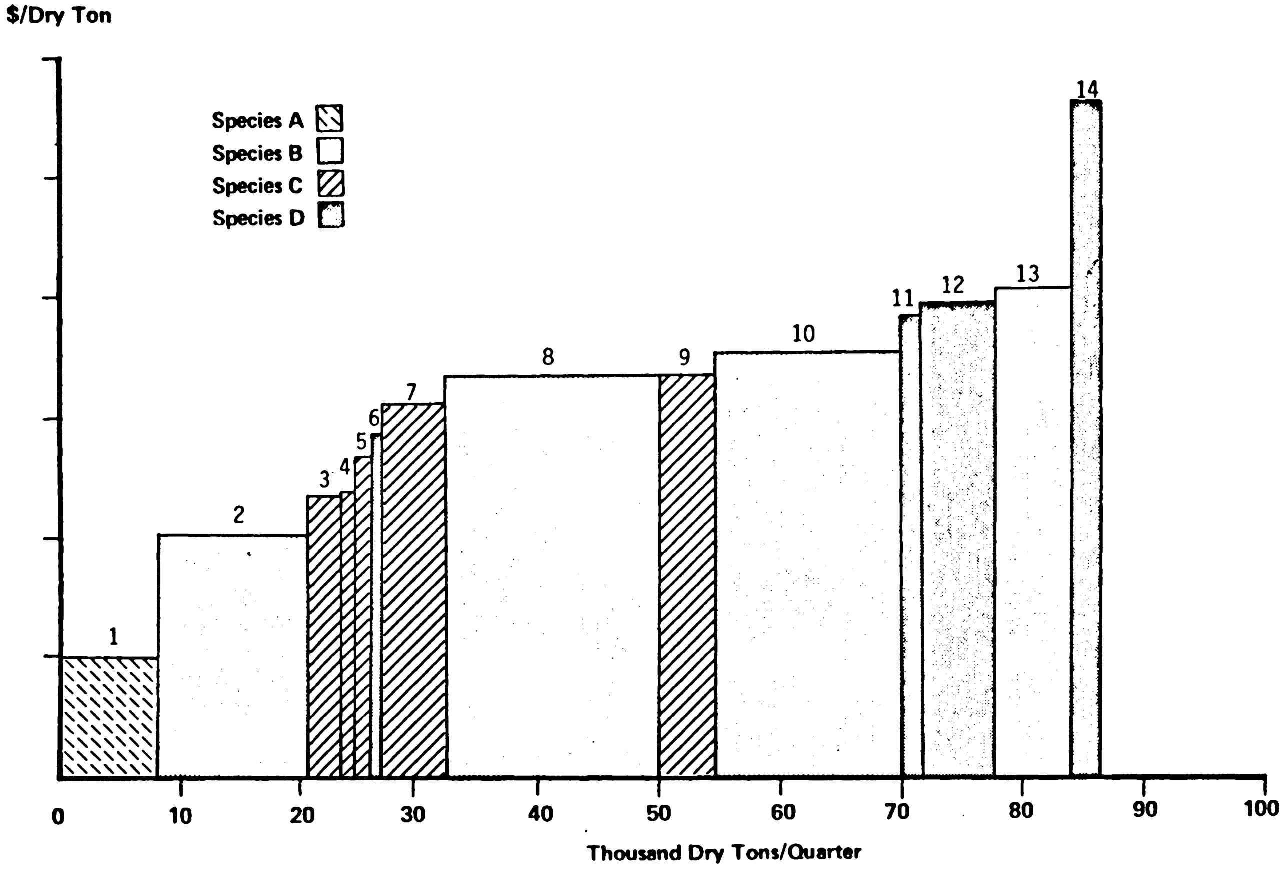


FIGURE 28
Wood Supply Function

Figure 27 shows that Supplier 4 offers the best deal to the firm. Paying Supplier 4's price and converting his wood to final product returns $2160 in contribution per percent of mill capacity expended in processing. Conversion of Supplier 1's wood, on the other hand, returns only $2000 per percent of capacity, even though Supplier 1 sells his wood most cheaply (refer again to Figure 28).

To determine how much the firm should be willing to pay for wood from a given supplier, the fiber manager should calculate the wood cost that causes the return-to-capital to equal that of the best available alternative: the wood type whose return-to-capital places it next in line for admission into the mill. (Figure 27 shows this to be Supplier 11.) This price is the maximum that the firm should be prepared to pay. A higher price will cause the alternative to be preferred. No wood type should be processed, of course, that promises a negative return-to-capital.

Wood should be allocated within the region so as to maximize total return-to-capital for all converting facilities. This does not mean necessarily that each wood source should be assigned to the facility where its return-to-capital is highest. The effect of each assignment on the *system* of facilities must be considered. The problem is well-tailored for a linear programming solution.

We have seen that difficulty in *ranking* wood sources is experienced each time wood's "value" is expressed on a dollar-per-ton basis. While conversion surplus provides an accurate measure of value in production, it fails to account for differences in productivity resulting from differences in physical properties.

Relative fiber value analysis considers differences in contribution, but fails to provide an index having the flexibility to be used in all fiber substitution situations. Relative values are valid only for the specific substitution alternative (e.g., wood type A for wood type B at price Y) addressed in the calculations. Return-to-capital ranks wood sources on the basis of contribution per unit of capital expended in their conversion. Willingness-to-pay is calculated relative to the marginal supplier: a source that should not be identified on the basis of cost alone. Region contribution is maximized by selecting and allocating wood sources in a way that maximizes region return-to-capital.

B. Long-Run Analysis

We discussed the economic trade-off between wood and fossil fuel in Chapter IV, and between different types of wood fuels in the first section of this chapter. To this point, our analyses all have been for the short run; i.e., an existing array of capital assets was assumed and no thought was given to changing it. As the planning horizon is extended, we find that there are opportunities to design capital assets around a new (expected) set of relative prices and thereby improve the firm's profitability and net worth.

Selection of the "best" fuel for use in production over the firm's planning period is made through capital budgeting analysis. In essence, this procedure involves estimating all after-tax costs and benefits that may accrue to the choice of a fuel and its associated system of assets over their useful lives, and then discounting or compounding this stream of cash flows, using the firm's cost of capital,[3] to a single point in time for analysis. Alternatively, an internal rate of return[4] may be calculated for an investment showing the discount rate at which the present values of estimated costs and revenues equate. The analysis then is made by comparing this discount rate with the firm's cost of capital to see what effect the return expected from the project will have on the firm's total worth. Many excellent treatments of capital budgeting procedure exist, and we have no intention of duplicating them here.[5]

The problem, after all, is not in the procedure to follow in making the analysis, but in the numbers to use. More fundamentally, the problem relates to the very real possibility that the numbers that the firm chooses are wrong and that, in consequence, the wrong capital investment decision will be made.

The capital investment decision lies at the very heart of the firm's continued viability: its ability to compete in future markets. The decision results in a long-term loss in flexibility. It commits the firm to a specific production technology, scale of operation, and product mix, all of which can be modified only at high cost. Indeed, as we discussed in the opening pages of this paper, the energy crisis has arisen largely as the result of our selection of an energy-intensive and fluid-fuel specific stock of capital assets that will require enormous investments in time, labor, and natural resources to replace.

Capital budgeting analysis requires these inputs:

(1) A project's initial investment cost.

(2) The timing and amount of future cash flows that accrue to the investment.

(3) The firm's cost of capital for *this* project.

Given these estimates for each investment opportunity, capital budgeting analysis enables the firm to rank its alternatives on the basis of the extent to which each promises to increase the value of the firm.

Such ranking, of course, must be made with an eye toward project risk. For the firm does not *know* the value of *any* of its inputs into the capital budgeting equation: they are mere estimates. Some of the estimates are made with much greater certainty than others, however. The cost of the initial capital investment is predictable with reasonable assurance, for example, because the transaction occurs in the not-too-distant future. Bids on alternative asset configurations may be solicited from construction firms, and contracts may be effected to provide the firm with relatively sound estimates of investment costs. Even the cost of capital, with all of the problems that may surround its precise numerical determination, is observable, at least indirectly, in today's market. It is a *present* concept, as opposed to a future one. The firm may observe from present market transactions the impact that the adoption of a given type of project has on the value of equity shares. The cost of capital for a given firm adopting a given project exists *today*.

It is the timing and amount of future cash flows that is subject to the greatest degree of uncertainty, for these costs and revenues all occur in the future.

Risk is associated with the course of future events. The farther into the future that one attempts to predict, the greater is the risk that will be involved.

In the case of the firm's selection of a fuel and associated assets to provide energy for Kraft pulp-paper manufacture, the risk is that it makes the wrong choice. The firm may choose to invest in a wood-fired system today, for example, only to find that future relative fuel prices are such that it would have been better off to have invested in an oil-fired system instead. In consequence, it is left with a stock of capital that may place it at a disadvantage with respect to its competitors. This is risk. Risk is not merely a measure of the firm's failure to predict future fuel prices accurately, but the chance that the predictive failure is *so great* as to make the firm better off to have selected an alternative system. The firm is unconcerned with its error, so long as the fuel sytem that has been selected remains preferable to the alternatives, for then it remains better off. This discussion defines risk in terms of semi-variance.

The use of semi-variance as a measure of risk is described by Markowitz (1959, pgs. 188-194, 287-297), Porter (1975), Hogan (1974), Mao (1970), and Morton (1969), among others. The principle of semi-variance defines risk, not in terms of the traditional expected value-variance measure,[6] but as the probability that some minimum or target return (e.g., the cost of capital) will fail to be achieved. The problem with using variance as a measure of risk is that extreme gains and losses are both identified as undesirable. Semi-variance concentrates only on the probability of loss. In capital budgeting analysis, semi-variance sometimes is used as a measure of the probability that an investment will fail to earn its opportunity cost of capital, and that the value of the firm will be eroded. (See Figure 29.) This, then, is risk: the probability of earning a rate of return which is less than the cost of capital.

For the firm considering a fuel and associated conversion system for investment, risk should be measured as the probability that the wrong choice is made: that, relative to an alternative which could be selected, the investment under consideration will result in a loss. Let us illustrate our point with the aid of an example using a framework proposed by Ellis (1978). Tables 9 and 10 are hypothetical before-tax cash-flow analyses of alternative wood and oil-fired systems that can be installed in a new Kraft mill. Assume that the decision has been made to construct the new mill and that the only question remaining with regard to the power boiler is the type of fuel around which it should be designed. Assume that both systems fully satisfy the mill's energy requirements and that both are identical as regards expected physical life, reliability, and output. The total cost columns are combined in Table 11 to determine the expected net present value of the cost savings that the firm would enjoy if it were to choose the oil-fired system in preference to wood. The elements of the analysis in Table 11 are those that we discussed previously, but note that we now deal with cost *differences* instead of costs. Uncertainty is involved in all of the estimates in each of the tables. An error in any one of them may cause the wrong investment alternative to be identified as preferred. But, as we have discussed, risk is most evident in predictions of the course and magnitude of future cash flows.

Uncertainty in these estimates places a probability distribution[7] around Table 11's expected net present value, as shown in Figure 30. Risk is shown to be

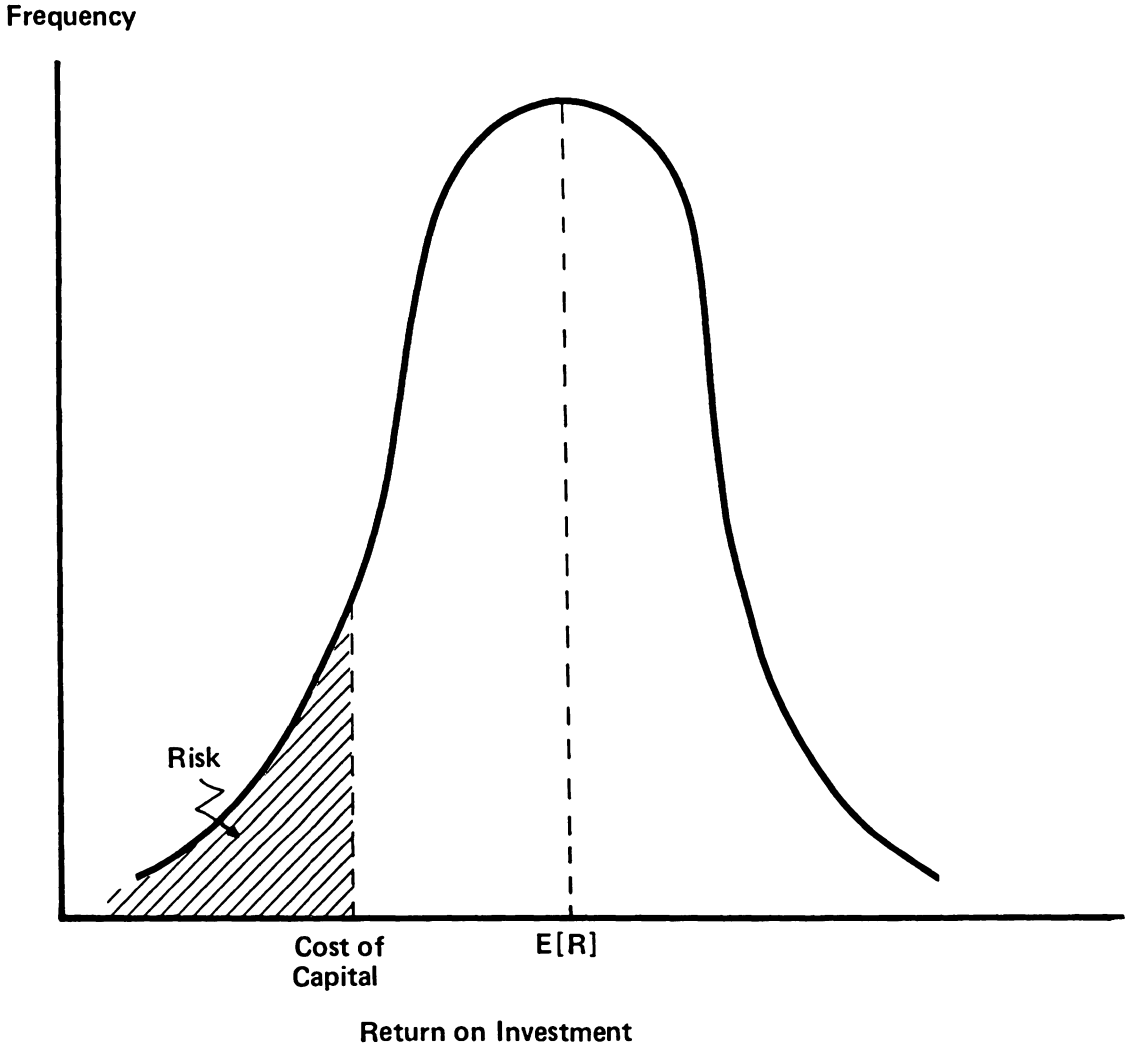


FIGURE 29

Semi-Variance as a Measure of Risk in Capital Budgeting Analysis

TABLE 9

Wood Fuel System Cash Flow Analysis

Year	Capital Investment	Fuel Cost	O&M* Cost	Property Tax & Insurance Cost	Total Cost
0	500,000				500,000
1		70,000	28,000	10,000	108,000
2		75,600	29,400	9,500	114,500
3		81,648	30,870	9,025	121,534
4		88,180	32,414	8,574	129,168
5		95,234	34,034	8,145	137,413
6		102,853	35,736	7,738	146,327
7		111,081	37,523	7,351	155,955
8		119,968	39,399	6,983	166,350
9		129,565	41,369	6,634	177,568
10		139,930	43,437	6,302	189,669
Escalation Rate Used	0%/year	+8%/year	+5%/year	-5%/year	

* Operation and Maintenance

TABLE 10

Oil-Fired System Cash Flow Analysis

Year	Capital Investment	Fuel Cost	O&M* Cost	Property Tax & Investment Cost	Total Cost
0	250,000				250,000
1		140,000	12,000	5,000	157,000
2		159,600	12,600	4,750	176,950
3		181,944	13,230	4,513	199,687
4		207,416	13,892	4,287	225,595
5		236,454	14,586	4,073	255,113
6		269,558	15,315	3,869	288,742
7		307,296	16,081	3,675	327,052
8		350,318	16,885	3,492	370,695
9		399,362	17,729	3,317	420,408
10		455,273	18,616	3,151	477,004
Escalation Rate Used	0%/year	+14%/year	+5%/year	-5%/year	

* Operation and Maintenance

TABLE 11

Capital Investment Analysis: Oil- Versus Wood-Fired Systems

Year	Cost of Oil-Fired System	-	Cost of Wood-Fired System	=	Nominal Cost Savings	Present Value @ 20%
0	250,000		500,000		-250,000	-250,000
1	157,000		108,000		49,000	40,833
2	176,950		114,500		62,450	43,368
3	199,687		121,534		78,153	45,227
4	225,595		129,168		96,427	46,502
5	255,113		137,413		117,700	47,301
6	288,742		146,327		142,415	47,694
7	327,052		155,955		171,097	47,750
8	370,695		166,350		204,345	47,524
9	420,408		177,568		242,840	47,064
10	477,004		189,669		287,335	46,406
					Expected Net Present Value =	209,669

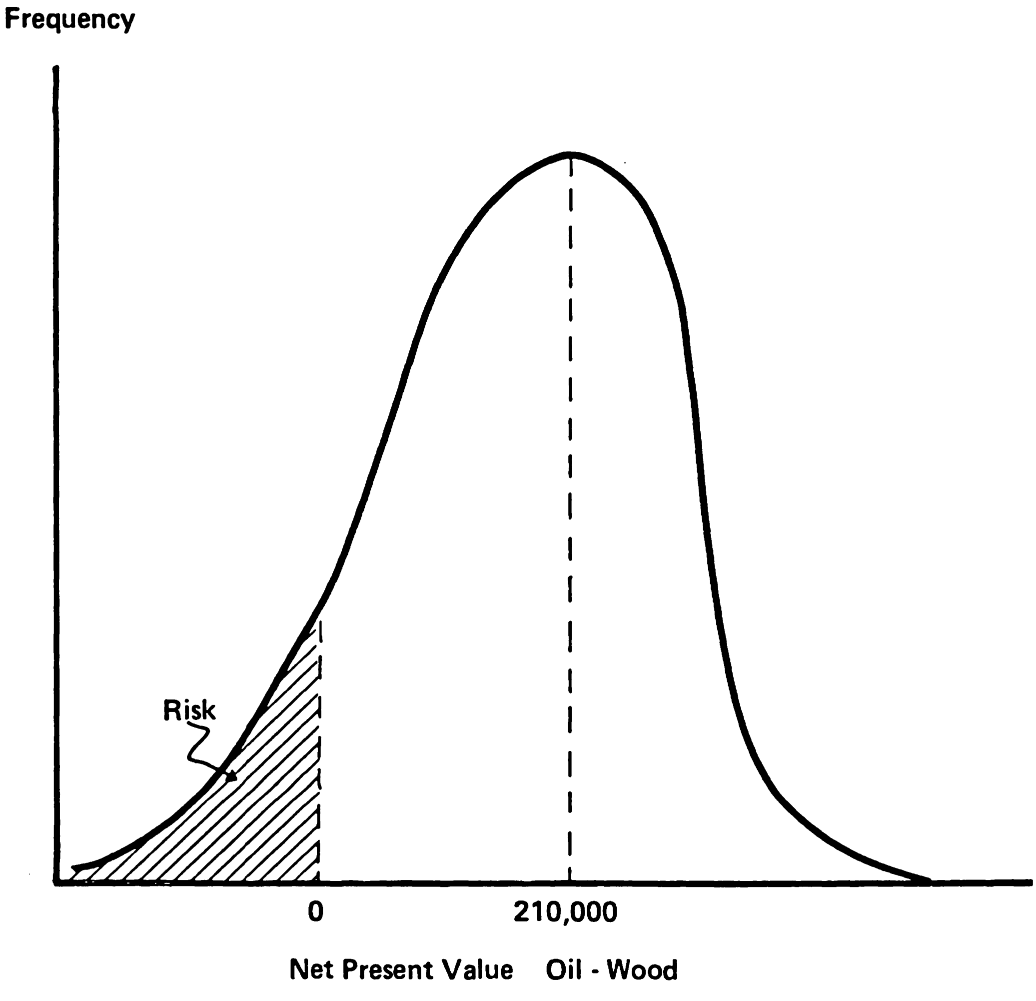


FIGURE 30

Semi-Variance Risk in Selection of the Oil-Fired System the area that corresponds to a negative net present value: the area describing the probabilty that the wood-fired alternative would prove less costly.

The problem comes in describing the probability density function of Figure 30 mathematically so that semi-variance can be measured. This is exceedingly difficult because of the large number of uncertain elements that have been combined and, especially, because of the interactions between them. These estimates are not independent: a change in the expected value of the cost of one fuel affects the expected values of all others; costs in one period affect expected costs in each succeeding period and, in all likelihood, the probability distributions surrounding them as well. Sorting through these multiple probabilities, joint probabilities, and conditional probabilities would be an extremely difficult task. Furthermore, the business community would never adopt it. We need a simple, understandable method to evaluate risk: one that yields a measure approximating the area that has been defined as semi-variance.

Let us consider the capital budgeting problem outlined in Tables 9 through 11. For the sake of simplifying the example, assume that the firm's managers are confident that they can predict accurately all costs and discount rates required for the analysis with the exception of future fuel prices. While present prices are known, the escalation rates that should be used for the two fuels are subject to great uncertainty. Assume, however, that the firm's financial analysts are able to assign subjective probabilities to various fuel price inflation rates, and, further, that they have compiled historical data to show some measure of covariability: the way the fuel prices move relative to one another. After much research and analysis, the firm's financial experts provide the estimates given in Table 12.

TABLE 12

Fuel Price Escalation Probabilities

Wood Fuel Price Escalation Rate			Oil Price Escalation Rate	
Rate	Probability		Rate	Probability
			18	.10
			17	.15
10	.10	High Case	16	.35
			15	.20
			14	.20
			16	.10
9	.20		15	.25
8	.40	Most Likely	14	.30
7	.20		13	.25
			12	.10
			14	.20
			13	.20
6	.10	Low Case	12	.35
			11	.15
			10	.10

Using this data, we can *simulate* solution of the capital budgeting equation over a large number of trials, and, in this way, describe with reasonable accuracy the probability distribution shown in Figure 30.

While the analysts foresee no significant interaction while wood prices inflate in the range 7 to 9 percent per year, they feel that an economy that would give rise to a 10 percent per year increase in the price of wood fuel would have an accompanying higher expected escalation rate for oil prices. Similarly, wood price escalation at the low end of the range would be expected to accompany lower oil price inflation. The probabilities shown for each escalation rate are the analysts' best estimates, based on regression analysis of past price trends.

The simulation analysis proceeds as follows:

(1) Our computer selects a random number that corresponds, on the basis of our assignment in Table 13, to a wood fuel escalation rate. The number chosen will designate one of three possible oil price distributions from which a second escalation rate is to be selected. For example, the number 93 tells us that a wood fuel escalation rate of 6 percent should be used for the trial, and that the oil price escalation rate should be selected randomly from the "Low" probability distribution.

(2) A second random number is selected and, depending on the probability distribution that has been identified, matched with its corresponding oil price escalation rate.

TABLE 13

Cumulative Probabilities and Random Number Assignment

Wood Fuel Price Escalation Rate					Oil Price Escalation Rate			
Rate	Probability	Cumulative Probability	Random Number Assignment		Rate	Probability	Cumulative Probability	Random Number Assignment
					10	.10	.10	01 to 10
					17	.15	.25	11 to 25
10	.10	.10	01 to 10	High Case	16	.35	.60	26 to 60
					15	.20	.80	61 to 80
					14	.20	1.00	81 to 99 and 00
					16	.10	.10	01 to 10
9	.20	.30	11 to 30		15	.25	.35	11 to 35
8	.40	.70	31 to 70	Most Likely	14	.30	.65	36 to 65
7	.20	.90	71 to 90		13	.25	.90	66 to 90
					12	.10	1.00	91 to 99 and 00
					14	.20	.20	01 to 20
					13	.20	.40	21 to 40
6	.10	1.00	91 to 99 and 00	Low Case	12	.35	.75	41 to 90
					11	.15	.90	76 to 90
					10	.10	1.00	91 to 99 and 00

(3) The two price escalation rates are then used to calculate a new net present value, precisely as we have shown in Tables 9 through 11. (Only this time, it is to be hoped, with the aid of a computer!)

(4) A large number of trials are run.

(5) The percentage of the time that a negative net present value is calculated becomes our estimate of semi-variance and our index of risk.

Any level of complexity can be added, of course. Simple and conditional probability distributions may be described for other elements of the capital budgeting equation or, indeed, for all of them! The only requirement is that the firm devote sufficient expertise and effort to the task to make the results meaningful.

Clearly, the analysis of risk adds a new dimension to capital budgeting analysis: complicating an already difficult process with requirements for more estimates that require more labor and more computer time. The point is that expected values simply are not sufficient bases for decision-making. Managers want to know how good their numbers are, and how confident they can be in the accuracy of the "bottom line." The method of risk analysis outlined here provides this information.

This chapter has been concerned with near and long term fuel selection criteria. We have described an index, return-to-capital, that can be used to rank alternative fuelwood sources on the basis of their contribution to fixed costs and profits. We have developed a framework for risk analysis in capital budgeting that provides managers with a measure of reliability in the estimated payoff from alternative systems of energy conversion assets. All that remains is to pull together our thoughts and to speculate on wood's future as an energy source in the kraft industry.

VI. CONCLUSION

What have we accomplished? Hopefully, we have laid a foundation for analysis and provided some insight to assist kraft industry managers in weighing the financial trade-off between use of wood as a source of fiber versus a source of energy. This analysis is not a simple one. Rising energy costs have caused some wood types to become strong candidates for energy conversion that heretofore would not have been considered. Why should the industry manager be concerned with this trade-off? Because wood remains his most expensive input. Wood's allocation between its many possible end uses in the modern kraft mill will significantly affect mill profitability and, in consequence, the firm's net worth. It is important that the proper choices be made. The following paragraphs summarize our major points from each chapter.

We asserted in Chapter I that the so-called "Energy-Crisis" has arisen largely from two factors: (1) a radical shift in relative prices, and (2) a lag in development of new capital that is required to adjust to the new price structure. While it appears that increased energy consumption is not a necessary condition for economic growth, this may be true only for the long run, after capital adjustments have been made. This short-run adjustment to a new relative price structure results in a transfer of wealth from those who possess fluid fuel-intensive capital to those who possess fluid fuel.

Wood is a low-grade substitute for fossil fuels and contains roughly one-third the recoverable energy of bituminous coal (although this varies enormously). Fuelwood's advantage lies in its environmental compatibility. Its combustion emits virtually no sulfur dioxide emissions - the plague of coal-fire boilers - and its generation of nitrous oxides and particulates is controllable at reasonable cost with existing technology. Water removal appears to be the most practical way of imparting higher value to fuelwood, but the use of "waste heat" or another fuel in a drying facility seems justified only under special circumstances.

It appears that the cost of energy derived from wood is greatly dependent on the level of "subsidy" provided by other, "higher" products of the log. Given the present relative price structure, wood does not seem able to pay its full way from seedling to boiler without depending on other products to bear a portion of the cost. The price that the kraft manufacturer must pay for energy derived from wood depends on this level of subsidy.

The Hopewell case study illustrated the practical problems involved with a short-run analysis of the least-cost fuel mix to satisfy a kraft mill's steam demand. Considering wood fuel to be a homogeneous commodity, the economic trade-off between wood and an alternative fuel can be determined using the techniques of linear programming. The problem comes in assigning variable costs by fuel type.

In the final chapter, we developed "guides" for industry managers to enable them to better assess wood's fuel potential for short and long-run production. Indices of "value," where value is expressed in dollars per dry ton, were found to provide accurate ranking of wood sources only if wood input was held constant. Since wood properties generally affect its rate of input, value indices may be inappropriate guides to wood sourcing and allocation. A new index, return-to-capital, was developed as a measure of contribution to fixed costs and profits per percent of capital "expended" in the process. Willingness-to-pay may be calculated as equivalent value relative to the marginal supplier: the one whose wood stands next in line for admission to the mill after both delivered price and value in production are considered.

Selection of the best fuel for long-run production is made by assuming an array of future relative prices and applying the methods of capital budgeting analysis. In general, risk increases with distance into the future that the firm attempts to forecast relative prices. Using semi-variance as a measure of risk, a method of analysis was developed to assist in evaluation of alternative investments in energy conversion assets. This approach provides an explicit measure of risk and, hence, an index of the analyst's confidence in his findings.

We find ourselves in these latter decades of the twentieth century extolling the virtues of fuels of a bygone era - wind, coal, wood - that are unquestionably of lower quality than the fuels that they must now displace. Greater inputs of labor and capital will be required to convert these low-grade energy sources to useful form. We may now exist in the twilight of the era of fossil fuel. For decades, the New Age was thought to be nuclear: electricity was to be produced so cheaply that it would not be economic to meter. Now the bets are being hedged. Wood's future as an energy source will be determined by relative prices. In the short run, our challenge is to determine what relative prices are; for long-run planning, to determine what they will be.

There is nothing sinister or inherently wasteful in burning wood that heretofore was converted to lumber or paper. Providing warmth is no less noble an end than providing shelter; no less noble than conserving fossil fuel that has required eons to produce. When relative prices identify energy conversion as wood's highest and best use, we should throw it into the boiler... and do so cheerfully.

FOOTNOTES

Chapter 1

[1] The OPEC cartel presently controls more than 70 percent of the world's proven oil reserves, with over 25 percent of the world total belonging to Saudi Arabia alone (Time, May 7, 1979, pgs. 73, 78).

[2] Labor, materials and time: the combination of which yields capital

Chapter 2

[1] Between 1965 and 1973, 84 percent of the industrial boilers sold in this country in the less than 500,000 lb of steam per hour size-class were designed for oil or natural gas as the principal fuel. Only 3.9 percent were designed primarily for coal and 1.3 percent for wood (Battelle 1976, pg. 22). This boiler size-class is significant to our discussion because a 500,000 lb/hour boiler generally is taken to fall near the upper limit of wood-firing feasibility due to the relatively short distances over which wood may be transported economically. See Hall (FPRS 1976, pg. 141).

[2] Hydrolysis is a chemical process of decomposition involving addition of the elements of water, usually induced by the presence of an enzyme or dilute acid.

[3] Hans Thirring (in Tillman 1978, pg. 210) calculates that sugar crops have a maximum potential yield of roughly 265 gallons/acre/year of alcohol, compared to 180 gallons for potatoes, 90 gallons for corn, and 70 gallons for wood. See also USFS (1976, pg. 175).

[4] Pyrolysis is destructive distillation that occurs when an organic material is heated in the absence of oxygen.

[5] Wood gasification is carried on at approximately 80 percent efficiency, for example.

[6] In assessing the economic feasibility of retrofitting existing oil- and gas-fired boilers in the pulp and paper industry with wood gasification units, for example, MITRE (1979, pg. 27) concluded that direct firing of wood in boilers designed specifically for this purpose was the preferred alternative. More will be said on this subject later.

[7] Excess air is air in excess of that which is theoretically required for combustion. Wood typically is fired with 25 to 50 percent excess air (Corder in FPRS 1975, pg. 31), while gas, oil, and pulverized coal are fired with roughly 15 percent (Flick in FPRS 1976, pg. 150, and Battelle 1976, pg. 29).

[8] Moisture percentages given here are percentages of total weight (wet basis).

[9] An excellent reference for southern hardwood species is Floyd G. Manwiller, 1975. Wood and bark moisture contents of small-diameter hardwoods growing on Southern pine sites. Forest Science. 8(1): 384-388.

[10] This calculation is made as follows:

For hardwood versus coal $\frac{6{,}500 \text{ BTU/lb} \times .75}{14{,}000 \text{ BTU/lb} \times .85} = 41$ percent

For softwood versus coal $\frac{4{,}000 \text{ BTU/lb} \times .70}{14{,}000 \text{ BTU/lb} \times .85} = 24$ percent

Wood fuel combustion efficiencies were derived from Figure 11, assuming as-received moisture levels given in Table 1. The oil calculations are carried out in precisely the same manner.

[11] Derived from Tillman (1978, pgs. 76, 79), assuming a 67 percent conversion efficiency for bark and an 85 percent conversion efficiency for coal.

[12] Ash contents for North American woods typically are found to be on the order of 1 percent of dry weight (Wise 1946, pg. 434).

[13] All except nitrogen

[14] Initial toxicity disappears after a year or two of normal weathering (Terman n.d., pg. 6).

[15] See Wise (1946, pg. 435).

[16] Wood ash may be used to increase the permeability of heavy soils and raise the pH of acidic soils (Battelle 1976, pg. 81).

[17] These comments are based on the results of an unpublished study performed by Continental Forest Industries soil scientist Ken Xydias and environmental director Dave Muntz in which the minimum application rates of combined coal and wood ash were calculated for CFI timberlands.

[18] If water is mixed with wood ash, the potassium compounds dissolve and can be separated from the remaining material. On evaporation, potash is recovered (Koch 1971, pg. 37).

[19] Mr. Farber of the National Ash Association reports that roughly 25 percent of the coal fly ash produced in this country is used for commercial purposes (primarily as a filler for concrete blocks, bricks and asphalt). This information resulted from personal communication in March 1979.

[20] The portion of this discussion that deals with existing federal regulation draws heavily from Gillespie (FPRS 1976, pg. 146-149).

[21] These categories are: sulfur dioxide, particulates, carbon monoxide, oxidants, hydrocarbons and nitrous oxides.

[22] Except where otherwise indicated, the dicussion in this section draws heavily from Slack (1975, pgs. 1-25).

[23] Sulfur tends to become concentrated in the residual fraction during the refining process. Even low-sulfur oil (having less than 0.25 percent sulfur) may yield residual fuel containing high sulfur. Typically, it is this residual that is burned in oil-fired power boilers of the pulp and paper industry.

[24] A Battelle study found that one-quarter of eastern coal was either naturally-occurring low sulfur or could be "washed" to the degree necessary to meet EPA's 1.2 lb SO_2/million BTU standard and avoid the expense of additional control methods.

[25] New plants in the utility industry may have stacks in excess of 1,000 ft in height.

[26] England - for obvious geographical reasons - still considers this method to be an entirely adequate means of sulfur dioxide control and has given little attention to other approaches.

[27] Remaining methods of control and accompanying discussion, except where otherwise indicated, are drawn from Battelle (1976, pgs. 84-86).

[28] See Arola (FPRS 1976, pg. 38), Tillman (1978, pg. 77), Koch (1971, pg. 36), and Corder (FPRS 1975, pg. 30).

[29] See Forest Products Research Society 1976, Table 9, pg. 11, and Table 6, pg. 10.

[30]

$$\frac{2.125 \times 10^{7} \text{ output BTUs/ton coal}}{6.45 \times 10^{6} \text{ output BTUs/ton 50\% m.c. wood}} = 3.3$$

Therefore, 3.3 tons of wood having 50 percent moisture provide the same effective energy as 1 ton of coal.

$$\frac{(225 \text{ lb fly ash})(1 \text{ ton coal})}{(72 \text{ lb fly ash})(3.3 \text{ tons wood})} = 1.07$$

[31] This section draws heavily from MITRE (1979, pgs. 12-21), Battelle (1976, pgs. 18-48), and Babcock & Wilcox (1963, Chapers 16 and 17). No pretense of originality is made.

[32] Wood is composed of a volatile component (75-85 percent), a fixed carbon component (15-25 percent), and ash (1 percent). Volatiles are driven off in the furnace and burn in the gaseous phase while fixed carbon burns as a solid. Coal's composition is much higher in fixed carbon and ash, and much lower in volatiles. (See Corder (FPRS 1975, pg. 31) and Arola (1978, pgs. 49-51).)

[33] This discussion draws heavily from Grant (1979), Daman (1979), Keller (FPRS 1976, pg. 73), and MITRE (1979).

[34] This section draws heavily from Tillman (1978, pgs. 107-109) and MITRE (1979, pgs. 30-33).

[35] See Domino (1979, pgs. 43-46).

[36] This discussion draws heavily from Tillman (1978, pgs. 109-113), Liu (1976, pgs. 26-27), and MITRE (1979, pgs. 22-30).

Chapter 3

[1] Residues are defined here is byproducts of wood production and conversion that are not used as inputs into subsequent production processes.

[2] This "principle," of course, refutes the primacy of consumer sovereignity in determining resource allocation. If consumers value wood more highly as a source of energy than as a source of fiber, who is Glesinger to tell them they should not burn it?

[3] This differential is labeled the log's conversion-surplus value by Duerr and Guttenberg (Rumsey and Duerr 1975, pgs. 332-337). This concept differs from one of maximizing *profit* for each unit of input only in the sense that fixed costs and revenues - which, by definition, are non-decisionable - are ignored.

[4] Marginal sawlogs are those for which the conversion-surplus value for use as sawtimber is zero. Marginal pulpwood is wood raw material for which the conversion-surplus value for use as pulpwood is zero.

[5] This designation includes such commodities as black liquor, bark, sawdust and shavings.

[6] This is a 1976 figure derived from Tillman (1978, pg. 42).

[7] Effective energy is defined as that which is recovered in the traditional medium of distribution (e.g., steam) following energy conversion. Put another way, this is *output* energy, as opposed to input energy released by fuel combustion.

Chapter 4

[1] Fuel consumed by mobile equipment in and around the mill is omitted from this analysis.

[2] The proportions of wood and coal used to fuel the power boiler are variable, within limits. The figures given here were used by the firm for planning.

[3] Process steam is steam used in the manufacturing process, and is of lower pressure than the 1,250 psig steam produced in the boilers. Boiler steam pressure is reduced in pressure-reducing valves (PRVs) or in the turbogenerator in the process of electrical generation.

[4] The location of Curve A' is an estimate; its precise location must await operational testing of the system.

[5] Small particles burn in suspension as they fall to the grate.

[6] The "short run" is a period during which no changes in fixed assets or process technology are possible, but the mix of variable inputs - here, coal and wood fuel - may be altered to take advantage of changes in relative prices.

[7] This time period is quite arbitrary, but is selected to enable us to conform to steam demand and other accounting figures, which are tabulated monthly.

[8] Defined here as costs that vary with the fuel mix.

[9] Which exceeds the boiler's capacity in each case

[10] Primarily through unemployment compensation costs

[11] This term refers to the requirement that some coal be fired continuously to compensate for combustion irregularities in wood fuel and maintain an even rate of steam production.

[12] Assuming that the coal cushion acts as the upper limit to wood-firing.

[13] The assumption is made that coal steam is never wasted, since the coal-firing system adjusts automatically and instantaneously to downward swings in steam demand.

[14] The total variable cost of steam production is represented by the area under the relevant marginal cost curves.

Chapter 5

[1] Let us take decisions regarding continued operation of the facilities at full capacity out of the fiber manager's hands.

[2] Figures used in this example are absolutely hypothetical. While all relationships are shown to be linear (with respect to wood input or production), they needn't be, of course. Also, the assumption is made implicitly that the variable costs per unit input or output do not vary with wood type. This, generally, will not be true.

[3] The firm's cost of capital is the rate of return that must be earned from a new investment in order that the value of the firm remain unchanged.

[4] Also known as Return on Investment, or ROI.

[5] For discussions of capital budgeting analysis applied specifically to wood versus alternative-fuel fired systems, see Ellis (1978) and Skog (1979). See also Ralph L. Mason in FPRS (1976, pgs. 27-29).

[6] See, for example, Weston and Bringham (1975, pg. 309).

[7] This probabilty distribution is not necessarily normal, of course.

LITERATURE CITED

Anonymous. 1963. Steam: its generation and use. 37th ed. New York: Babcock & Wilcox.

Arola, Rodger A. 1978. Fuel definition and analysis. In Wood energy: proceedings of Governor William G. Milliken's conference of Nov. 29, 1977. Ann Arbor: Ann Arbor Science Publishers.

Arola, Rodger A. 1976. Wood fuels: how do they stack up? In Energy and the wood products industry. Madison, Wisc.: Forest Products Research Society.

Beardsley, William H. 1976. Commodity and material needs: forestry in an age of shortages. Journal of Forestry. 74: 71-74.

Berg, Charles A. 1978. Process innovation and changes in industrial energy use. Science. 199: (608-614).

Bryan, Richard W. 1979. Getting serious about wood fuel: public utility begins conversion. Forest Industries 106: 31-33.

Cheremisinoff, Paul N., et al. 1976. Woodwastes utilization and disposal. Westport, Ct.: Technomic Publishing Co.

Corder, Stanley E. 1975. Fuel characteristics of wood and bark, and factors affecting heat recovery. In Wood residue as an energy source. Proceedings No. P-75-13. Madison, Wisc.: Forest Products Research Society.

Corder, Stanley E. 1973. Wood and bark as fuel. For. Res. Bul. No. 14. Corvallis, Oregon: Oregon State University.

Daman, Ernest L. 1979. Fluidized bed combustion: technology and economics for industrial steam generation. TAPPI 62(3): 47-50.

Domino, Francis A. (ed.) 1979. Energy from solid waste: recent development. Park Ridge, N.J.: Noyes Data Corp.

Duerr, William A. 1960. Fundamentals of forestry economics. New York: McGraw-Hill Book Company.

Ellis, Thomas H. 1978. Economic analysis of wood or bark-fired systems. General technical report FPL 16. Madison: Forest Products Laboratory.

Enzer, Herman et al. 1975. Energy perspectives: a presentation of major energy and energy-related data. Washington, D.C.: U.S. Department of the Interior.

Fisher, Joseph and Edward Boorstein. 1959. The adequacy of resources for economic growth in the U.S. Study Paper No. 13, prepared in connection with the Study of Employment, Growth, and Price Levels. 86th Congress. Washington, D.C.: U.S. Government Printing Office.

Flick, R. A. 1976. Pulping industry experience with control of flue gas emissions from bark and wood fired boilers. In Energy and the wood products industry. Madison, Wisc.: Forest Products Research Society.

Forest Products Research Society. 1976. Wood residues as an energy source. In Proceedings No. P-75-13 (proceedings of a workshop held Sept. 3-5, 1976, in Denver). Madison, Wisc.: Forest Products Research Society.

Fryling, Glenn R. (ed.). 1967. Combustion engineering. Rev. ed. New York: Combustion Engineering, Inc.

Gillespie, William J. 1976. Brief overview of air quality regulation affecting the forest products industry. In Energy and the wood products industry. Madison, Wisc.: Forest Products Research Society.

Grant, Andrew J. and Thomas F. Walsh. 1979. Fluidized bed is competitive with conventional furnaces. Southern Pulp and Paper 42(5): 28-29.

Hall, E. H. et al. 1976. Comparison of fossil and wood fuels. Prepared for U.S. Environmental Protection Agency (EPA - 600/2-76-056). Columbus, Ohio: Battelle-Columbus Labs.

Hall, E. H. 1976. Comparison of fossil and wood fuels. In Energy and the wood products industry. Madison, Wisc.: Forest Products Research Society.

Hayes, Earl T. 1976. Energy implications of materials processing. Science. 191: 661-665.

Hogan, William W. and James M. Warren. 1974. Toward the development of an equilibrium capital-market model based on semi-variance. Journal of Financial and Quantitative Analysis 9(1): 1-11.

Keller, Ralph. 1976. Fluidized bed combustion systems for energy recovery of forest products industry wastes. In Wood residue as an energy source. Madison, Wisc.: Forest Products Research Society.

Koch, Peter and J. F. Mullen. 1971. Bark from southern pines may find use as fuel. Forest Industries 98(4): 36-37.

Liu, M. S. and R. Serenius. 1976. Fluidized bed solids waste gasifier. In Jean Mater (ed.). Technology of utilizing bark and residues as an energy and chemical resource. Madison, Wisc.: Forest Products Research Society.

Manwiller, Floyd G. 1975. Wood and bark moisture contents of small-diameter hardwoods growing on southern pine sites. Forest Sciences 8(1): 384-388.

Mao, James C. T. 1970. Models of capital budgeting, E-V versus E-S. Journal of Finanical and Quantitative Analysis 4(5): 657-675.

Markowitz, H. M. 1959. Portfolio selection. New York: John Wiley and Sons, Inc.

McRae, Alexander, and Dudas, Janice L. (eds.). 1977. The energy sourcebook. Germantown, Md.: Aspen Press.

MITRE. 1979. Near term potential of wood as a fuel. Prepared for U.S. Department of Energy. Springfield, Va.: NTIS, U.S. Department of Commerce.

MITRE Corporation. 1977. Silvicultural biomass forms, Vol. 1, Summary. Technical report 7347. Prepared for U.S. Energy Research and Development Association. n.p.

Morton, Walter A. 1969. Risk and return: instability of earnings as a measure of risk. Land Economics 45(2).

Naill, Roger F. 1977. Managing the energy transition: a system dynamics search for alternatives to oil and gas. Cambridge: Ballinger.

Perry, Robert H. 1969. Chemical engineer's handbook. 4th ed. New York: McGraw-Hill.

Porter, R. Burr, Roger P. Bey, and David C. Lewis. 1975. The development of a mean-semivariance approach to cpaital budgeting. Journal of Financial and Quantitative Analysis 10(4): 639-649.

Roberson, James E. 1968. Bark burning methods. TAPPI 51(6): 90A-98A.

Rumsey, Fay, and William A. Duerr. 1975. Social sciences in forestry: a book of readings. Philadelphia: W. B. Saunders Co.

Sherwood, Larry, and Dennis Meadows. 1978. The fuel requirements of a 50 MW wood fired electrical generating facility in northern Vermont. DSD No. 106. Hanover, N.H.: Dartmouth College.

Skog, Kenneth E. 1979. The economics of wood fuel use. In Proceedings of the Mid-American Wood Combustion Conference, Nov. 8-9. Transverse City: Northwestern Michigan College.

Slack, A. V., and G. A. Hollinden. 1975. Sulfur dioxide removal from waste gases. 2nd ed. Park Ridge, N.H.: Noyes Data Corp.

Study Committee on Environmental Aspects of a National Materials Policy. 1973. Man, materials, and environment. Cambridge: MIT Press.

Terman, G. L. n.d. Solid wastes from coal-fired power plants: use or disposal on agricultural lands. Muscle Shoals, Ala.: National Fertilizer Development Center.

Tillman, David A. 1978. Wood as an energy resource. New York: Academic Press.

U.S. Congress. Joint Economic Committee. 1977. Achieving the goals of the Employment Act of 1946 - thirtieth anniversary review, Vol. 2, paper 2, Energy and economic growth, by M. H. Ross and R. H. Williams. Joint Committee Print. Washington, D.C.: U.S. Government Printing Office.

U.S. Forest Service. 1976. The feasibility of utilizing forest residues for energy and chemicals. Prepared for the National Science Foundation (PB 258 630). Springfield, Va.: NTIS, U.S. Dept. of Commerce.

U.S. Forest Service. 1958. Timber resources for America's future. Forest Resource Report No. 14. Washington, D.C.: U.S. Government Printing Office.

Weston, J. Fred, and Eugene F. Bringham. 1975. Managerial finance. 5th ed. Hinesdale, Ill.: Dryden Press.

Wisdom, Harold W. 1978. Will steadily rising energy costs have an effect on timber supply? Forest Industries 105(10): 78.

Wise, Louis E. (ed.) 1946. Wood chemistry. New York: Reinhold.

Yaverbaum, L. H. 1979. Nitrogen oxides control and removal: recent developments. Park Ridge, N.J.: Noyes Data Corp.

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WOOD AS AN ENERGY SOURCE IN THE KRAFT PULP-PAPER INDUSTRY OF THE SOUTHEAST

By

William Michael Liebenow

ABSTRACT

This is a study in the economics of deriving energy from wood. Its objective is to provide guides to industry managers that will enable them to better assess wood's fuel potential. It is written with this business audience in mind.

An introductory section describes the "energy crisis" as nothing more than a radical shift in relative prices, requiring that a significant investment be made in capital assets designed to economize on high-cost, fluid fuels. A second discusses wood fuel supply within the context of the total timber supply. Heightened demand for fuelwood unleashes both opposing and complementary forces that affect the supply of wood fiber. These are described. A continuum is developed to show how the marginal cost of deriving effective energy from wood changes depending on the level of subsidy provided by other joint-products of the log. One chapter is devoted to a comparison between wood and fossil fuels on the basis of caloric value, combustion efficiency, environmental impact, and fuel form conversion.

Final sections set forth guides for profit-maximizing fuel selection:

- A case study of Continental's Hopewell, Virginia, Kraft linerboard mill is used to develop a linear programming model that selects the optimal wood-coal mix for a combination boiler.

- A short-run analysis section discusses wood sourcing and allocation between energy and fiber uses. Four methods are described: Least-Cost Sourcing, Conversion Surplus Valuation, Relative Fiber Valuation, and Return-to-Capital Valuation. The last approach is shown to be superior.

- Finally, a long-run analysis section looks at risk in capital investment for energy assets, and defines it in terms of semi-variance. A simulation approach is described that allows one to calculate an index of risk for various fuel system investment alternatives.