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WOOD AS AN ENERGY SUBSTITUTE

By

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Abstract

WOOD AS AN ENERGY SUBSTITUTE

by

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This study evaluates wood fuel's substitution potential in a modern American economy. Purpose is to show how cost-efficient wood fuels were during pre- and post-oil embargo periods, identify fuels for which wood showed positive cost savings potential, and show how to make preliminary cost savings comparisons. Although a cost minimization objective is assumed, safety and environmental concerns are also discussed.

Focus narrows progressively from a national supply including all fuel and product derivatives; e.g., gasoline, plastics, lubricating oil, and asphalt for petroleum based fuels, through sectorial demand and price situations, to decision criteria. Economic implications of of firewood substitution are examined. Analyses and decision criteria are based upon energy time series quantity and price data for the 14-year period, 1967-80. Findings include the following.

Annual wood fuel supply potential, excluding reductions in growing stock and diversions from conventional products, amounts to 731 M tons (11.7 quads of energy). Only 156 M tons (2.5 quads), or 21 percent of the total, is currently economic.

If labor costs are ignored, wood- fuel oil substitutes became marginally economic in the commercial sector after 1974. If labor, maintenance, and repair are included in a cost equation, both natural gas and coal were better oil substitutes than wood.

Since 1974, only wood- electricity electricity substitutes provided cost savings in residential heating. High costs of delivered firewood and high transportation costs for free firewood--average haul distance is 200 miles per cord--substituting wood heat for any fossil fuel resulted in negative savings between 1974-80.

Industrial firewood substitution potential was also strong. The pulp and paper industry substituted about 52 percent of their energy needs with bark, wood, and black liquor solids. Residential firewood prices, which were more than double delivered wood prices to the paper industry, suggest the residential sector can outbid the industry for hardwood resources. Intersector price disparity encourages crossovers between industrial pulpwood and residential firewood.

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James Anderson Pharo

Table of Contents

List of Tables

List of Figures

Figure

Chapter 1

Introduction

Background

History records a pattern of moving from wood to other fuels; e.g., wood to coal, oil, gas, and electricity. Since 1974 and the oil embargo, however, residential and industrial demand has reversed the historical trend away from wood and now looks at it as a popular energy substitute. That wood and wood based substitutes are economic may be erroneous; only history and analysis will bear that out.

Early nineteenth century lumber mills and Erie Canal boats used wood energy; national rail systems guided wood-powered locomotives over 9,000 miles of track (Jones 1970). Textile manufacturing was in its ascendancy; wood-fired steam engines powered the country's industrial plants (Hunter 1975). And Mississippi riverboats steamed the nation's greatest waterway. Between 1800 and 1850, our energy base shifted from wood to coal; population grew to 15 million people; agriculture bloomed from small-scale subsistence farming into large-scale commercial enterprise and cash crops (e.g., cotton and tobacco).

Coal substitutes and charcoal were common by 1850. Iron processes using anthracite coal realized a 490 percent advantage over iron made with wood (Walker 1966). Mechanical pulping, introduced about 1850, helped maintain wood use but not as fuel. Paper and paper products shifted from rag-based to wood derivatives. Iron demand during the Civil War increased wood use and helped introduce coal. A building boom helped establish the forest industry; more wood generated steam for sawmills. Transcontinental railroad locomotives could travel further between fuel stops with coal. After the industrial transition only the residential sector stayed firmly in the wood use camp. Wood fuel uses increased between 1850 and 1870, but use relative to total energy demand declined (Schurr and Netschert 1960, Tillman 1978).

Wood fuel use declined over the next century; periodic events such as the Great Depression and WWII created new, but short-lived, demand increases. Wood became a reliable substitute for energy sources in short supply (Stone 1977). Renewed wood fuel use in residential and industrial sectors after 1974 is the most dramatic substitution example of wood fuel. Annual wood stove sales increased from 250 thousand to 2 million, in 1977 (Shapiro 1979); pulp and paper wood waste for fuel use increased from 74 to 91 million tons per year (American Paper Institute 1981). Wood stove sale increases and wood fuel use in paper production suggest a reversal in the 100-year decline in wood use, at least since 1974.

Return to wood stoves in the residential sector and a growing dependence on wood fuel in the pulp and paper industry signaled some shift towards wood. Yet, wood can only substitute for other fuels if it can compete with them and established wood product uses.

The 1973 oil embargo led to an unprecedented period of unemployment and inflation. Price control removal in late 1973, crop failures in 1974, and natural gas shortages in the eastern United States in 1975 helped move Gross National Product downward and culminated in stagflation--the simultaneous conditions of stagnant economic growth and inflation (Baumol and Blinder 1979). The embargo, its aftermath, and preoccupation with inexpensive energy renewed wood fuel uses.

Problem Statement

Wood fuel substitutes have concerned the wood products industry (Seidl 1979). Realistic estimates of the amount of wood used for energy are inexact; e.g., media speculation on the possibility of wood fuel as a viable alternative to nuclear power panders to that vocal segment of society seeking to shut down reactors--such speculation sells copy, not energy (Smith 1981, and Stokes 1981). Even if the speculation were true; it helps little in deciding which fuels, conditions, or how much cost savings a serious user might expect with a wood substitute.

Although balanced arguments for near- and long-term fuel substitutes have been offered (Rider 1981; Schurr, et al. 1979; and Stobaugh and Yergin 1979), most analyses focus on gross supply potential. Comparative economies of wood fuel for heating or driving industry have been ignored. Supply orientation, recently yielding to consumption documentation, ignores price, the major resource allocation mechanism in our society.

Objective and Scope

This study will identify potential wood substitutes and offer a rationale to decide when wood fuel is economic. The data base from which the rationale is developed centers around 1967-1980.

Scope is essentially sectorial: major fuel uses in commercial, residential, and industrial sectors are examined relative to substitution by wood fuel. Demand and price data are organized into time series. Although scope is national, local cases also illustrate fuel use and economy.

Approach and Orientation

Major fuels are selected and defined in Chapter 2. Importance of combustor efficiency and wood moisture content are demonstrated.

Chapter 3 presents time series data for fuel supply. Quantity and price data represent production; coal price is taken at the mine-mouth, wellhead or refiner's acquisition and wellhead prices are used for oil and gas; stumpage prices and quantities are used for wood. Because products are also made from fuels, all production is taken into account and expressed in comparative energy units (conversion factors are given in Appendix A). Average production and price averages are compared for two periods, 1967-73 and 1974-79. Unpriced wood supply is also estimated on an annual basis; mill residues, urban wastes, and potential from biomass farms are included.

Demand and price data for fuels in commercial, residential, and industrial sectors are recorded and examined in Chapter 4; quantity and prices are recorded at their point of use. Demand and price averages for 1967-1973 and 1974-1980 are analyzed relative to firewood demand and prices. Firewood includes chips, bark, edgings, sawdust, shavings, and black liquors used by the pulp and paper industry. All components are expressed in equivalent energy units to facilitate comparisons.

Commercial and residential heating uses are examined for wood substitution potential in Chapter 5. The commercial sector includes non-manufacturing businesses, health and educational institutions, and government. Because actual firewood amounts used are unknown for the commercial sector--cottage industries are often mistakenly included in commercial accounting--residential firewood is utilized for comparative purposes. Cost minimization is the assumed decision criterion for both sectors; substitution potential and two case studies are examined. The residential sector includes single- and multi-family housing units.

Cost minimization, especially in input factor markets, is the assumed objective function in industry. Chapter 6 provides a general record of quantity and price relationships designed to identify industrial substitution potential. The industrial sector includes construction, manufacturing, agriculture, and mining establishments. Special attention is given to the wood products industry and the problem of crossovers. The term "crossover" refers to intentional diversion of wood from conventional products to firewood in the residential sector.

All three sectors are reexamined in Chapter 7 from a fuel use decision viewpoint. Wood substitution alternatives, environmental concerns and safety are examined. Economic objectives are combined with physical needs for heat; a simple discounting approach is offered for industrial wood use.

Chapter 8 summarizes findings from previous chapters. Conclusions are drawn about wood substitution potential and where it fits in an energy economy.

Chapter 2

Fuel Selection and Description

This chapter identifies major wood-using economic sectors and fuels for which wood is a potential substitute. To identify these substitutes, national consumption characteristics are reviewed by economic sector. Fuels are chosen on a use basis; fuels whose use was less than 5 percent of the 1979 national total are not viewed as strong firewood substitutes. Economic implications of firewood's physical characteristics are also examined.

Fuels selected are then compared. Bases for comparisons are potential and usable heat content. Potential heat is total heat available from a given fuel. Usable, or sensible, heat takes intended use into account; e.g., natural gas heaters are generally more efficient than oil furnaces; thus, a million British thermal units of natural gas have more heat potential than a million Btu of heating oil.

Two conventions found in the literature are followed: average potential heat (average highest heat expected from a particular fuel) is used for simple comparisons; and, heat is expressed in "Btu." A quadrillion, or (10^{15}), Btu is a "quad." With few exceptions current energy literature refers to heat in the English system. In keeping with that convention, energy will be expressed in similar units; although, Appendix A provides some metric conversion factors.

Fuel Use

In 1979, about 80 quads of energy were used in five major consuming sectors of our economy (see Table 2.1). The extent of commercial sector wood use, unknown in 1979, may soon parallel residential use. Other fuels (e.g., geothermal, hydro- and nuclear power) were used primarily at electric generating plants where very small quantities of wood were used. Commercial, residential, and industrial sector fuel-use characteristics will be examined in detail; wood substitution potential is strongest in these sectors.

Fuel Selection

Wood fuel substitutes are coal, gas, and petroleum (Table 2.1). Electricity, also a potential substitute, is widely used for heating and cooking. Only fuels for which wood is a strong substitute will be considered beyond Chapter 3, Energy Supply and Prices (e.g., petroleum byproducts such as tars and lubricants will be ignored). Specific fuel characteristics follow.

Anthracite. A hard, black, lustrous coal containing a high percentage of fixed carbon and often referred to as "hard coal."
Bituminous. Often referred to as "soft coal," bituminous is more volatile than anthracite. Lignite, included in this category, is a volatile brownish-black coal having a high moisture content.

Dry Natural Gas. A gaseous mixture of hydrocarbon compounds from which liquids and other miscellaneous products have been removed; the amount of marketable, consumable natural gas available.

Table 2.1. Energy consumption, 1979[a]

	Consuming Sectors					
Sources	Commercial	Residential	Industrial	Transport	Electric	Total
	Quadrillion Btu					
Coal	0.129	0.082	3.702	0.000	11.263	15.176
Gas	2.836	5.055	8.549	0.539	3.609	20.588
Petroleum	2.428	2.297	9.262	19.778	3.357	37.122
Other[b]	0.000	0.000	0.034	0.000	5.969	6.003
Wood[c]	--d--	0.212[e]	1.025[f]	0.000	--g--	1.237
Total Use	5.393	7.646	22.572	20.317	24.198	80.126
Electric sales	1.854	2.330	2.873	0.011	(7.068)	
Losses[h]	4.493	5.647	6.963	0.024	(17.127)	
Sub total	6.347	7.977	9.836	0.035	(24.195)	
Total with electricity distributed	11.740	15.623	32.408	20.352	0.003[i]	80.126

[a]Source: USDOE (1981a). [b]Geothermal, hydro, nuclear, and wastes. [c]Source: USDA (1981a).

[d]Unknown. [e]Includes free firewood. [f]Pulp and paper.

[g]Less than 500 billion. [h]Transmission losses. [i]Plant use.

<u>Distillate Oil</u>. A fractional oil refinery distillate; also known as No. 1 and No. 2 heating oils; major use is space heating.

<u>Residual Oil</u>. A heavy oil remaining after distilled oils and lighter hydrocarbons are boiled off in refineries; also known as No. 5 and No. 6 oils; major uses are electric power generation, space heating, vessel bunkering, and other industrial uses.

<u>Liquid Petroleum Gas</u>. Propane, propylene, butanes, butylene, ethane-propane mixtures, and propane-butane mixtures; produced at refineries and natural gas processing plants; primary uses include space heating and cooking.

<u>Kerosene</u>. A petroleum middle distillate suitable as an illuminant in a wick lamp with properties similar to No. 1 fuel oil; primary uses are in space heaters, cooking stoves, and water heaters.

<u>Electricity</u>. Highly versatile energy usually produced by consuming other energy fuels. Primary uses are communication, light, machine power, residential appliances, and almost any other task calling for a large substitution of energy for labor.

<u>Wood</u>. Hardwood and softwood are the two wood types used for fuel. Firewood is normally sold (and accounted) on a "cord" basis; i.e., 8 x 4 x 4 ft^3 stack containing less than 128 ft^3 of solid wood. Differences in physical characteristics (e.g., shape, taper, and moisture content) usually account for differences in a cord's mass and volume measurements. The volumetric standard adopted here, to account for air spaces between logs, is 80 ft^3 of solid wood and bark per cord.

Wood Fuel Description

Wood heat yield depends upon many variables such as volume-to-density ratio, species, and moisture content. In general, hardwoods possess better burning characteristics than softwoods (Reynolds and Pierson 1942). Density changes as moisture content changes, or as wood is mechanically compressed into briquets or pellets. But it is moisture, more than any other variable, which segregates wood into distinct fuel classes. Freshly cut wood may contain water varying from 20 to 67 percent (or more) of total material weight. Moisture content by weight, used throughout this paper, influences net heat values, heat efficiency, ignition properties, and physical potential for pellitizing.

Net heat. The general relationship between net heat (NH) and moisture content (MC) of wood as a percent of potential heat (PH) is

$$NH = PH(1.0 - 0.0114\ MC) \tag{2.1}$$

when moisture content is expressed as a percent. Equation (2.1) expresses a physical relationship, adapted from Tillman (1978), directly impacting economic considerations and it will be used in examples elsewhere (e.g., see Appendix B).

Heat Efficiency. Impact on net energy values can be seen in the following example. A cord of hardwood, whose (MC) is 50 percent by weight, has a net heat value of about 9.4 million Btu by equation (2.1). (Heat potential in an oven dry cord of hardwood is about 21.0 million Btu, while a softwood cord is about 17.5 million Btu.) If that firewood's intended use is a fireplace whose efficiency is 20 percent, its net heat value is reduced further due to combustor inefficiency. The reduced net heat due to moisture, and combustor inefficiency for the residential sector, reduces net heat value of firewood (see Table 2.2). This reduction also has an economic impact. Reduced heat values of firewood elevate the value of other fuels relative to hardwood. Consider the following example. The net heat value of a barrel of distillate, relative to a cord of hardwood, is elevated from 0.6 of a hardwood cord to 1.9 of a hardwood cord after adjustments for 50 percent moisture content and combustor efficiency (an increase in heat value of 217 percent).

Ignition Properties. Shafizadeh and Degroot (1977) used a variety of analytical methods to demonstrate moisture effect on wood ignition and heat yields. They found that a dry pound of cellulose needs an energy input of 225 Btu at 575^{o} F for ignition to yield 5,070 Btu. Cellulose at 50-percent moisture content required an energy input of 1,400 Btu at 600^{o} F to ignite and yield 3,700 Btu. A 50-percent increase in fuel moisture content almost tripled the input heat requirement, raised ignition temperatures by 4 percent, and reduced net heat value by 27 percent.

Pelletized Wood. Wood within a 10- to 25-percent moisture content by weight can be compressed into easily portable volumes. Densification processes usually result in cylindrical fiber rolls of 20 to 50 lb/ft^3. Shapes can vary considerably as fireplace logs, briquets, or pellets (Reed and Bryant 1978). Briquets have been sold as a substitute fuel since fuel economy measures instituted during World War II. Wood pellets, developed over the last decade, are also a densified

Table 2.2. Heat comparisons.[a]

Fuel	Relative to hardwood[b]		
	Potential	Net (1)	Net (2)
Coal (M Btu/ton)		(0.20)	(0.70)
Anthracite (22.7)	1.1	1.1	1.1
Bituminous (23.4)	1.1	1.1	1.1
Natural gas (M Btu/k ft^3)		(0.70)	(0.85)
Gas (1.0)	0.1	0.2	0.1
Oil Derivatives (M Btu/bl)		(0.60)	(0.80)
Distillate (5.8)	0.3	0.8	0.3
Residual (6.3)	0.3	0.9	0.3
LPG (3.7)	0.2	0.5	0.2
Kerosene (5.7)	0.3	0.8	0.3
Electric power (M Btu/kwh)		(0.95)	(0.99)
Electricity (3.4)	0.3	0.8	0.2
Wood (M Btu/cord)[d]		(0.20)	(0.70)
Hardwood (21.0)	1.0	1.0	1.0
Softwood (17.5)	0.8	0.8	0.8

[a]Adapted from Choong (1974), DeVriend (1978), EG&G, Inc. (1978), Kelsey, Shafizadeh, and Lowery (1979), USDA (1977), and USDOE (1981b and 1982).

[b]Fractional hardwood equivalents (e.g., potential heat for gas is 1.0/21.0). Net (1) is the potential heat adjusted for combustor efficiency in the commercial-residential sector. Net (2) is adjusted for the industrial sector. Adjustment factors, are in parentheses and underlined (after Nordhaus 1975). Standard units and heat potential are in parentheses after each fuel.

[c]Standard is a 42 gallon barrel (bl).

[d]Energy values were estimated using 8,000 Btu/lb for hardwood at 32.8 lb/ft^3 and softwood at 27.4 lb/ft^3 (both oven dry).

form of wood more easily transported than solid wood (Zerbe 1980).

Wood pellets are an uneconomic substitute for coal in an electric plant, according to a 3-month study by the Department of Energy at Hanford, Washington. Savings through reduced plant emissions and ash disposal costs were too small to offset additional expenses associated with receiving, storage, fire, and explosion hazards (USDA 1980).

Summary and Conclusions

Wood fuel characteristics have been examined and nine fuels for which wood might substitute as an energy source have been selected for further analysis. Selection basis was prior use in an economic sector where wood has been used for fuel. Preliminary examination of fuels suggests wood has a potential role in energy production, if combustor efficiencies can be improved and firewood moisture content is 15 percent or less.

Moisture content is the most important variable affecting usable heat. As moisture content increases, more heat and higher ignition temperature needs sap a wood fuel's heat potential, dramatically reducing its heat value. Moisture content also plays an important role in wood densifying processes. At moisture contents more than 10 to 25 percent, very high pressures are required to pelletize wood fuels, and equipment tends to fail as pressures increase.

Potential heat differences due to combustor efficiency were slight within the industrial sector. Combustor efficiency differences between sectors ensure that commercial and residential solid fuel users pay more per fuel unit than industrial solid fuel users.

Chapter 3

Energy Supply and Prices

This chapter presents time series production data for fuels identified in Chapter 2 and examines national wood supply potential in detail. Production data cover the 1967-79 period for all major fuels and economic sectors. Production of individual fuels identified in Chapter 2 is brought into sharper focus; their scope, however, remains national.

Energy and price statistics include domestic production and net imports taken close to supply sources; e.g., coal at the mine and petroleum at the refinery.

Total production data represent all raw materials provided from a particular fuel; e.g., petroleum includes unfinished oils, ethane, gasoline, jet fuels, distillate oil, residual oil, other oils, lubricants, petroleum coke, asphalt, road oil, still gas, and other miscellaneous products (plastics).

Wood data (also domestic production plus net imports) include softwood and hardwood firewood, lumber, miscellaneous products, pulpwood, and veneer. Price data are taken from state, private, and federal lands (USDA 1981a).

General Background

The U.S. economy produced 81.1 quads of energy; consumed 77.1 quads; and either discarded, lost, or stored 4.0 quads of energy in 1976 (Table 3.1). Energy consumption was 6 percent less in 1976 (the latest year wood data are available) than it was in 1979 (Table 2.1). In 1979, a declining demand for petroleum products was offset by an 11-percent higher demand for coal. Electric utilities used 25 percent more coal in 1979 than in 1976.

A simplified supply-demand balance is offered in Figure 3.1 to show general relationships between total petroleum supply and specific production. (Other fuel supply-demand balances are similar.) Market prices, policy, and technology provided signals to producers so that 42.72 quads of petroleum products were supplied to markets. (About 35.26 quads of refinery inputs were expanded to 42.72 quads of outputs net of exports.) Production included 6.21 quads of distillate, 6.43 quads of residual oil, and 1.79 quads of LPG. These products, along with other fuels and miscellaneous products, are shown at the right of Figure 3.1.

Production Data, 1967-1979

Supply. Fuel supply includes the nine fuels identified in Chapter 2. Coal production is at the mine. Gas is the marketable equivalent from wells. Oil products originate at refineries. Electricity is the amount generated at large utilities and small industrial generators. Wood includes all products such as lumber, veneer, pulpwood, posts and

Table 3.1. Energy balance, 1976.[a]

Fuel	Total Production	Total Consumption	Total Residual
	---------- Quadrillion Btu	-----------	
Petroleum	19.59	35.17	0.09
Net imports	15.67		
Natural Gas	19.48	20.35	0.12
Net imports	0.99		
Coal	15.85	13.73	0.50
Net imports	(1.62)		
Nuclear and Hydro	5.09	5.18	(0.09)[b]
Wood	5.16	2.58	3.22
Net imports	0.64		
Other	0.08	0.08	0.18
Net imports	0.18		
Total	81.11	77.09	4.02

[a]Sources: USDOE (1981b) and USDA (1981a). Fuels include all production; e.g., petroleum is conventional fuel, asphalt, and other products such as plastics. Wood includes lumber, veneer, pulpwood, and firewood.

[b]Some hydropower and electricity is also included in the other category.

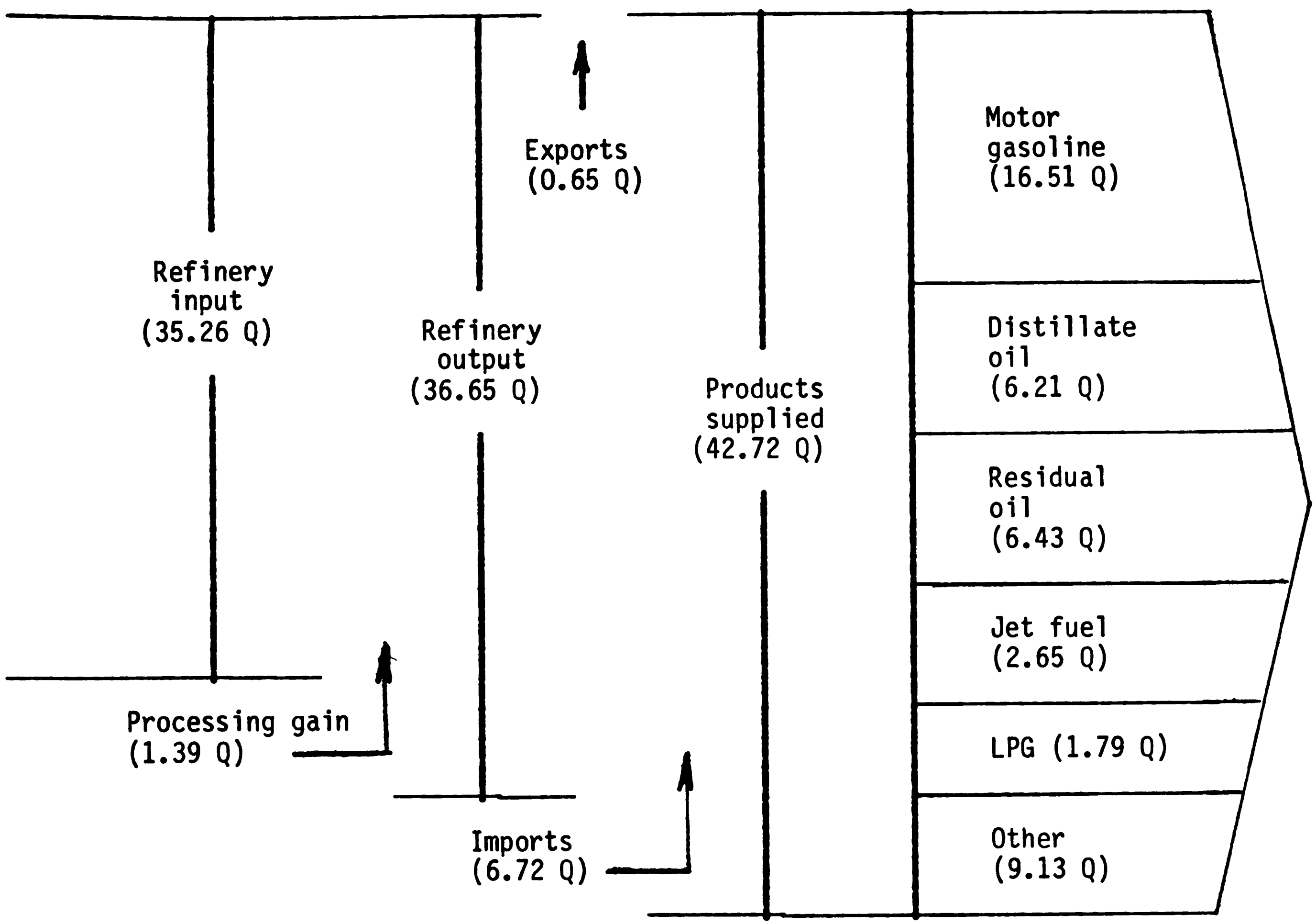

Figure 3.1. Petroleum supply-demand balance for 1976 (source: USDOE 1981b).

other miscellaneous materials, and firewood. Sources for these data are the American Gas Association (1980), USDOE (1981b) and USDA (1981a and 1981b).

All energy supplies increased 40 percent between 1967 and 1979 (see Table 3.2), except anthracite (down by 58 percent) and kerosene (down by 33 percent). Bituminous coal supply increased 41 percent in response to electricity demand. Seventy-seven percent of all coal use was for electric generation in 1979 (USDOE 1982). Production of the other six remaining fuel supplies increased over the 13-year period: natural gas, up 8 percent; wood product supplies up 18 percent; and distillate, residual, and LPG supplies, up 43 percent or more.

Price. Table 3.3 price data provides wholesale prices received by producers for anthracite, bituminous, and natural gas (American Gas Association 1980 and USDOE 1981b). Oil product prices are an aggregate of supply-weighted wholesale prices by sector. Electricity prices are a use-weighted average of sector supply prices to end-product users. Wood prices are production-weighted stumpage for firewood, pulpwood, sawtimber, and veneer. Firewood prices were artificially deflated to stumpage using delivered-pulpwood-to-stumpage price ratios for 13 years of record.

Largest nominal supply price increase observed in Table 3.3 was 613-percent in the price of natural gas. Electric utility price increases, although large in terms of dollar values, only amounted to 141 percent over the 13-year period. Bituminous prices increased 470 percent, residual and kerosene prices increased between 406 and 445 percent, and LPG prices increased just over 300 percent.

Table 3.2. National supply.[a]

Year	Fuel[b] (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	Total
	Quadrillion Btu									
1967	0.280	13.913	20.087	4.678	4.108	0.559	1.220	12.730	2.589	60.164
1968	0.232	13.658	21.548	4.869	4.199	0.559	1.363	13.923	2.706	63.057
1969	0.234	13.969	22.838	4.933	4.544	0.580	1.570	15.247	2.685	66.600
1970	0.234	14.822	24.154	5.209	5.048	0.538	1.567	16.294	2.677	70.543
1971	0.212	13.888	24.805	5.315	5.278	0.497	1.601	17.225	2.651	68.821
1972	0.164	14.310	24.792	5.592	5.806	0.455	1.823	18.584	2.736	74.262
1973	0.162	14.238	27.764	5.996	6.471	0.455	1.856	20.010	2.858	79.810
1974	0.158	14.309	23.689	5.677	6.058	0.331	1.799	20.160	2.783	74.964
1975	0.140	15.034	22.022	5.634	5.645	0.311	1.696	20.418	2.557	73.457
1976	0.137	15.719	21.831	6.208	6.425	0.311	1.794	21.553	2.849	76.827
1977	0.139	15.686	21.892	6.974	7.045	0.352	1.798	22.830	2.894	79.610
1978	0.118	18.304	21.730	6.740	6.930	0.311	1.797	23.537	2.972	82.439
1979	0.118	19.578	21.636	6.697	6.494	0.373	2.050	24.198	3.064	84.208

[a]Sources: USDOE (1981b) and USDA (1981a).

[b]Fuel: (1) anthracite, (2) Bituminous, (3) natural gas, (4) distillate oil, (5) residual oil, (6) kerosene, (7) liquid petroleum gas, (8) electricity, and (9) wood.

Table 3.3. National supply prices.[a]

	Fuel[b]								
Year	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)[c]
	Nominal dollars per million Btu								
1967	0.35	0.18	0.16	0.72	0.51	0.87	0.76	4.56	0.85
1968	0.37	0.19	0.16	0.74	0.52	0.90	0.61	4.53	0.92
1969	0.42	0.20	0.17	0.77	0.57	0.91	0.57	4.52	1.04
1970	0.47	0.26	0.17	0.79	0.57	0.94	0.73	4.66	0.94
1971	0.51	0.29	0.18	0.82	0.67	0.97	0.73	4.95	1.07
1972	0.53	0.32	0.19	0.81	0.65	0.98	0.72	5.20	1.19
1973	0.59	0.36	0.22	1.03	0.83	1.04	1.06	5.46	1.65
1974	0.98	0.66	0.30	1.90	1.85	2.00	1.72	6.75	1.66
1975	1.35	0.83	0.45	2.11	1.94	2.25	1.90	7.89	1.62
1976	1.49	0.84	0.58	2.30	1.69	2.42	2.19	8.42	1.86
1977	1.50	0.87	0.79	2.59	2.01	2.76	2.61	9.35	2.14
1978	1.50	0.97	0.91	2.68	1.86	2.91	2.56	10.10	2.43
1979	1.61	1.04	1.14	4.13	2.78	4.40	3.06	10.97	3.10

[a]Sources: USDOE (1981b) and USDA (1981a).

[b]Fuels: (1) anthracite, (2) bituminous, (3) natural gas, (4) distillate oil, (5) residual oil, (6) kerosene, (7) Liquid petroleum gas, (8) electricity, and (9) wood.

[c]Use weighted prices of sawtimber, veneer, pulpwood, and firewood production.

Price and Quantity Relationships. Average real price increases were determined for the pre- and post-oil embargo periods using producer's price index for crude materials (CEA 1981). Supply data, from Tables 3.2 and 3.3 were averaged for the two periods and their percent changes plotted in Figure 3.2. Some supply declines occurred between 6-year periods as their average prices rose. Anthracite, gas, and kerosene prices rose 38, 73, and 34 percent respectively, while their supplies declined by 34, 9, and 35 percent. Bituminous, distillate, residual, and LPG supplies increased 12 to 23 percent over the two periods as their prices rose from 49 to 55 percent. Wood and electricity prices fell 7 and 14 percent as their average supplies increased 5 and 31 percent respectively.

Supply from Wood

Commercial forests, about 483 million acres of land capable of producing 20 ft^3 of industrial quality wood per acre per year, contained some 693 billion ft^3 of growing stock timber in 1976. Distribution was about 64 percent softwood and 36 percent hardwood (Table 3.4). Growth was 21.7 billion ft^3, another 3.9 billion ft^3 died during the year, and some 14.3 billion ft^3 was removed for industrial use. Net growing stock at the end of the 1976 was 659.7 billion ft^3 (USDA 1981b).

Only commercial wood volume components are published regularly; branches, rotten sections, tops, limbs, and bark above a one-foot stump are often ignored (Spurr and Vaux 1976). Full-tree components, material above a one-foot stump, are added to removal components examined here.

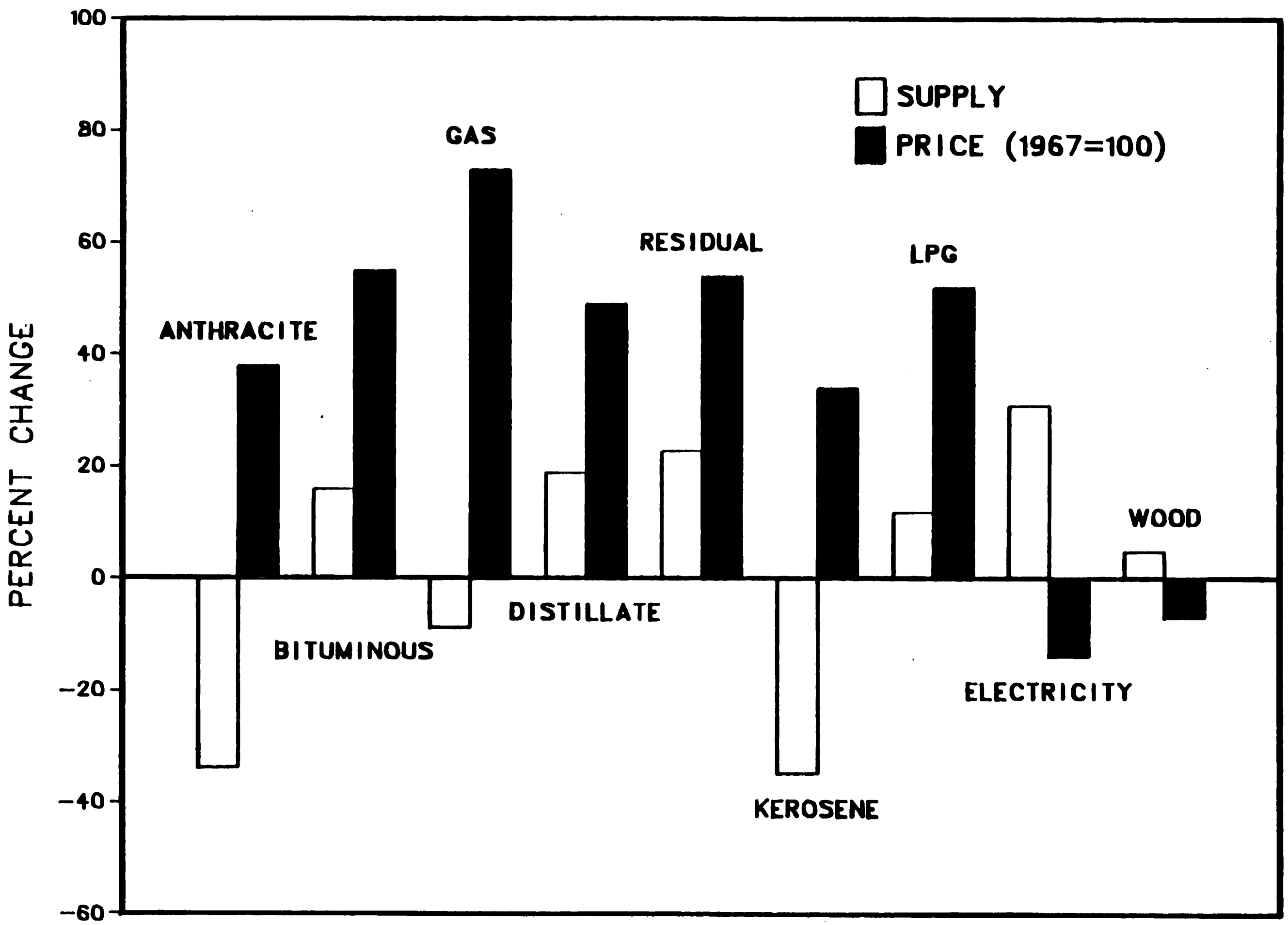

Figure 3.2. Supply price and quantity averages for pre- and post-oil embargo periods.

Table 3.4. Commercial forest volume.[a]

Source	Softwood	Hardwood	Total
	------- Billion cubic feet --------		
Growing stock	445.8	247.4	693.2
Growth	12.3	9.4	21.7
Mortality	(2.3)	(1.6)	(3.9)
Available	454.8	255.2	710.0
Removals	(10.1)	(4.2)	(14.3)
Net balance	444.7	251.0	695.7

[a]Source: USDA (1981b). Growing stock includes merchantable components only. Removals include rotten mainstem, mainstem bark, branches and tops, and top bark. Growing stock components, if included, would increase net balance by 63 percent (see Appendix C). Data are for 1976 and correspond in time with the data of Table 3.1.

Removals include all full-tree components frequently left in the woods. Harvest residuals, tree components, or whole trees left after harvests (according to Young, 1981), and other residues such as trees felled for rights of way, land-clearing operations, or silvicultural work, are classified as removals. Tables 3.5a and 3.5b show removals cycled through our economy. Forty-seven percent of harvested material is available for final products. The simplicity of these tables, however, hides interactions between industries. For example, veneer mills sell (or consume) their waste material. Wood scraps may become pulp for paper or inputs for particleboard. Lumber mills sell chips to pulp mills, and shavings and trim to particleboard plants (Koch 1976). Sawdust and bark make excellent fuel.

The aim of such production is consumption but with some waste disposal. Table 3.5b shows the bulk of the wood used, 7.7 billion ft^3, is eventually discarded as waste. Twenty-four percent, or 2.6 billion ft^3, is recycled and 5 percent, or 0.5 billion ft^3, is consumed for energy (Cordell and Clements 1979).

<u>Production</u>. About 75 percent of all wood production is sawtimber, veneer, pulpwood, and firewood; combined total production averaged 3.4 quads in 1967-1979 (see Table 3.6). The largest supply increase, 57 percent, was firewood, which may displace other wood product uses (Glasser 1981). Pulpwood supply increased 29 percent and timber supplies increased 7 percent.

<u>Prices</u>. Table 3.7 presents wood prices for the same period. Firewood stumpage prices were competitive with pulpwood stumpage prices; but,

Table 3.5a. Removal disposition.[a]

Products	Softwood	Hardwood	Total
	------- Billion cubic feet --------		
Removals[b]	15.9	7.2	23.1
Harvest residues	4.5	3.7	8.2
Logs, bolts, etc.	11.4	3.5	14.9
Firewood	0.2	0.6	0.8
Industrial roundwood	11.2	2.9	14.1
Primary residues	2.0	0.6	2.6
Primary products	9.2	2.3	11.5
Secondary residues	0.3	0.4	0.7
Final products	8.9	1.9	10.8

[a]Adapted from Bethel, et al. (1979), Marty and Webster (1976), and USDA (1981a and 1981b).

[b]Includes the rotten sections, tops, branches and bark that were excluded in Table 3.4 (see Appendix C).

Table 3.5b. Removal consumption.[a]

Consumption uses	Amount
	Billion cubic feet
Discarded waste material	7.7
Recycled material	2.6
Burned for energy	0.5

[a]Adapted from Cordell and Clements (1979).

Table 3.6. Wood production.[a]

Year	Sawtimber	Veneer	Pulpwood	Firewood	Total
	Quadrillion Btu				
1967	1.216	0.230	0.739	0.772	2.957
1968	1.263	0.251	0.783	0.859	3.156
1969	1.236	0.236	0.831	0.864	3.167
1970	1.190	0.229	0.888	0.869	3.176
1971	1.227	0.262	0.825	0.893	3.207
1972	1.368	0.291	0.820	0.972	3.451
1973	1.290	0.295	0.877	1.007	3.469
1974	1.165	0.257	0.982	1.050	3.454
1975	1.113	0.260	0.807	0.959	3.139
1976	1.246	0.300	0.886	1.074	3.506
1977	1.304	0.317	0.851	1.125	3.597
1978	1.327	0.324	0.877	1.192	3.720
1979	1.297	0.311	0.954	1.212	3.774

[a]Adapted from USDA (1981a). Firewood is the sum of consumption totals from Chapter 4 (Tables 4.4 and 4.6).

Table 3.7. Average wood production prices.[a]

Year	Sawtimber	Veneer	Pulpwood	Firewood[b]
	----------- Nominal dollars per million Btu[c] -----------			
1967	1.11 (1.11)	3.49 (3.49)	0.22 (0.22)	0.31 (0.31)
1968	1.26 (1.23)	3.43 (3.36)	0.23 (0.23)	0.33 (0.32)
1969	1.55 (1.45)	3.78 (3.54)	0.23 (0.22)	0.34 (0.32)
1970	1.31 (1.16)	3.95 (3.50)	0.22 (0.20)	0.36 (0.32)
1971	1.46 (1.25)	4.33 (3.70)	0.21 (0.18)	0.36 (0.31)
1972	1.72 (1.34)	4.26 (3.33)	0.21 (0.16)	0.36 (0.28)
1973	2.61 (1.61)	5.79 (3.56)	0.23 (0.14)	0.43 (0.26)
1974	2.73 (1.31)	7.19 (3.44)	0.24 (0.11)	0.46 (0.22)
1975	2.49 (1.20)	5.95 (2.88)	0.30 (0.14)	0.56 (0.27)
1976	2.98 (1.28)	6.48 (2.77)	0.30 (0.13)	0.55 (0.24)
1977	3.60 (1.39)	6.60 (2.55)	0.29 (0.11)	0.59 (0.23)
1978	4.21 (1.47)	8.00 (2.79)	0.30 (0.10)	0.61 (0.21)
1979	5.56 (1.60)	10.36 (2.97)	0.36 (0.10)	0.76 (0.22)

[a]Source: USDA (1981a) and CEA (1981).

[b]Estimated by multiplying delivered prices by annual average ratios of pulpwood stumpage to delivered price.

[c]Constant dollars, 1967=100, are in parentheses.

while firewood prices increased 145 percent, pulpwood stumpage only increased 64 percent. In 1979, firewood sold for more than double pulpwood stumpage; pulpwood suppliers were at a 50 percent disadvantage if they sold to pulp interests.

Supply Price and Quantity Relationships. Pulpwood, sawtimber, veneer, and firewood are compared on an energy potential basis. Figure 3.3 plots average real soft- and hardwood prices, and supply changes for pre- and post-oil embargo periods. Sources are Tables 3.6 and 3.7; prices were deflated to a 1967 base year using the producer fuel index for crude materials (CEA 1981).

Average real prices declined in all wood products except sawtimber in the two six-year periods. Sawtimber supply declined 2 percent in response to a 3-percent price increase. Real pulpwood, firewood, and veneer prices declined 37 percent, 23 percent, and 17 percent respectively while their supplies increased 7 percent, 21 percent, and 13 percent (Figure 3.3).

Potential Wood Supply

Commercial forests are only one of many wood sources. For example, Table 3.5a indicates a combined harvest and mill residue heat potential of 2.724 quads; unfortunately, their supply prices are unknown. In other situations, quantity and prices are unknown; and in still more situations, quantity estimates may be highly speculative or based upon economic growth when, in fact, a decline in supply quantity occurs. An example from noncommercial forests illustrates this point: Assuming an 80-year rotation, 10 ft^3

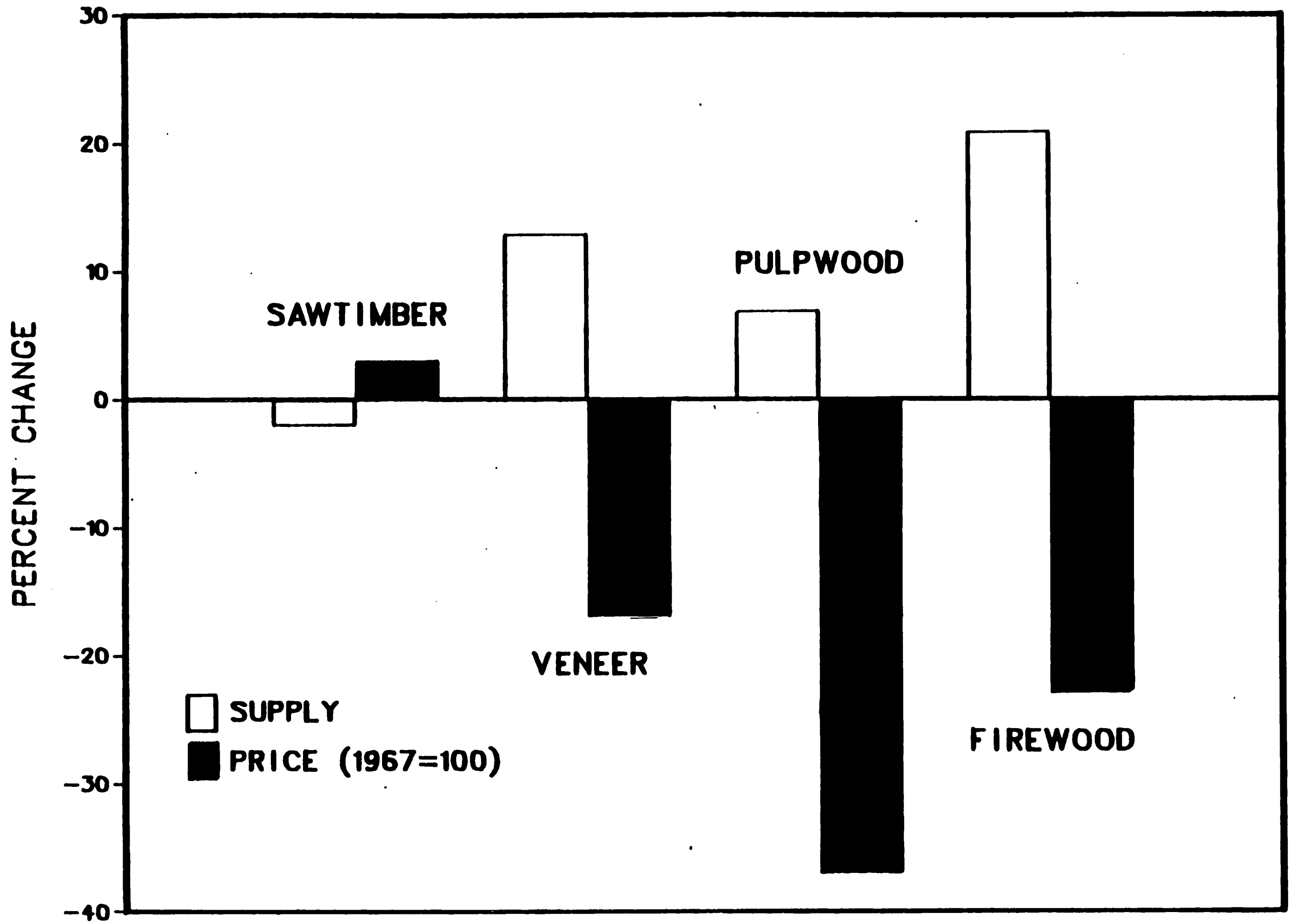

Figure 3.3. Wood product supply price and quantity averages for pre- and post-oil embargo periods.

of annual growth, and annual harvests of 0.674 quads, noncommercial forest supply potential is double 1980 residential consumption (USDA 1981a). Associated production costs, however, make it uneconomic. Figure 3.4, a modified McKelvey diagram summarizes potential wood fuel supply and designates this section's presentation order (U.S. Bureau of Mines, 1976). Order is: left to right, demonstrated to inferred; top to bottom, economic to submarginal supply sources. Costs increase downward; supply certainties increase right to left. Assignment of a particular fuel to a figure location is arbitrary. Annual heat potential (quads) is given below each figure classification.

Economic Potential. Average annual supply, mill residues, and urban wastes are considered economic. Average annual supply includes the known component of wood and bark used at paper mills for energy and a residential firewood component. Known supply has been 1.012 ± 0.158 quads over the last 13 years. Mill residues of 0.598 ± 0.200 quads are based upon primary and secondary plant residues shown in Table 3.5a (average net wood and bark quantities used at pulp and paper mills--American Paper Institute 1981). Urban wood wastes of 0.950 ± 0.682 quads reflect urban consumption habits. High variability shows a propensity to discard wastes rather than use them fuel. Whether or not discarding is more economic is unknown.

Paramarginal Supply. Excess growing stock (2.614 ± 0.859 quads), harvest residue (1.957 ± 0.150 quads), and unharvested residual trees (2.698 ± 0.100 quads) are paramarginal components. Excess growing

		Potential annual supply (11.701 Q)		
		Demonstrated (7.379 Q)		
		Reported (4.550 Q)	Estimated (2.829 Q)	Inferred (4.322 Q)
Economic (2.560 Q)		Firewood use (1.012 Q)	Mill residue (0.598 Q)	Urban wastes (0.950 Q)
Subeconomic (9.141 Q)	Paramarginal (7.269 Q)	Excess growing stock (2.614 Q)	Harvest residues (1.957 Q)	Unharvested residual (2.698 Q)
	Submarginal (1.872 Q)	Mortality (0.924 Q)	Trees from deferred and reserved forests (0.274 Q)	Trees from biomass farms and noncommercial forests (0.674 Q)

Increasing recovery costs

Increasing supply certainty

Figure 3.4. Potential supply sources for wood fuel. (A modified McKelvey Diagram--U.S. Bureau of Mines 1976. Parenthetical terms are energy equivalents in quads.)

stock accumulated at 8 percent per annum between 1970 and 1976 (USDA 1974 and 1981b). Lack of harvest residue variability reflects fairly constant harvest schedules over time, and little change in harvest and end-use technologies. Residual tree volume--tree volume left after harvests--estimates are based on the assumption that all growing stock trees are distributed evenly in commercial forests. Thus, average harvest removed and total growing stock are the data needed to estimate residuals (see Appendix C for more detail).

Submarginal Supply. Mortality (0.924 $\pm$ 0.470 quad), trees from deferred and reserved (0.274 quad), and noncommercial (0.674 $\pm$ 0.300 quad) forests are submarginal components.

Mortality declined at 2 percent per annum between 1970 and 1976 (USDA 1974 and 1981b). Much dead and dying timber is inaccessible; thus, variability is about half the total annual potential.

Trees from deferred and reserved forests--lands capable of 20 ft^3 of merchantable wood per acre per year--are on land under consideration for, or already part of, the National Wilderness System. As of January 1977, some 25.1 million acres were classified as productive-reserved, and 5.2 million acres were classified as productive-deferred. Estimated volume was 68.6 billion ft^3 of growing stock. A 60-year rotation might produce 1.1 billion ft^3 per year, half hardwoods and half softwoods. Variability is unknown--such forests cannot be harvested by law. Their contribution to a wood fuel supply is doubtful, except in an extreme emergency. Noncommercial forests are subject to large variability due to uncertain existence and harvest economies. Biomass farms, though reputedly capable of producing up to 5 percent of current energy needs (Inman 1977 and Fege 1979), are doubtful supply sources. Impacts of monocultures on soils (Calef 1976 and Grantham 1977), a farm's economic inefficiency as a producer of electric power (Tillman 1981), and high capital investments required for synthetic fuel development (Jelinek and Gushee 1981) suggest biomass farms will remain uneconomic.

Summary and Conclusions

The embargo shock of rapid real fuel price increases has moderated over time. Average real firewood supply price declines relative to fossil fuel prices during the six years following 1973 suggest wood has become competitive with other energy supplies.

Average firewood supply prices were larger than pulpwood supply prices, indicating pulpwood suppliers have an economic incentive to divert pulpwood to firewood uses. Stumpage differentials between pulpwood and firewood in 1979 suggest pulpwood sales to homeowners could have returned $6.00 more for each stumpage dollar invested.

Wood fuel supply potential, excluding additional reductions in total growing stock and diversions of wood from conventional products, amounts to 11.701 quads annually. Components of this total are 2.560 quads considered economic, 7.269 quads considered paramarginally economic, and 1.872 quads considered submarginally economic. On average, 1.012 quads of economic potential are realized each year. The 1.548-quad balance requires additional monetary incentive to bring that supply to market. On average, 1.012 quads of economic potential are realized each year. The 1.548-quad balance requires additional monetary incentive to bring that supply to market. Paramarginal supply, also dependent upon higher prices, may provide up to 3.600 additional quads of energy during a period of great need. At best, only 0.700 quad submarginal potential may ever be realized. Prices and conditions necessary to make these supplies available are unknown and speculative at present.

Chapter 4

Energy Demand and Prices

This chapter provides time series demand and price data for the nine fuels identified in Chapter 2. Data cover the 1967-1980 period for commercial, residential, and industrial sectors. Differences in consumption patterns occur between sectors because of pricing practices, national policy, or bulk purchases and long-term contracts. Attention is focused on end users or consumers rather than suppliers. Consumption data are presented in current, or nominal, dollars per million Btu. A brief analysis of each sector compares average energy use and real energy price (1967=100) changes during pre- (1967-1973) and post-oil embargo (1974-1979) periods.

General Background

In 1980, Table 4.1's three sector economy used 35.6 quads of energy. Differences between Tables 4.1 and 2.1 are due to a 27-percent decrease in imported fuels between 1979 and 1980, and a 3-percent decline in total energy use over the 2-year period. Also data in Table 2.1 and 3.1 represent major fuel components of all five economic sectors (including transportation and electric utilities), whereas these data in Table 4.1 represent nine fuel components over three economic sectors. Nonfuel components--plastics, laminates, and tar, included in Chapter 3 supply data--are excluded.

Table 4.1. Quantity demanded, 1980.[a]

Supply	Consumption: Commercial	Residential	Industrial	Total
	------------ Quadrillion Btu ------------			
Anthracite	0.010	0.015	0.022	0.047
Bituminous	0.091	0.049	3.275	3.415
Natural gas	2.745	4.880	8.451	16.076
Distillate oil	0.497	1.385	1.502	3.384
Residual oil	0.451	0.000	1.513	1.964
Kerosene	0.000	0.215	0.133	0.348
Liquid petroleum gas	0.075	0.422	1.441	1.938
Purchased Electricity	1.910	2.448	2.781	7.139
Wood	-b-	0.290	1.025	1.315
	5.779	9.704	20.143	35.626

[a]Sources: American Paper Institute (1981), USDA (1981a), and USDOE (1981a, 1981b, and 1982).

[b]Included in residential sector statistics.

Natural gas represented 45 percent of the 35.6-quad demand. Electricity use was 20 percent of that total, bituminous coal and distillate oil use about 10 percent each, and residual oil and LPG about 5 percent each. Anthracite, kerosene, and wood fuel use were 5 percent of the total.

Intrasector fuel demands, also in Table 4.1, followed the same general pattern as the three sector economy. Important commercial sector exceptions were less use of coal, LPG, kerosene, and unknown (perhaps small) firewood use. Commercial and residential sectors are not combined, as done so often (USDOE), but will be analyzed together in Chapter 5. Residential firewood statistics will be used there for substitution estimates in the commercial sector.

Residual oil was not used in the residential sector and coal played a minor role. Apparent firewood use was 3 percent of total residential demand and 5 percent of total industrial demand. Only industrial kerosene and anthracite demand combined was less than 1-quad during 1980.

Commercial Sector

Demand. Average energy use during 1967-1980 was 6.0 $\pm$ 0.4 quads (USDOE 1981a and American Gas Association 1980). Except for natural gas use, up 26 percent, and electricity use, up 106 percent, their demand declined (see Table 4.2). Coal use declined 71 percent. These declines, which occurred in steps after 1969, 1971, and 1974, were probably labor-cost related as were demand declines after 1978 (USDOE 1978).

Table 4.2. Commercial demand.[a]

Year	Fuels[b] (1)	(2)	(3)	(4)	(5)	(6)	(7)	Total
	Quadrillion Btu							
1967	0.047	0.297	2.022	0.703	1.128	0.085	0.926	5.208
1968	0.044	0.265	2.140	0.730	1.094	0.092	1.016	5.381
1969	0.039	0.256	2.323	0.736	1.119	0.104	1.110	5.687
1970	0.037	0.211	2.473	0.751	1.168	0.102	1.203	5.945
1971	0.036	0.200	2.587	0.753	1.145	0.103	1.290	6.114
1972	0.027	0.153	2.678	0.800	1.202	0.111	1.410	6.381
1973	0.028	0.143	2.649	0.804	1.209	0.105	1.519	6.457
1974	0.025	0.150	2.617	0.744	1.087	0.096	1.502	6.221
1975	0.020	0.122	2.559	0.744	0.969	0.093	1.593	6.100
1976	0.019	0.116	2.718	0.850	1.120	0.097	1.672	6.592
1977	0.019	0.115	2.548	0.865	1.058	0.094	1.748	6.447
1978	0.016	0.129	2.643	0.868	1.034	0.091	1.810	6.591
1979	0.013	0.116	2.836	0.574	0.511	0.081	1.854	5.985
1980	0.010	0.091	2.745	0.497	0.451	0.075	1.910	5.779

[a]Sources: USDOE (1981a and 1981b) and American Gas Association (1980).

[b]Fuels: (1) anthracite, (2) bituminous, (3) natural gas, (4) Distillate oil, (5) residual oil, (6) Liquid petroleum gas, and (7) electricity.

The oil embargo and inflation, spurred by elimination of price controls in 1974, precipitated the most severe decline in real GNP since the Depression (Baumol and Binder 1979). But that recession and lack of supply only partly explains energy demand declines and resurgent wood use.

Price. Nominal electricity prices almost tripled between 1967 and 1980. Aggregate coal prices more than tripled; residual oil prices increased nine-fold; distillate prices more than seven-fold; and LPG prices quadrupled (see Table 4.3). The largest single price increase occurred during the 1973-74 embargo years. Residual oil prices increased 100 percent. Percentage changes are misleading, however. Nominal price increases of $2.89 per million Btu in distillate, and $2.21 per million Btu in electricity for 1978-1979, were larger than price increases during the embargo. Natural gas prices increased steadily during the period and were 4.5 times higher in 1980 than in 1967 (USDOE 1981b and American Gas Association 1980).

Price and Quantity Comparisons. Table 4.2 and 4.3 prices and quantities were averaged for periods 1967-1973 and 1974-1980. Prices were deflated to a 1967 base year using the consumer energy price index (CEA 1981). Price and quantity changes from pre-embargo averages were estimated--Figure 4.1 shows commercial sector results.

Anthracite demand declined between pre- and post-oil embargo periods. Natural gas use increased 11 percent despite a 23-percent increase in price; otherwise, price-quantity relationships behaved almost as expected. Where prices increased,demands declined; where

Table 4.3. Commercial prices.[a]

Year	Fuels[b]						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Nominal dollars per million Btu						
1967	1.54	1.24	0.71	1.03	0.58	1.20	5.78
1968	1.58	1.27	0.71	1.06	0.59	0.95	5.69
1969	1.66	1.30	0.72	1.08	0.60	0.90	5.64
1970	1.74	1.48	0.75	1.13	0.64	1.18	5.72
1971	1.79	1.65	0.80	1.19	0.79	1.14	6.03
1972	1.85	1.70	0.85	1.21	0.73	1.21	6.33
1973	2.37	2.32	0.91	1.40	1.01	1.60	6.60
1974	2.50	2.45	1.04	2.36	2.02	2.32	8.17
1975	2.60	2.57	1.31	2.60	2.26	2.48	9.25
1976	2.90	2.88	1.59	2.73	2.12	3.00	9.91
1977	3.23	3.47	1.97	3.20	2.33	3.40	10.99
1978	3.55	3.85	2.17	3.39	2.20	3.35	11.69
1979	4.18	4.54	2.67	4.94	3.38	3.75	12.90
1980	4.44	4.56	3.28	7.83	5.35	5.95	15.11

[a]Sources: American Gas Association (1980), USDOE (1981b), and USDOE 1981 computer run of state fuel price data.

[b]Fuels: (1) anthracite, (2) bituminous, (3) natural gas, (4) distillate oil, (5) residual oil, (6) liquid petroleum gas, and (7) electricity.

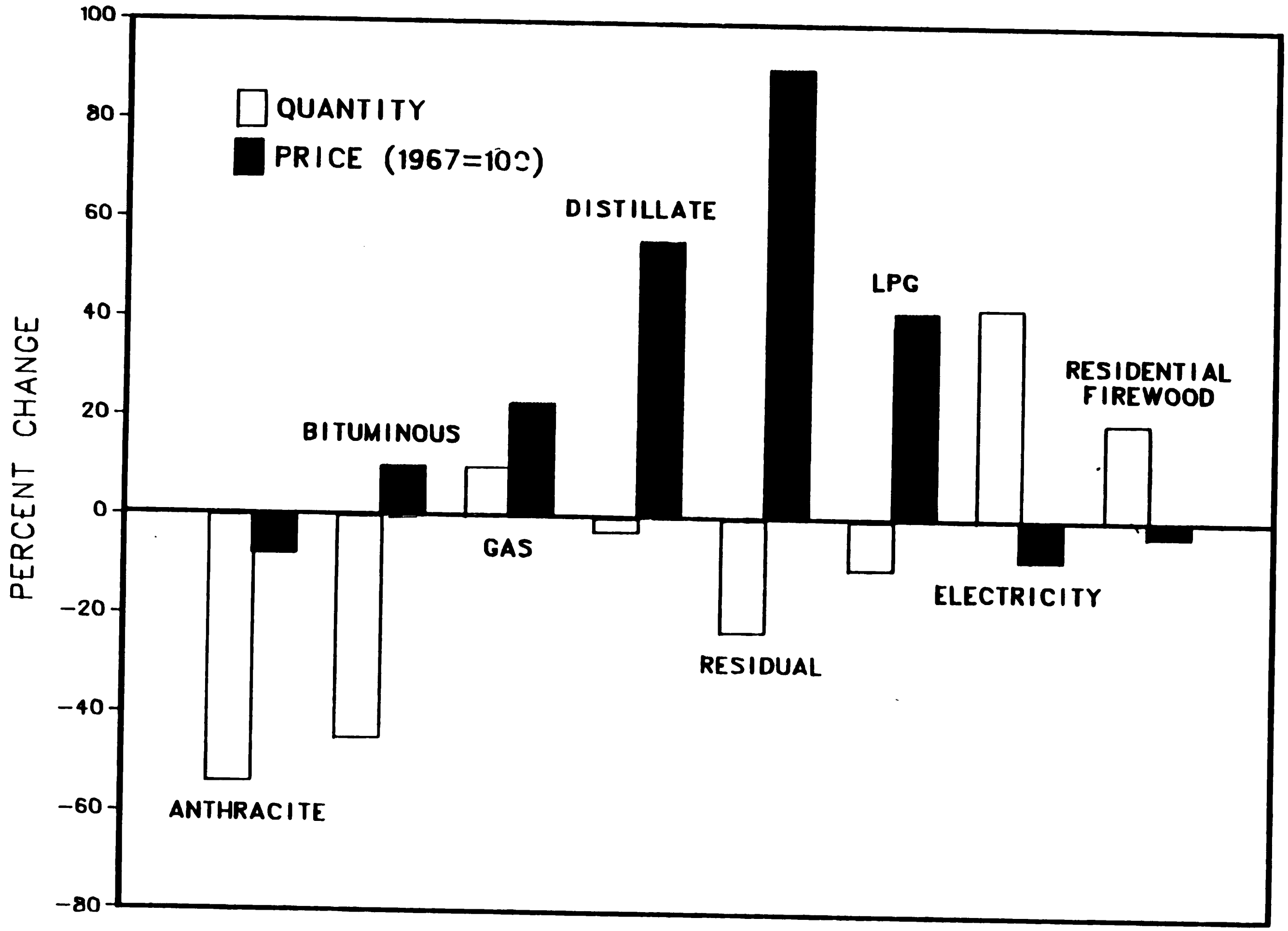

Figure 4.1. Average pre- and post-oil embargo commercial fuel prices and quantities demanded.

real prices declined, demands increased. For example, electricity demand was up 43 percent as its real price declined 8 percent.

Residential Sector

Demand. The 14-year demand averaged 10.1 ± 0.5 quads. Anthracite and bituminous coal, distillate oil, kerosene, and LPG fuel uses declined. Natural gas, electricity, and firewood use increased (see Table 4.4).

Price. Largest price increases for all fuels occurred during the embargo period, but nominal firewood price increases were only 6 percent. The largest firewood price increases were between 1972 and 1973 (22 percent) and again between 1978 and 1979 (18 percent). Petroleum prices increased about 36 percent between pre- and post-embargo periods, while all other fuel prices increased about 15 percent (see Table 4.5). Commercial sector coal switching during 1977-78 gas shortages made prices higher than residential coal prices (USDOE 1979a).

Price and Quantity Comparisons. Natural gas remained the most sought after residential-commercial sector fuel. Real price increases are shown for each fuel in Tables 4.4 and 4.5 except for anthracite, electricity, and firewood. Anthracite consumption, obviously not price driven, declined 53 percent as its real price fell 4 percent between pre- and post-oil embargo periods. All petroleum products shown in Figure 4.2 also declined as average prices rose 40 percent. Electric use rose 40 percent; its price declined 14 percent. Firewood use rose 20 percent; its average real price declined 3 percent.

Table 4.4. Residential demand.[a]

Year	Fuel[b] (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	Total
	Quadrillion Btu								
1967	0.070	0.160	4.451	2.177	0.388	0.483	1.161	0.207	9.097
1968	0.066	0.143	4.588	2.249	0.432	0.520	1.302	0.185	9.485
1969	0.058	0.138	4.875	2.245	0.428	0.590	1.456	0.164	9.954
1970	0.056	0.113	4.987	2.285	0.415	0.578	1.591	0.141	10.166
1971	0.054	0.108	5.126	2.290	0.401	0.585	1.704	0.136	10.404
1972	0.041	0.083	5.264	2.366	0.375	0.628	1.838	0.129	10.724
1973	0.043	0.077	4.977	2.324	0.347	0.595	1.976	0.140	10.479
1974	0.037	0.081	4.901	2.129	0.283	0.546	1.973	0.145	10.095
1975	0.030	0.066	5.023	2.101	0.248	0.528	1.995	0.155	10.146
1976	0.029	0.063	5.147	2.319	0.266	0.549	2.057	0.163	10.593
1977	0.029	0.062	4.913	2.273	0.260	0.533	2.188	0.172	10.430
1978	0.024	0.069	4.982	2.237	0.250	0.516	2.290	0.185	10.553
1979	0.019	0.063	5.055	1.600	0.242	0.456	2.330	0.212	9.977
1980	0.015	0.049	4.880	1.385	0.215	0.422	2.488	0.290	9.704

[a]Sources: American Gas Association (1980), USDOE (1981a and 1981b), and USDA (1981a).

[b]Fuels: (1) anthracite, (2) Bituminous, (3) natural gas, (4) distillate oil, (5) kerosene, (6) liquid petroleum gas, (7) electricity, and (8) firewood.

Table 4.5. Residential prices.[a]

	Fuel[b]							
Year	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Nominal dollars per million Btu							
1967	1.59	1.29	1.00	1.18	1.32	1.22	6.35	1.39
1968	1.63	1.31	1.00	1.21	1.35	0.97	6.22	1.51
1969	1.71	1.36	1.01	1.25	1.39	0.92	6.13	1.64
1970	1.79	1.54	1.06	1.30	1.44	1.20	6.16	1.78
1971	1.87	1.65	1.12	1.37	1.51	1.22	6.41	1.91
1972	1.89	1.73	1.19	1.39	1.55	1.24	6.72	1.97
1973	1.98	1.85	1.25	1.62	1.63	1.63	6.98	2.53
1974	2.57	2.87	1.42	2.58	2.63	2.35	8.29	2.68
1975	3.28	3.35	1.69	2.81	2.95	2.51	9.40	2.78
1976	3.39	3.38	1.98	3.03	3.18	2.89	10.11	3.08
1977	3.46	3.43	2.38	3.42	3.63	3.44	11.09	3.45
1978	3.49	3.71	2.59	3.66	3.88	3.36	11.82	3.79
1979	3.68	3.95	3.17	5 25	5.49	3.78	12.68	4.47
1980	3.89	4.30	3.84	7.83	8.71	5.99	14.90	4.75

[a]Sources: American Gas Association (1980), USDOE (1981a, 1981b, and 1982), USDOE 1981 computer run of state fuel price data, and firewood price survey in Appendix D.

[b]Fuels: (1) anthracite, (2) bituminous, (3) natural gas, (4) distillate oil, (5) kerosene, (6) Liquid petroleum gas, (7) electricity, and (8) firewood.

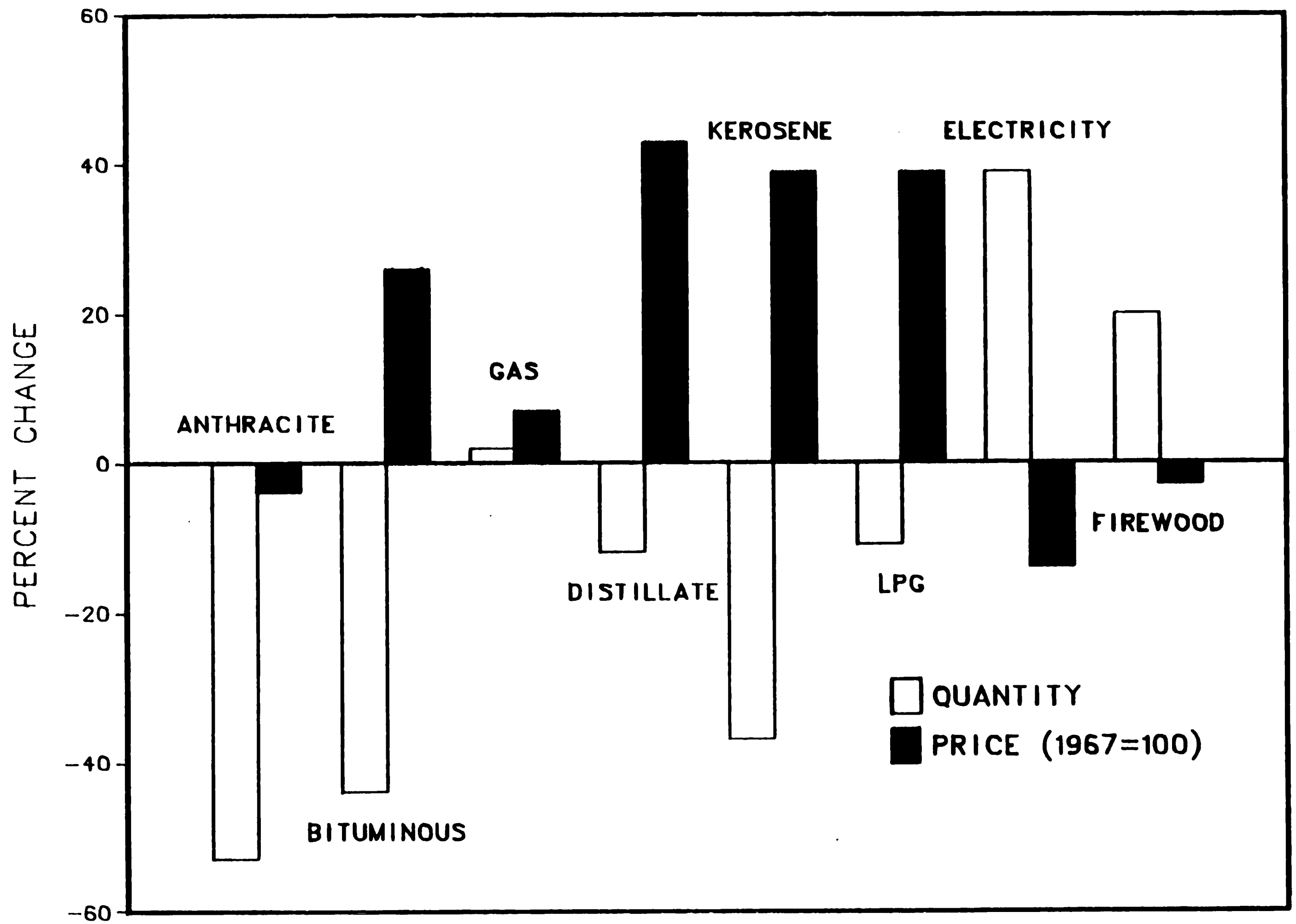

Figure 4.2. Average pre- and post-oil embargo residential fuel prices and quantities demanded.

Industrial Sector

Demand. Average fuel use for 1967-1980 was 20.0 $\pm$ 1.0 quads, while total overall use increased 10 percent, but the industrial sector witnessed more turbulent overall changes than the other two sectors.

All fuel demand was down marginally except for anthracite and firewood, up about 4 percent (Table 4.6). Industrial sector firewood includes bark, waste wood, and black liquor solids from pulping processes (American Paper Institute 1981). The 1975 recession and a natural gas supply shortage and caused major demand declines, but anthracite demand was up about 6 percent. Natural gas and residual oil demand declined 17 percent in 1975; firewood by 13 percent; and distillate oil by 8 percent. By 1980, distillate oil, LPG, electricity, and firewood demands reversed themselves enough to post a 40 percent increase between 1967-80 (see Table 4.6).

Price. As in other sectors, the most pronounced price rises occurred in 1973-74 and 1978-79. (Anthracite prices declined after 1977, then increased 12 percent in 1979-80, according to Table 4.7 data). Kerosene prices continued to rise dramatically between 1979-80. Nominal firewood prices--average mill pulpwood cost (USDA 1981a)--increased moderately during the period. Largest firewood price increases, +10 percent were in 1972-73, 1976-77, and 1979-80. Low prices, by comparison the other sector prices, were due to long-term contracts and large volume purchases. Intersector price differentials began to disappear by 1980.

Price and Quantity Comparisons. Tables' 4.6 and 4.7 data were averaged to compare 1967-73 and 1974-80 periods; prices were deflated

Table 4.6. Industrial demand.[a]

Year	Fuel[b]									
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	Total
	Quadrillion Btu									
1967	0.083	5.111	8.043	0.705	1.144	0.179	0.737	1.655	0.565	18.222
1968	0.074	5.049	8.627	0.671	1.151	0.151	0.843	1.778	0.674	19.018
1969	0.063	4.929	9.234	0.689	1.119	0.141	0.981	1.909	0.700	19.765
1970	0.053	4.947	9.536	0.653	1.165	0.129	0.989	1.948	0.728	20.148
1971	0.043	4.259	9.892	0.710	1.100	0.115	1.015	2.011	0.757	20.902
1972	0.032	4.289	9.884	0.785	1.229	0.111	1.195	2.187	0.843	20.555
1973	0.032	4.317	10.388	0.872	1.333	0.100	1.261	2.341	0.867	21.511
1974	0.033	4.015	10.000	0.805	1.273	0.082	1.253	2.337	0.905	20.703
1975	0.035	3.762	8.532	0.796	1.089	0.081	1.170	2.304	0.804	18.573
1976	0.040	3.746	8.762	0.934	1.368	0.085	1.245	2.525	0.911	19.616
1977	0.037	3.462	8.635	1.149	1.492	0.103	1.265	2.635	0.953	19.730
1978	0.031	3.341	8.539	1.154	1.454	0.113	1.271	2.732	1.007	19.642
1979	0.024	3.612	8.549	1.736	1.674	0.147	1.594	2.873	1.000	21.209
1980	0.022	3.275	8.451	1.502	1.513	0.133	1.441	2.781	1.025	20.143

[a]Sources: American Gas Association (1980), USDOE (1981a, 1981b, and 1982), American Paper Institute (1981), and USDA (1981a).

[b]Fuels: (1) anthracite, (2) Bituminous, (3) natural gas, (4) distillate oil, (5) residual oil, (6) kerosene, (7) liquid petroleum gas, (8) electricity, and (9) firewood.

Table 4.7. Industrial prices.[a]

Year	Fuel[b]								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Nominal dollars per million Btu								
1967	0.41	0.17	0.30	1.02	0.58	1.16	1.06	2.63	1.02
1968	0.44	0.18	0.30	1.04	0.59	1.19	0.84	2.64	1.04
1969	0.50	0.19	0.31	1.08	0.60	1.23	0.80	2.65	1.07
1970	0.55	0.25	0.33	1.12	0.64	1.27	1.04	2.78	1.08
1971	0.58	0.33	0.37	1.18	0.79	1.33	1.05	3.03	1.09
1972	0.61	0.36	0.40	1.18	0.73	1.36	1.06	3.20	1.18
1973	0.61	0.40	0.44	1.42	1.00	1.43	1.43	3.44	1.32
1974	1.05	0.73	0.63	2.37	2.02	2.42	2.16	4.54	1.45
1975	1.68	0.86	0.85	2.59	2.25	2.72	2.33	5.63	1.51
1976	1.78	0.88	1.08	2.88	2.08	2.55	3.02	6.06	1.67
1977	1.71	1.00	1.30	3.18	2.30	3.36	3.22	6.82	1.75
1978	1.68	1.15	1.48	3.33	2.16	3.61	3.28	7.60	1.82
1979	1.69	1.22	2.16	4.86	3.21	5.20	3.59	8.35	2.06
1980	1.93	1.33	2.80	7.70	5.08	8.24	5.69	10.10	2.28

[a]Sources: American Gas Association (1980), USDOE (1981b and 1982), USDA (1981a), and USDOE computer run of state fuel price data.

[b]Fuels: (1) anthracite, (2) bituminous, (3) natural gas, (4) distillate oil, (5) residual oil, (6) kerosene, (7) Liquid petroleum gas, (8) electricity, and (9) wood.

[c]Delivered pulpwood prices.

using the crude materials for further processing producer price index for fuels (CEA 1981). Of those prices examined only electricity and firewood real prices declined after the embargo. Anthracite, bituminous, gas, and kerosene demand declined in response to price increases averaging more than 50 percent. Distillate, residual, and LPG demand increased despite average price increases of more than 50 percent. Electricity and firewood demand both increased about 30 percent as their real prices declined 14 and 6 percent respectively (Figure 4.3).

Summary and Conclusions

From 1967 to 1980, total energy demand increased 10 percent in the economy made up of three sectors: commercial, residential, and industrial sectors. Demand increases were: electricity was up by 91 percent, firewood by 70 percent, LPG by 49 percent, and natural gas by 11 percent. Coal and kerosene demand declined 40 percent each; distillate and residual oil demand was down 6 and 14 percent respectively.

Declines were observed in electricity, firewood, and coal prices. Coal price declines were the exception in an industrial sector where prices increased more than 30 percent over the 14-year period. Natural gas prices rose 106 percent. Firewood substitutes for electricity seem rational choices meriting further study in the industrial sector.

Residual and distillate oil prices rose 106 and 92 percent respectively in the commercial sector. Real coal price declines and a declining demand, suggest price declines may continue. Anthracite,

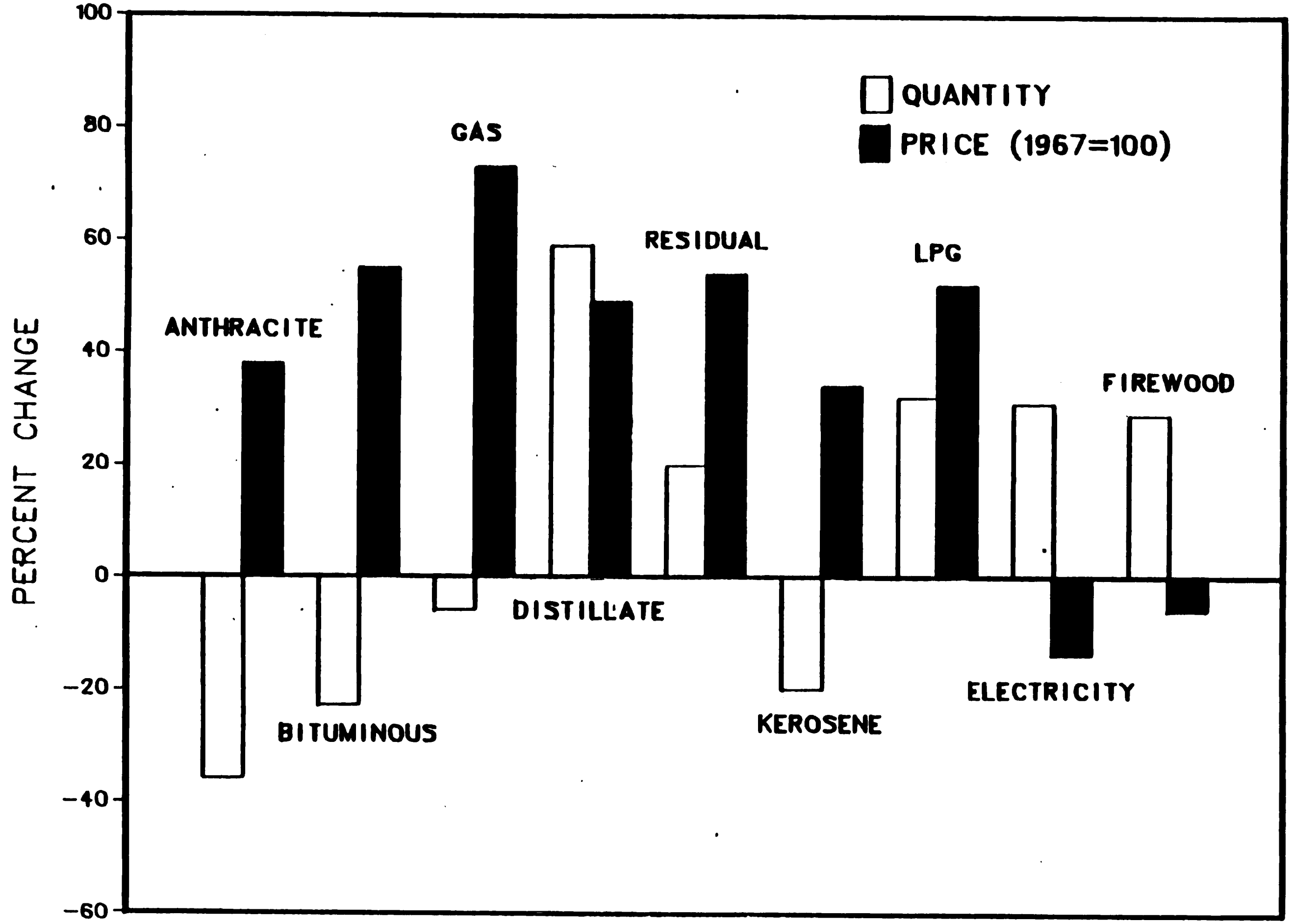

Figure 4.3. Average pre- and post-oil embargo industrial fuel prices and quantities demanded.

firewood, and natural gas (whose real price increase has been legally restrained) seem to be rational choices for a cost-minimization objective.

Percentage changes on which these observations were made can be misleading. Therefore fuels identified in Chapter 2 will be examined for substitution potential in commercial, residential, and industrial sectors in both following chapters.

Chapter 5

Commercial and Residential Space Heating with Wood

Energy demand in the residential-commercial sector averaged 15.722 $\pm$ 1.706 quads during the 1967-1980 period. Over that period grew a dependence upon natural gas, electricity, and wood and a decreased dependence upon coal and oil products.

This chapter will explore potential wood fuel substitutes by analyzing demand and price data for 1967-1980 (from Tables 4.2 through 4.5). First, the economic rationale for analysis is presented and applied using Chapter 4 data. Next, two cases are examined: commercial and residential. Finally, implications associated with substitution choices are summarized.

Economic Rationale

Both sectors assume cost minimization objectives . Utility is maximized if fuel needs are met at lesser costs. This assertion--true if more consumer goods are of greater utility than less consumer goods--is similar to providing more disposable income. The necessary condition for cost minimizing objectives are equating marginal rates of substitution (MRS) to the price ratio of two equally feasible fuel choices; e.g.,

$$\text{MRS (fuel}_2 \text{ for fuel}_1) = P_2/P_1. \tag{5.1}$$

Equation (5.1) is a true minimum, if MRS diminishes when the ratio of $fuel_2/fuel_1$ increases.

If cross-price elasticities, given by

$$E_{ij} = (P_j/\text{Delta } P_j)(\text{Delta } f_i/f_i), \qquad (5.2)$$

are positive, two fuels are substitutes. If cross-elasticities are negative, fuels are complements (Nicholson 1972). Elasticity magnitude infers demand change impact for firewood; e.g., brought about by a price change in distillate oil.

Applications

Elasticities. Fuels with plentiful substitutes have an elastic demand (E_{ii} is less than -1.0), whereas fuels with few substitutes have an inelastic demand (E_{ii} is more than -1.0). Coal had relatively plentiful substitutes during the 1967-1980 period (and a negative E_{ii}). Other fuels satisfied substitution criterion occasionally; e.g., commercial sector distillate oil in 1978-1980, residual oil in 1974-1976 and 1978-1979, and LPG in 1978-1979 (see own-price elasticities in Table 5.1).

Cross-price Elasticities. Firewood was a gross substitute whenever E_{ij} was positive; e.g., most fuels, except residual oil, LPG, and electricity in the commercial sector during 1972-1980. Residential sector cross-price elesticities were similar to the commercial sector (Table 5.2), although residential sector elasticities are not reproduced here. All residential fuel demand elasticities changed from negative to positive after 1971.

Table 5.1. Commercial sector elasticities.[a]

	Fuel[b]							
Years	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
67-68	(2.57)	(4.76)	c	1.31	(1.79)	(0.34)	(5.91)	(1.36)
68-69	(2.44)	(1.48)	5.86	0.44	1.34	(2.27)	(10.02)	(1.46)
69-70	(1.12)	(1.49)	1.53	0.45	0.66	(0.07)	11.97	(1.84)
70-71	(0.97)	(0.49)	0.70	0.05	(0.09)	(0.28)	1.32	(0.51)
71-72	(8.67)	(8.92)	0.57	3.63	(0.62)	1.26	1.83	(1.71)
72-73	0.15	(0.22)	(0.16)	0.03	0.02	(0.20)	1.78	0.33
73-74	(2.12)	0.88	(0.09)	(0.15)	(0.16)	(0.24)	(0.05)	0.61
74-75	(5.67)	(4.31)	(0.10)	0.00	(1.02)	(0.48)	0.47	1.82
75-76	(0.47)	(0.44)	0.31	2.73	(2.26)	0.22	0.70	0.49
76-77	0.00	(0.05)	(0.30)	0.11	(0.60)	(0.25)	0.43	0.47
77-78	(1.82)	1.11	0.12	0.06	0.40	2.19	0.56	0.78
78-79	(1.27)	(0.65)	0.34	(1.10)	(1.60)	(1.03)	0.24	0.83
79-80	(4.32)	(54.95)	(0.16)	(0.32)	(0.28)	(0.17)	0.19	5.12

[a]Source: Equation 5.2 (i=j), and Tables 4.2 through 4.5.

[b]Fuel: (1) anthracite, (2) bituminous, (3) natural gas, (4) distillate, (5) residual, (6) LPG, (7) electricity, and (8) firewood from the residential sector.

[c]Undefined.

Table 5.2. Commercial sector cross-price elasticities.[a]

	Fuel[b]						
Years	(1)	(2)	(3)	(4)	(5)	(6)	(7)
67-68	(4.38)	(4.70)	c	(3.91)	(6.57)	0.48	7.15
68-69	(2.44)	(5.15)	(8.60)	(6.44)	(7.16)	2.23	(0.16)
69-70	(3.20)	(1.16)	(3.70)	(3.33)	(2.34)	(0.56)	(10.71)
70-71	(1.27)	(0.33)	(0.56)	(0.70)	(0.17)	1.05	(0.68)
71-72	(1.60)	(1.77)	(0.87)	(3.17)	0.67	(0.89)	(1.09)
72-73	0.33	0.27	1.20	0.56	0.25	0.29	1.96
73-74	0.66	0.64	0.26	0.07	0.05	0.10	0.19
74-75	1.70	1.39	0.29	0.69	0.59	1.00	0.54
75-76	0.46	0.44	0.26	1.03	(0.79)	0.27	0.73
76-77	0.50	0.29	0.25	0.34	0.57	0.43	0.52
77-78	0.77	0.70	0.75	1.26	(1.27)	(4.92)	1.18
78-79	0.83	0.83	0.66	0.37	0.32	1.21	1.38
79-80	5.15	70.70	1.52	0.69	0.69	0.69	1.97

[a]Sources: Equation 5.2 and Tables 4.2 through 4.4.

[b]Fuels: (1) anthracite, (2) bituminous, (3) natural gas, (4) distillate, (5) residual, (6) LPG, (7) electricity.

[c]Undefined.

Marginal Rates of Substitution. Cost minimizing concerns should equate firewood MRS to the ratio of other fuels' market prices. Tables 5.1 and 5.2 suggest firewood could have been a strong commercial-residential fuel substitute after 1972.

All oil and gas products exhibited declining MRS (firewood for other fuels) during 1973-1980. Distillate, LPG, and residual oil provide examples of wood fuel substitution opportunities (since their MRS', shown in Table 5.3, decreased most during 1967-1980). Electricity, whose MRS shows a mixed trend, should always be a candidate for wood substitutes. Natural gas, whose MRS declined but remained large, was a good firewood substitute. In 1967-1980, wood substitution potential should have been strong since all fuels shown in Table 5.3 had a positive MRS.

Marginal rates of firewood substitution in the residential sector were computed from Table 4.5 data using equation 5.1. An MRS equaling 1.0 means two fuels are equally economic, and utility would be maximized using either. An MRS less than 1.0 means firewood should be a fuel substitute on the basis of prices. An MRS greater than 1.0 means wood should be replaced by the fuel under study.

By 1980, using these critera, firewood was a better substitute for electricity, distillate and residual oil, and LPG. Bituminous and anthracite coal, and natural gas were promising substitutes for firewood (Table 5.4).

Although electricity, after 1977 appears a poor fuel choice vis-a-vis wood, a paradox exists. In 1980 coal accounted for more than 60 percent of all electric generating fuels (USDOE 1982). Much

Table 5.3. Commercial marginal rates of substitution.[a]

Year	Fuel[b] (1)	(2)	(3)	(4)	(5)	(6)	(7)
1967	0.90	1.12	1.96	1.35	2.40	1.16	0.24
1968	0.96	1.19	2.13	1.42	2.56	1.59	0.27
1969	0.99	1.26	2.28	1.52	2.73	1.82	0.29
1970	1.02	1.20	2.37	1.58	2.78	1.51	0.31
1971	1.07	1.16	2.39	1.61	2.42	1.68	0.32
1972	1.06	1.16	2.32	1.63	2.70	1.63	0.31
1973	1.07	1.09	2.78	1.81	2.50	1.58	0.38
1974	1.07	1.09	2.58	1.14	1.33	1.16	0.33
1975	1.07	1.08	2.12	1.07	1.23	1.12	0.30
1976	1.06	1.07	1.94	1.13	1.45	1.03	0.31
1977	1.07	0.99	1.75	1.08	1.48	1.01	0.31
1978	1.07	0.98	1.75	1.12	1.72	1.13	0.32
1979	1.07	0.98	1.67	0.90	1.32	1.19	0.35
1980	1.07	1.04	1.45	0.61	0.89	0.80	0.31

[a]Sources: equation 6.1 and Tables 4.3 and 4.5.

[b]Fuels: (1) anthracite, (2) bituminous, (3) natural gas, (4) distillate, (5) residual, (6) LPG, and (7) electricity.

Table 5.4. Residential marginal rates of substitution.[a]

	Fuel[b]						
Year	(1)	(2)	(3)	(4)	(5)	(6)	(7)
1967	0.87	1.08	1.39	1.18	1.05	1.14	0.22
1968	0.93	1.15	1.51	1.25	1.12	1.56	0.24
1969	0.96	1.21	1.62	1.31	1.18	1.78	0.27
1970	0.99	1.16	1.68	1.37	1.24	1.48	0.29
1971	1.02	1.16	1.71	1.39	1.26	1.57	0.30
1972	1.04	1.14	1.66	1.42	1.27	1.59	0.29
1973	1.28	1.37	2.02	1.56	1.55	1.55	0.36
1974	1.04	0.93	1.89	1.04	1.02	1.14	0.32
1975	0.85	0.83	1.64	0.99	0.94	1.11	0.30
1976	0.91	0.91	1.56	1.02	0.97	1.07	0.30
1977	1.00	1.01	1.45	1.01	0.95	1.00	0.31
1978	1.09	1.02	1.46	1.04	0.98	1.13	0.32
1979	1.21	1.13	1.41	0.85	0.81	1.18	0.35
1980	1.22	1.10	1.24	0.61	0.55	0.79	0.32

[a]Source: Table 4.5 and equation (5.1).

[b]Fuel: (1) anthracite, (2) bituminous, (3) natural gas, (4) distillate, (5) kerosene, (6) LPG, and (7) electricity.

more coal than is indicated was used indirectly by residential and commercial sectors. However, direct fuel use, and wood substitution potential for those uses, is the main concern here.

Case Studies

Two cases are examined. One analyses fuel alternatives for commercial heating and cooling in the Southeastern U.S.; the other examines residential heating by comparing a hypothetical situation very close to actual conditions. Implications are drawn from both examples.

Commercial Sector, Case 1. The facility to be heated and cooled--22,000 ft^2 of office space--was insulated on three sides with earth. Total energy input need varied according to system efficiency. Calculations, adapted here, were taken from an unpublished report (USDA 1979); wood moisture content was 50 percent by weight and firewood prices were taken from Table 4.5.

Table 5.5 indicates the most efficient fuel was natural gas: if the objective was cost minimization. It should have been selected because annual fuel costs for gas were 2.5 times less than firewood costs. Decision to install a wood system was based either upon information unavailable in the case's literature or fear of future shortages.

Residential Sector, Case 2. In 1977, some 2.3 million housing units used wood in stoves and fireplaces for primary heating. Supplemental firewood users, classed by primary fuel use, are: 4.6 million units with natural gas; 3.0 million units with fuel oil and kerosene and an

Table 5.5. Comparative heating costs.[a]

Item	Fuel		
	Gas	Electricity	Wood
Energy need (M Btu)[b]	1,363	1,076	2,045
Energy costs ($/M Btu)[c]	x 2.17	x 11.69	x 3.79
Annual costs (nearest $)	2,958	12,582	7,750

[a]Source: Unpublished fuel cost estimate (USDA 1979).

[b]Required outputs are 1.022 B Btu per year. Equipment efficiencies are 0.75, 0.95, and 0.50 for the gas, electric, and wood systems respectively.

[c]Firewood price data were taken from Table 4.5.

equal number using electricity; and 1.5 million with LPG. Wood fuel was a secondary heat source for 12.1 million housing units in total, more than five times the number of 1977 primary wood burning units (USDOE 1979b).

Neither the MRS of firewood for other fuels, nor the market rate of exchange offered consumers--implied in Table 5.4--shows the drama of substitution taking place since 1977. Recent fuel use surveys, beginning to converge upon a similar amount of residential sector firewood use,[1] suggest Table 4.4 demand figures are modest. Some 40 to 45 million cords of firewood (0.812 to 0.914 quads--about 0.091 quads of free firewood in fiscal year 81[2]) are thought to have been consumed in the 1980-1981 winter. But were those substitutes economic, or was there a net loss associated with investments?

Several hypothetical firewood substitutions are examined to try to answer the economic substitute question. Assumptions are: 50-percent efficiency for wood stoves purchased during the 1973-1974 period and firewood--at 30 percent moisture content--purchases through local newspaper advertisements. Heating needs, based upon national averages, for 1,000-square foot single-level homes are about 52 million Btu (about 2.5 cords of firewood) per season.

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[1]Preliminary results of a firewood survey conducted by USDA, Forest Service, Forest Products Laboratory, P.O. Box 5130, Madison WI, 53705.

[2]Fiscal year began October 1, 1979. Information source is USDA, Forest Service, Timber Management Staff, P.O. Box 2417, Washington DC, 20013.

Hypothetical distillate and electric heating systems are compared for 1974-1980 (Table 5.6). All energy prices are adjusted for combustor efficiency; firewood prices are adjusted for moisture content as well. Cost differences indicate people who replaced oil furnaces with wood stoves for economy measures, and bought their wood at advertised prices, experienced a net loss of 1.21 $\$/ft^2$ of floor heated space. Those who substituted firewood for electricity fared somewhat better: a net savings of about 27 cents per square foot.

Favorable substitution results might be obtained if firewood were dryer, if discount rates were less than 7 percent, or cost differences were larger and positive. (A free firewood case will be examined in Chapter 7.) In some locations, fossil fuels may be unavailable at any price; e.g., gas and heating oil shortages during the 1977 winter made firewood an expediency measure. Cost savings were neither objectives nor motives behind such investments.

Summary and Conclusions

Firewood was not an economic substitute for most fuels identified in Chapter 2 during 1972-1980. Prior to 1972, firewood complemented other fuels; firewood cross-elasticities were negative. Marginal rates of substitution, in commercial and residential sectors, were similar. Some kerosene (after 1972) and electricity (during the whole 14-year period) seemed promising candidates for firewood substitution, based upon nominal market prices and demand criteria. By the same measure, natural gas, bituminous, and anthracite seemed better firewood substitutes.

Table 5.6. Substitution comparisons.[a]

	Firewood		Distillate		Electricity		Fuel	
Year	Price	Cost[b]	Price	Cost[c]	Price	Cost[d]	(1)[e]	(2)[e]
	--------- Dollars per million Btu ----------						- 1974 dollars -	
1974	2.68	8.12	2.58	4.30	8.29	8.73	-198.64	31.72
1975	2.78	8.42	2.81	4.68	9.40	9.89	-181.76	71.44
1976	3.08	9.33	3.03	5.05	10.11	10.64	-195.23	59.76
1977	3.45	10.45	3.42	5.70	11.09	11.67	-200.81	27.06
1978	3.79	11.48	3.66	6.10	11.82	12.44	-213.56	38.11
1979	4.47	13.55	5.25	8.75	12.68	13.35	-178.29	-7.43
1980	4.75	14.39	7.83	13.05	14.90	15.68	-46.45	44.72
Seven year net savings (or losses)							-1,214.74	265.36

[a]Prices are taken from Table 4.5.

[b]Firewood costs are prices adjusted for 30 percent moisture content and 50 percent combustion efficiency (Price/[0.50 x 0.66]); heating needs are assumed to be 2.5 cords per season.

[c]Distillate costs are prices adjusted for 60 percent combustor efficiency (Price/0.60).

[d]Electricity costs are prices adjusted for 95 percent efficiency (Price/0.95).

[e]Seasonal costs are the original fuel costs less firewood costs multiplied by 52 million Btu per season and divided by a 7 percent discount factor. Distillate is (1) and electricity is (2).

Two case studies bear out these assertions. A cost-minimization objective would not support wood substitution for natural gas in the commercial sector. Natural gas was the most economic fuel in both commercial and residential sectors; coal next best, and firewood was third.

If residential firewood purchase prices were consistent with average advertised prices during 1974-1980, savings realized for a wood fuel substitute were minimal (and sometimes negative). A firewood-distillate oil system substitution might cost over $1,200, while firewood-electric substitutes may have saved $265.

These findings run counter to most individual expectations; however, total savings for the 7-year period would not cover a stove's purchase and installation costs.

People who heat with natural gas favor dual heating systems; they purchase flexibility to switch fuels during shortages. They also build a hedge against nonwood fuel price increases without high regard for cost factors.

Chapter 6

Industrial Sector Wood Use

Any industrial sector production factor is usually examined from two perspectives; cost minimization and profit maximization. Mathematical expressions meeting a cost minimization objective are presented and examined for efficient substitution potential. Then, potential crossovers of industrial wood for residential firewood uses are analyzed. Conventional wood products exhibiting strong residential fuel potential are identified and compared with residential firewood demand. Economic implications of intersector wood resource competition are discussed.

Cost Minimization

Firms and industries are not subject to budget constraints but respond to demands for finished goods and services. Production factors are employed if they pay what they cost; i.e., additional factors are used by a firm or industry as long as marginal cost is less than marginal value product. Revenue obtained by selling one more output unit is a relevant criterion for buying additional production inputs. Marginal return on that investment determines profitability and signals need for further adjustments in input factor markets (Baumol and Blinder 1979).

Cost minimization condition for a firm is given as a rate of technical substitution (RTS), or price ratios, thus:

$$\text{RTS (Fuel}_2 \text{ for Fuel}_1) = P_2/P_1. \tag{6.1}$$

(Note: the possibility of inferior factors [marginal costs shifting up with decreases in fuel factor prices] are ignored. Thus, a firm's demand for a production factor is negatively sloped.)

One wood products industry concern is how increasing firewood use effects income distribution shares. Will factor market use and prices, relative to that use, rise or fall over time? If, for example, the ratio of firewood to distillate oil falls more rapidly than the ratio of their quantities consumed rises, firewood's input factor market share declines. If the price ratio remains constant in response to major increases in the price ratio, firewood's share increases.

If factor markets are reasonably competitive, the elasticity of substitution, (S), which is defined as

$$S = \text{percent change (Fuel}_1/\text{Fuel}_2)/\text{percent change } (P_2/P_1), \tag{6.2}$$

can measure production factor shares. Equation 6.2 measures percent change in fuel ratios--such as firewood to residual oil--to percent change in RTS of residual oil for firewood. Since the RTS is the slope of an isoquant, information about its shape will indicate how easily firewood may be substituted for another fuel (Kogiku 1971). When S equals 1.0, price ratio (P_2/P_1), or the reciprocal of equation 6.1, will change in exact proportion to increases in fuel ratios ($\text{Fuel}_1/\text{Fuel}_2$). Marginal productivities will counterbalance any increase in fuel ratio use over time. When S is less than 1.0, percent increases in use ratios exceed percent increases in price ratios; thus firewood's total production share rises as S becomes large. The opposite is true whenever S is less than 1.0 (Lancaster 1974).

Elasticity of substitution may vary along an isoquant and as scales of production change. Assumptions are: S is constant along isoquants, and returns to scale are constant in the firm or industry studied here (Nicholson 1972).

Applications

Rates of technical substitution of firewood for other fuels were calculated according to equation 6.1 using data from Table 4.7, adjusted for consumption efficiency according to Appendix B. After 1973, all fuel oil derivatives were good candidates for firewood substitution (see Table 6.1). Natural gas, which exhibited strong resistance to firewood substitution in 1967, showed an RTS less than 1.0 in 1980. The RTS for electricity indicated firewood should substitute anytime it is technically feasible to do so. Only coal, particularly bituminous, maintained strong resistance to firewood substitutes.

Elasticity of substitution measures, using equation 6.2, yield conflicting results. In 25 of Table 6.2's 104 cases, firewood's industrial production share rose; e.g., bituminous coal between 1976-79, natural gas between 1975-78, and electricity between 1972-74. Firewood substitution for natural gas also was reasonable between 1967-1969. In 56 of 79 remaining cases firewood's production share fell; there were 9 cases of constant use and 14 constant prices.

Table 6.1. Ratios of industrial prices.[a]

	Fuel[b]							
Year	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1967	2.49	6.00	4.13	1.14	2.01	1.01	1.10	0.55
1968	2.36	5.78	4.21	1.14	2.01	0.99	1.42	0.55
1969	2.14	5.63	4.19	1.13	2.03	0.99	1.53	0.57
1970	1.96	4.32	3.97	1.10	1.93	0.97	1.19	0.55
1971	1.88	3.30	3.58	1.05	1.58	0.94	1.19	0.51
1972	1.93	3.28	3.58	1.14	1.85	0.99	1.27	0.52
1973	2.16	3.30	3.64	1.06	1.51	1.05	1.05	0.54
1974	1.38	1.99	2.79	0.70	0.82	0.69	0.77	0.45
1975	0.90	1.76	2.16	0.66	0.77	0.64	0.74	0.38
1976	0.94	1.90	1.88	0.66	0.91	0.74	0.63	0.40
1977	1.02	1.75	1.64	0.63	0.87	0.59	0.62	0.37
1978	1.08	1.58	1.49	0.63	0.96	0.57	0.63	0.34
1979	1.22	1.69	1.15	0.48	0.73	0.46	0.65	0.35
1980	1.18	1.71	0.98	0.34	0.51	0.32	0.46	0.33

[a]Sources: Equation (6.1), Table 4.7, and Appendix B for efficiency adjustments. Substitution is firewood for the indicated fuel.

[b]Fuel: (1) anthracite, (2) bituminous, (3) natural gas, (4) distillate, (5) residual, (6) kerosene, (7) LPG, and (8) electricity.

Table 6.2. Elasticity of substitution.[a]

	Fuel[b]							
Years	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
67-68	0.33	c	c	c	c	5.50	(0.18)	c
68-69	0.07	1.73	c	c	(2.75)	c	1.40	4.00
69-70	0.11	0.35	0.00	2.67	(0.25)	1.50	0.13	0.00
70-71	0.25	1.06	0.00	(1.00)	0.47	1.00	c	2.00
71-72	(0.50)	c	c	0.00	0.00	(0.40)	1.00	(8.00)
72-73	d	c	8.71	(0.88)	(0.24)	(0.33)	(0.17)	6.50
73-74	d	0.40	1.40	0.27	0.14	0.07	0.18	1.30
74-75	(0.02)	(1.58)	0.00	(2.25)	0.83	(0.20)	(2.00)	(3.86)
75-76	0.01	(4.69)	3.67	c	1.00	(0.11)	0.67	(4.00)
76-77	(0.13)	4.33	3.50	(5.33)	(1.50)	(0.06)	4.00	0.00
77-78	(0.20)	1.33	4.69	c	(1.33)	(0.20)	(6.00)	2.67
78-79	(0.07)	2.40	0.00	(2.65)	(0.77)	(0.25)	14.00	14.00
79-80	0.06	(12.33)	0.00	1.69	0.77	0.12	0.86	8.50

[a]Sources: Equation (6.2) and Tables 4.6 and 6.1. Parenthetical terms are negative values. Substitution is firewood for fuel_i, i=1,8.

[b]Fuel: (1) anthracite, (2) bituminous, (3) natural gas, (4) distillate, (5) residual, (6) kerosene, (7) LPG, and (8) electricity.

[c]Undefined: price ratio changes were zero.

[d]Less than 0.01, but not zero.

Tables 6.1 and 6.2 show strong substitution potential for firewood, based upon price differential; but other considerations made substitution difficult across the industrial sector. Ease of substitution, indicated by elasticity, was not strong during 1967-1980. If a strong tendency is to be found, it is in the wood products industry: wood supplies are available at lesser costs than in other industries.

Substitute Potential of Wood Products

Wood products industry production statistics suggest wood fuel use is in balance with economic need. Wood use in new technologies--e.g., particleboard--has reduced the amount of wood available for fuel (Siedl 1979).

If wood fuel is more economic than conventional fuels, impacts on wood products industries may be large; that input factor costs have direct impacts on production can be seen in Figure 6.1. (Note: all output units and demands are constant in [a] through [c]. Reduced fuel costs in [a] and [b] provide a positive marginal revenue. In [c] revenues exactly equal costs and profitability [or additional output] suffers. More output could be produced at either [a] or [b]; but [b] and [c] are clearly inefficient with respect to [a].)

Table 6.3 shows consumption quantities and prices adapted from USDA (1981a) and USDOE (1981a and 1981b), along with firewood use and price data. Production quantities are in quads; prices are nominal dollars per million Btu.

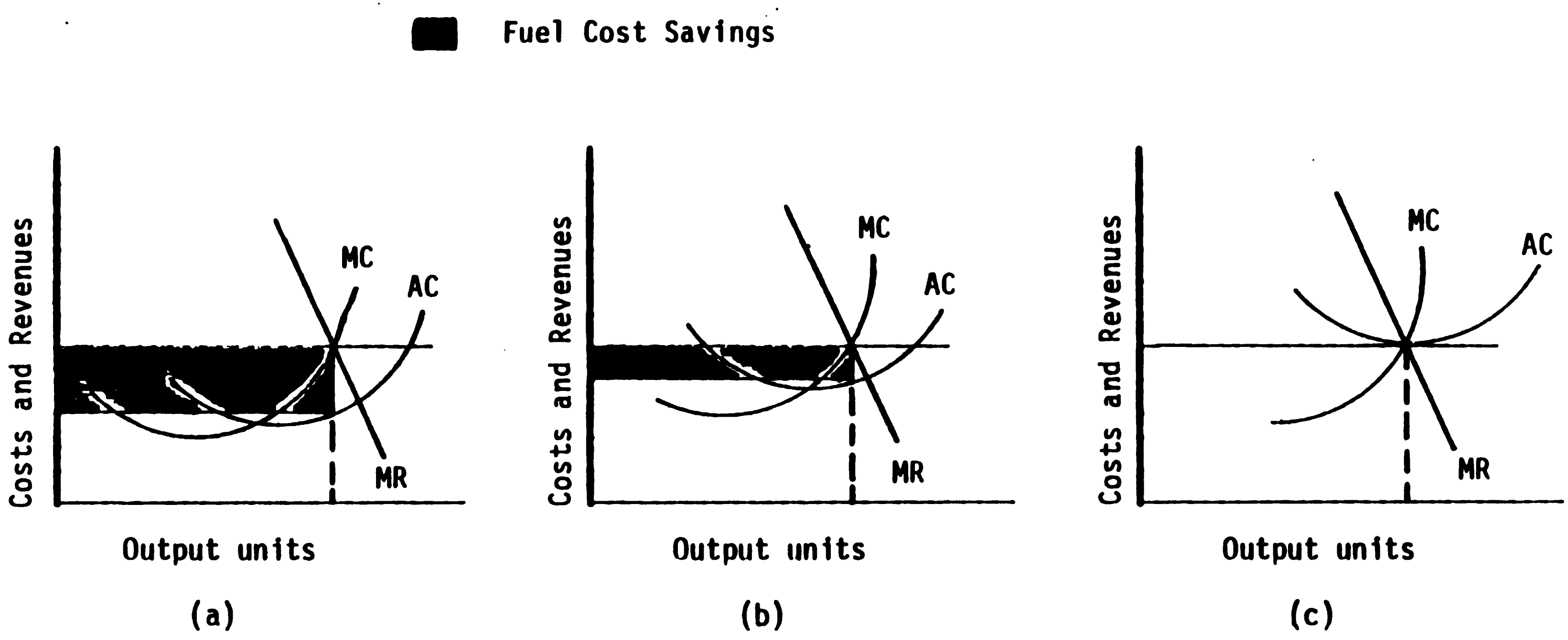

Figure 6.1. Effect of fuel costs on profitability (adapted from Barlowe, 1972).

Table 6.3. Wood consumption and price.[a]

	Lumber		Veneer		Pulp		Firewood			
							Residential		Industrial	
Year	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
1967	1.353	3.25	0.258	7.23	0.907	1.02	0.207	1.39	0.565	1.02
1968	1.434	3.56	0.292	8.37	0.941	1.04	0.185	1.51	0.674	1.04
1969	1.412	4.11	0.278	9.59	0.998	1.07	0.164	1.64	0.700	1.07
1970	1.355	3.85	0.268	9.63	1.005	1.08	0.141	1.78	0.728	1.08
1971	1.440	4.16	0.315	9.13	0.973	1.09	0.136	1.91	0.757	1.09
1972	1.523	4.52	0.357	11.23	0.977	1.18	0.129	1.97	0.843	1.18
1973	1.546	6.60	0.344	17.51	1.052	1.32	0.140	2.53	0.867	1.32
1974	1.350	6.95	0.285	18.28	1.123	1.45	0.145	2.68	0.905	1.45
1975	1.260	6.67	0.287	17.22	0.887	1.51	0.155	2.78	0.804	1.51
1976	1.465	7.83	0.340	22.14	1.013	1.67	0.163	3.08	0.911	1.67
1977	1.611	9.03	0.362	19.95	0.993	1.75	0.172	3.45	0.953	1.75
1978	1.684	10.84	0.374	26.68	1.065	1.82	0.185	3.79	1.007	1.82
1979	1.617	13.22	0.350	32.71	1.132	2.06	0.212	4.47	1.000	2.06
1980	1.354	11.27	0.297	27.66	1.178	2.28	0.290	4.75	1.025	2.28

[a]Sources: USDA (1981a) and USDC (1981). All quantities, numbered (1), are in quads; all prices, numbered (2), are in nominal dollars per million Btu.

In 1980, veneer and firewood consumption levels were similar; but veneer prices were far higher than firewood. Only pulp- and firewood prices were competitive. That higher prices for production factors reflect final products value can easily be seen in Table 6.4. Values added, obtained by deducting average mill purchase prices from final sales prices, imply that largest revenue gains were made in pulpwood, then plywood, and finally lumber. Because firewood is consumed, there is little added value and purchase price reflects value added. Firewood was always of less value than lumber and veneer; however, product use decisions are not necessarily made on the value added basis.

Crossover Potential

Based upon Table 6.3 data, strongest crossover potential occurred in pulpwood. Since hardwood is the preferred firewood, hardwood diversions are most likely unless only softwood species are available. Table 6.5 presents hardwood pulp consumption and residential firewood statistics.

Price elasticities suggest firewood crossovers occurred during 1969-70 and 1974-76. Cross-price elasticities, using firewood prices, indicate pulpwood was a good residential firewood substitute during 1967-68, 1971-73, and 1976-80. Results of two elasticity measures were conflicting; thus, ease of substitution indicated by elasticity of substitution was examined. Substitution was inhibited during 1971-74, 1976-77, and 1978-79 (see Table 6.6). Hardwood pulpwood crossover potential to firewood was strong, as expected, during the entire 1967-1980 period.

Table 6.4. Values added for wood products.[a]

Process	Product	Value ($/OD ton)
Hydrolysis	Ethanol, phenol, furfural	215
Pulping	Semi bleached kraft pulp	165
	Newsprint	150
Reconstitution	Plywood	135
	Particleboard	25
Sawmilling	Lumber	
	Hardwood furniture grade	65-80
	Softwood construction grade	60-70
Combustion	Heat, steam	8
Veneer slicing	Face veneers	?

[a]Source: Adapted from Glasser (1981). Based upon stumpage prices.

Table 6.5 Hardwood statistics.[a]

	Pulpwood		Firewood	
Year	Quantity	Price	Quantity	Price
1967	0.228	0.75	0.163	1.39
1968	0.236	0.76	0.147	1.51
1969	0.269	0.81	0.130	1.64
1970	0.253	0.83	0.113	1.78
1971	0.255	0.85	0.105	1.91
1972	0.276	0.90	0.101	1.97
1973	0.311	1.01	0.106	2.53
1974	0.321	1.15	0.112	2.68
1975	0.232	1.22	0.118	2.78
1976	0.281	1.27	0.123	3.08
1977	0.287	1.29	0.131	3.45
1978	0.320	1.41	0.142	3.79
1979	0.327	1.56	0.163	4.47
1980	0.340	1.74	0.223	4.75

[a]Sources: USDA (1981a) and USDC (1981). Quantities are in quads; prices are in dollars per million Btu. All quantities are hardwoods, however, general firewood prices (from Table 6.3) are used here.

Table 6.6. Elasticities.[a]

Years	Price	Cross-price[b]	Substitution[c]
1967-1968	2.60	0.42	2.50
1968-1969	2.05	1.58	16.00
1969-1970	(2.51)	(0.75)	1.33
1970-1971	0.33	0.11	1.50
1971-1972	1.38	2.56	(5.00)
1972-1973	1.04	0.48	0.33
1973-1974	0.24	0.55	0.33
1974-1975	(5.50)	(8.86)	13.00
1975-1976	(4.77)	1.87	2.67
1976-1977	1.35	0.19	(0.50)
1977-1978	1.22	1.16	2.50
1978-1979	0.21	0.13	(28.33)
1979-1980	0.36	0.64	7.00

[a]Sources: Equations (6.1), (6.2), and Table 6.5. Parenthetical terms are negative.

[b]Pulpwood quantities and firewood prices.

[c]Substitution of pulpwood for firewood.

Crossover Implications

Hardwood uses grew 50 percent in the paper industry for 1967-1980; for firewood, 37 percent during the same period. Delivered pulpwood prices increased 2.3 times and firewood prices increased 3.4 times (Table 6.5). An oven-dry cord of hardwood, averaging 21 million Btu, might have returned $100 per cord for home delivery in 1980; return for that same cord at a mill was about $37 per cord.

Most hardwood pulp is used for paperboard products; its short-term elasticity of demand is between -0.10 and -0.20, and -0.17 to -0.35 in the long term. Normal lag between price driven changes in consumption is 3 to 4 months (Buongiorno and Kang 1982).

After 1971-1972, firewood's own-price elasticity averaged between 0.50 and 0.90, neglecting some extremes during the 1973-1980 period (Table 6.6). Firewood demand is inelastic relative to paperboard; thus, firewood demand is less sensitive to price than paperboard demand. If hardwood factor inputs for paperboard are diverted to firewood in response to market demand, the paperboard industry will pay more for wood and try to pass added expenses on to users.

Summary and Conclusions

Firewood has had strong substitution potential in the paper industry since the oil embargo. Yet ease of substitution, measured by elasticity of substitution, has been relatively weak across the industrial sector. Substitution potential for conventional wood products was slight. Lumber and veneer could easily outbid firewood for a wood resource. Hardwood used for paperboard provides an exception to these findings.

Crossover potential between hardwood pulpwood and firewood became large as price differences increased. Higher priced residential firewood encouraged crossovers. Comparisons between own-price elasticities suggest paperboard consumption would decline 1 to 2 percent within 3 months in response to each 10-percent market price increase. To cover consumption losses, either new technologies must provide more complete use of raw materials, or additional fuel savings must be realized by consuming more waste for energy.

Chapter 7

Decision Factors in Wood Fuel Uses

Wood systems cost more than conventional systems, breakdown more frequently, and need more maintenance and repair; relative wood system advantages include their use to augment or substitute for existing systems. If fossil fuels are unavailable, or their costs climb steeply as in 1973-74, wood may help bridge a shortage or moderate expenses, even though storage, shipment, and handling costs are higher.

Initial system costs are usually not the overriding criterion for a substitute fuel system; fuel cost savings over a next best alternative is important. This chapter covers some substitute alternatives by examining comparative costs and expressing other concerns associated with wood systems.

General Approach

Fuel costs and combustor efficiencies play major roles by limiting economic substitution potential. In local situations, system needs are usually matched with several alternatives, which are then compared in cash flow terms. This approach will look at fuel cost differences over time and then decide which system is economic relative to cost savings and ability to defray initial system expenses.

Fuel availability and proximity, both conventional and wood alternatives, must first be assured and then matched to application need. Collector and arterial roads must be available to transport wood, and to withstand heavy and continuous loads for industrial uses. Continuing supplies often require improved access. (The 1.872 quads of submarginal supply shown in Figure 3.4 is one example of a supply that may never materialize due to lack of access.) Residential wood users also need supply assurance. Data and analyses presented in earlier chapters will be used to estimate substitution potential; concerns which should be addressed before investing in either a wood system or hiring consultants to evaluate specific circumstances will be discussed. The major economic concern is cost savings; but home safety and the environment are two other major concerns.

Commercial Wood Substitutes

Labor and maintenance costs are often overriding factors in making wood use uneconomic in comparison to natural gas and coal (when available). Government tries to minimize total life-cycle costs, which take into account annually recurring and non-recurring costs over a system's and building's expected life. Federal agencies use standard procedures to compare building and construction projects (Federal Register 1981). A sample case is offered to illustrate the total life-cycle approach.

Life-cycle Analysis. Extensive modifications, repair, and conservation measures were needed in three buildings totaling 70,000 ft^2. Cost comparisons were made under contract (CTA Architects, 1980).

System alternatives were coal, gas, oil, electricity, wood, and solar energy. Engineering estimates did not satisfy the contracting office; single discount options and maintenance estimates for wood systems were questioned.

Labor and Maintenance. The consultant's estimates were 45 minutes labor per day at a rate of 8.00 \$/hr. The Forest Service thought normal operations plus breakdowns, due to system newness, justified 8-hours labor at 12.00 \$/hr. Table 7.1 displays the consultant's estimates, which underestimated costs considered by decisionmakers by \$90 to \$320,000.[3]

Discount Factors and the Decision. Varying the discount factors from 3 to 10 percent did not improve wood system economics relative to other choices. All three commercial buildings were insulated and new gas boilers were installed with infrared heaters.

Environment and Safety. Commercial sector energy needs are usually between residential and industrial needs. Because emissions from wood boilers or heating systems are relatively clean, compared to coal and some heavy oils, systems rated below 1 million Btu per hour (1/21 of a cord per hour) are exempt from most air quality regulations. Commercial wood system emissions are usually below these minimums; thus, air quality has been of little concern.

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[3]Memorandum (7310 Buildings--dated 12/16/80) to the Chief from the Regional Forester, Region 1.

Table 7.1. Comparative heating system costs.[a]

Alternatives	Equipment	Life-cycle[b] Fuel	Maintenance	Total
	1,000 dollars			
Coal	152	184	42	378
Single gas boiler	94	260	2	356
Existing (gas) boiler	46	343	52	441
Fuel oil furnace	110	352	6	468
Electric furnace	182	220	2	404
Wood boiler[c]	152	199	32	383
Others:				
Solar with gas	1,046	130	6	1,182
Three gas boilers	112	260	6	378
Three gas plus infrared heaters	120	228	7	355

[a]A commercial sector example (CTA Architects 1980).

[b]Discount rate = $((1+e)/(i-e))(1-((1+e)/(1+i))^n$, where i is the discount rate (10 percent for government projects), e is the fuel escalation rate (projected by USDOE (1980) to be larger than the nominal inflation rate), and n is the number of periods. Constraint: $i \neq e$.

[c]USDA, Forest Service adopted a maintenance cost of $268,000.

New wood systems require different skills and safety measures than older, conventional equipment; e.g., oil or gas systems. Either a staff must be retrained or new people familiar with the system and safety precautions (e.g., pelletized and chipped fuel feed systems have explosive and fire hazard potential if improperly operated--USDA 1980).

Residential Wood Substitutes

Heating needs vary depending upon structural insulation, inside-outside temperature differences, and heating system efficiency. Potential economic savings, safety, and environmental concerns for homeowners is examined and general rules of thumb developed.

Heat Exchange. Some homes are well insulated; a total air exchange occurs every 3 hours. Other homes are poorly insulated; total air exchanges occur more than once per hour. Improving heat retaining capacities may result in savings; however, analysis of each individual situation is necessary (Meyers 1978).

Heat loss coefficients quantify air exchange; typical coefficient for a single story home with 1,000 ft^2 of floor space is 430 Btu per hour per ^oF (Sheldon and Shapiro 1978). Coefficients may vary from 30 to 100 percent of the typical coefficient offered here.

Temperature Differences. Heating degree days (HDD)--average number of degrees per hour a daily temperature is below 65 ^oF--is one common measure of inside-outside temperature differences. A national average of 4,778 $\pm$ 230 HDD was experienced during 1931-1980 (USDC 1980). Heating degree days and exchange coefficients can be used to estimate potential seasonal heating need. Average need for the typical single-family home is 49.3 ± 2.4 million Btu per heating season (e.g., 4,778 HDD x 430 Btu/hr/HDD/day/season x 24 hr/day = 49.3 M Btu/season). Total cost for the wood-distillate substitute shown in Table 5.6 declines to $1,151.67, while gain for a wood-electric substitute declines to $243.05 using long-term averages. Perhaps savings would increase and more firewood substitutes become economic if firewood were offered free.

Free Firewood. An opportunity cost is associated with cutting, gathering, and transporting firewood to a point of use. Cutting costs are minimal; nominal cost for a chain saw, fuel, and oil amount to 2.00 $/cord. Transportation costs may range from zero, for those individuals fortunate to live in or next to a woodlot, to 20 or 30 cents per mile (10 cents plus for a half-ton pick-up truck and 10 cents or more per mile for fuel).

An individual's time might also be considered: transporting a cord of wood 50 miles one way involves two round trips or 200 miles of travel in the pick-up truck (about 5.5 hours time). Felling, limbing, and bucking take 3 hours; loading, unloading, and stacking 1.5 hours. Out-of-pocket costs amount to 50 $/cord plus an average of 10 hours labor for free firewood gatherers (Force 1982, Smith and Corcoran 1976, and White and Wilson 1981).

Labor aside, free firewood burned at 30 percent moisture content and 50 percent efficiency costs about 7.22 $/M btu, about half the 1980 cost indicated in Table 5.6. If free firewood opportunity costs were half the cost of purchased firewood during 1974-1980, total savings for a wood-electricity substitute were $570.72 while losses associated with wood- distillate oil substitutes were reduced to $607.37.

Quality wood stoves cost $800 to $1,000 with chimney and installation (Wood Heating Alliance 1981). At a 7-percent discount rate, stove costs were $497 to $621 in 1974; a wood-electric substitute would pay for itself in 6 years.

Wood storage costs--averaging from a few pennies per month per cord for space in the back yard to $3 or more per month per cord in a basement--must be ignored to justify wood system substitutes for oil heating. Also, 10 additional hours labor per cord for stove tending and some $50 annually for chimney cleaning must be overlooked, if wood systems were attractive residential heating substitutes through 1980. Electric, gas, and oil systems usually do not require constant fuel handling and maintenance.

<u>Environment and Safety</u>. Wood stoves release more polycyclic organic matter than fireplaces, coke furnaces, and stoker-fed coal burners on a per unit-of-heat output basis. Polycyclic organics include hydrocarbons and condensable organic compounds (known carcinogens). Stove emissions have increased 40 or 50 percent right along with higher stove efficiency due to restricted air flow. Carbon monoxide from wood stoves is more than 10 times that from hand-stoked coal stoves and almost 1,000 times a natural gas furnace emission level. Benzo-a-pyrene--whose measurements are challenged because they vary up to 300 percent from standard emission tests--have been used as a

carcinogen estimator. Carcinogens from wood stoves, so estimated, are more than two orders of magnitude larger than levels estimated in any other home combustor (Jaasma and Kurstedt 1981).

A midwest study found 70 percent of recent home fires were caused by improperly installed wood stoves or unsafe materials used in their installation. Problems found included: melting chimney liners; inadequate clearance between ceilings, floors, and walls; and flue-sharing with other heating units. Also, small children and hot stoves do not mix well; tiny tots receive a disproportionate number of burns that are reportedly due to stove contact (Robinson 1981).

Accidents are not restricted to the home. Free firewood seekers briefly accept the same risk as professional woods workers, as they gather a winter's wood supply. Chain saws can cause nasty cuts, branches can poke eyes, and unaccustomed lifting can cause muscle strain. In 1976-78, nonfatal accidents numbered 9.6 per hundred and lost workdays numbered 6.4 per hundred full-time logging employees (National Safety Counsel 1979).

<u>Estimating Savings</u>. Before choosing wood fuel substitutes, several decisions must be made; then wood fuel costs must be compared with other fuel costs. First, questions of labor, wood storage, and stove-tending need resolving. Because equipment needed to gather wood fuel will normally be reimbursed out of fuel savings, it is not a consideration at this point. But, final questions involve estimating economics of each application. Because net annual cost savings must

pay off investments, they should be accounted in constant dollars using an appropriate discount rate and then compared with projections out to the end of a stove's useful life. (Since primary estimates assuming an equal system life are usually good enough.) Several approaches can be used to estimate fuel cost differences over time. Historic trends--e.g., 13 percent average increase in cost differential per year for electricity (from Table 5.6)--can be projected forward for a 10-year stove life. A more realistic approach would be to project a range of expectations forward over time.

Discounted cost differences should then be compared with expected initial investments; e.g., for stove, chimney, chimney liners, and other equipment. If savings at the end of the stove's expected life are larger than expenditures, wood substitutes are economic.

Industrial Wood Substitutes

A feasibility assessment must be made prior to an economic analysis; cost savings must exceed system costs and provide a return on investment. Wood storage spaces must be available; roads must be adequate; fuel supplies must be accessible and close to roads. Fuel and support systems must pose relatively few environmental problems.

Pulp and Paper Experience. Over the past decade wood-fuel substitutes--bark, hogged fuel, and black liquor solids--have increased at a 1-percent-per-annum rate in the paper industry.

Table 7.2 identifies future substitution potential based upon 1980 savings (American Paper Institute 1981). Coal and natural gas were less costly than wood; savings from distillate oil and LPG substitutes were relatively small compared to savings potential from a wood-residual oil substitute. Potential savings for an additional 1-percent black liquor-residual oil substitute was $10.8 million; a wood or bark substitute was $4.9 million.

Hypothetical Example. Consider a $2 million wood-fired system substitute replacing a $150,000 fossil fuel system. First-year fuel cost is $700,000 compared to $2 million for the current system. Operation and maintenance--including electricity, and mechanical and other repairs--labor costs, and operating costs of mobile equipment are $400,000 versus $100,000 for the old system. New system property tax and insurance are expected to be 2.5 percent of system cost, or $50,000 compared with $4,000 for the old system (Table 7.3).

To compare systems, year-by-year costs must be projected for their 10-year life-spans. (Initial costs are recorded in year zero; operational costs at year's end.) Projected annual costs are deducted from present system costs to determine cash flows. Table 7.3 assumes average fuel cost increases of 10 percent annually for both systems. First-year operational and maintenance costs are relatively high for the new system, drop during the second year, and increase 5 percent per year thereafter; operation and maintenance for the old system is 5 percent per year. New system property taxes and insurance

Table 7.2. Industrial fuel substitute assessment.[a]

Fuel	Use (quads)	Unit cost ($/M Btu)	Total cost (M $)	Savings Potential: Unit ($/M Btu) Liquor	Savings Potential: Unit ($/M Btu) Wood	Savings Potential: Total (M $)[b] Liquor	Savings Potential: Total (M $)[b] Wood
	---- 1980 dollars ----						
Coal	0.227	2.00	454	- c -	- c -	- c -	- c -
Distillate	0.008	9.63	77	6.37	4.68	0.5	0.4
Residual	0.350	6.35	2,223	3.09	1.40	10.8	4.9
LPG	0.003	7.11	21	3.85	2.16	0.1	0.1
Natural gas	0.208	3.29	684	0.03	- c -	0.1	- c -
Black liquors	0.810	3.26	2,641				
Hogged fuel	0.119	4.95	589				
Bark	0.103	4.95	510				

[a]Pulp and paper industry (American Paper Institute 1981).

[b]Total savings potential for a 1-percent wood-residual oil substitute is 4.9 M $ (e.g., 1.40 $/ M Btu x 0.01 x 0.350 x 10^{15} Btu).

[c]Negative potential savings.

Table 7.3. First year summary, industrial sector.[a]

Costs	Fuel Systems: Wood	Fuel Systems: oil
	---- 1980 (k $) ----	
Initial	2,000	0
Annual:		
Fuel	700	2,000
Operation and maintenance	400	100
Property tax and insurance	50	4
Subtotal	1,150	2,104
Total (including initial)	3,150	2,104

[a]Hypothetical case adapted from Ellis (1978).

decrease 5 percent annually due to depreciation; the old system schedule is based upon a $150,000 market value (depreciating to zero in 10 years). Systems' cash flow summary is illustrated in Table 7.4.

Economic Effectiveness. Net present worth of the hypothetical wood system is $4.7 million; payback period is 3 years; internal rate of return is 38 percent; benefit cost ratio is 3.1. By most economic measures wood substitutes, whose assumptions closely approximate real world situations, is competitive with other projects. A typical company's return-on-investment criterion is 15 percent; average return on assets is only 10 percent. Utilities often invest in new facilities that yield 8 percent on assets; other energy users turn down conservation investments whose returns fall below 30 percent. Competitive economic effectiveness measures do not ensure investments except in wood products; supply curtailments signaled need for a change (Hatsopoulos, et al. 1978).

Effectiveness Variability. Lin (1981) estimated effects of conditional changes on rates of return for steam boiler systems varying in size from 5,000 to 100,000 pounds per hour (i.e., 0.5 to 10.5 cords input per hour). Assumptions were: capital costs, $0.4 to $3.6 million; first-year operating and maintenance costs, 10 percent of capital costs; fuel escalation, 10 percent; annual operation, 8,000 hr/yr at 75 percent of capacity; tax rate, 50 percent; tax credit, 20 percent; investment finances, 80 percent of capital costs at 15 percent per annum; and system life, 20 years. Estimated rate of return was 42 percent annually.

Table 7.4. Cash flows.[a]

	Fuel Systems				
Year	Fossil -	Wood =	Net	Costs	Present Worth
	-------------------------	1980 (M $)	-----------------------		
0	0	2,000	-2,000	-2,000	
1	2,104	1,150	954		795
2	2,308	1,028	1,280		889
3	2,533	1,113	1,420		822
4	2,780	1,207	1,573		758
5	3,052	1,308	1,744		701
6	3,351	1,420	1,931		647
7	3,679	1,536	2,143		598
8	4,039	1,678	2,361		549
9	4,436	1,826	2,610		506
10	4,871	1,989	2,882		465
				-2,000	6,730[b]

[a]Adapted from Ellis (1978).

[b]Net Present Worth (1974 dollars) = 6,730 + (-2,000) = 4,730.

Altering investment conditions impacted the rate of return as follows: 10-percent capital-cost increase, a 3-percent decrease; 25-percent-per-million-Btu increase in wood fuel price, a 5-percent decrease; 1 $/M Btu increase in fossil fuel price, a 10-percent increase; 10-percent tax increase, a 3-percent decrease; and a 5-percent escalation, and a 5-percent increase. Twenty percent capital interest and 2-percent interest rate increases had negligible impacts on rate of return.

Equipment Costs. Equipment costs vary according to individual need; e.g., $2,000 to $35,000 for a 0.1 to 3.0 million Btu/hr system (i.e., 1/21 to 1/7 of a cord input per hour). Wood fuel feeder prices also vary according to size, type, and length (Ekono, Inc. 1982). Due to extreme variability--based upon need, location, technology, and fuel supply--detailed costs should be prepared only after on-site visits by qualified engineers familiar with wood substitute applications. Until recently, price estimates were obtained directly from equipment manufacturers or research publications. That trend is slowly reversing; Morbark Industries, Inc. (1982) has recently published an equipment catalogue with prices.

Summary and Conclusions

High labor and maintenance costs make commercial wood system substitutes marginally unacceptable. Failure to include all relevant costs make a 2.5 cord residential firewood substitute for electricity barely acceptable (e.g., a lesser wood need equals more than a 6-year payback). Industrial wood substitutes are economic; but, industry is reluctant to accept wood substitute projects on the basis of favorable economic evidence.

One decision approach, that will work in each economic sector, is to consider each aspect and condition associated with wood substitutes in an equation as follows.

> . . . divide half a sheet of paper by a line into two columns; writing over the one Pro, and over the other Con. Then during three or four days consideration, I put down under the different heads short hints of the different motives, that at different times occur to me, for or against the measure [wood fuel]. When I have thus got them all together in one view, I endeavor to estimate their respective weights: and where I find two, one on each side, that seem equal, I strike them both out. . . . and thus proceeding I find at length where the balance lies; and after a day or two of further consideration, nothing new that is of importance occurs on either side, I come to a determination accordingly. . . .I think I can judge better, and am less liable to make a rash step, and in fact I have found great advantage from this kind of equation.[4]

Although equipment costs vary across all sectors, only residential wood stoves endanger the environment and increase accident frequency perceptibly. Cost of reducing, or eliminating, carcinogens from wood stove smoke cannot be offset by fuel cost savings. Air pollution equipment is one small component of industrial wood systems' capital costs; 10-percent increases in them decrease annual rates of return by 3 percent.

Because prices and needs vary--perhaps in the same or similar locations--equipment suppliers are reluctant to publish price lists. Generally, costs vary directly with plant size and other variables; e.g., supply continuity. Preliminary analyses, like the

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[4]B. Franklin (Gramlich 1981).

ones in this chapter, should be followed by specific analyses, similar in approach but more exacting in content, before deciding on a wood system and fuel as a substitute.

Chapter 8

Summary and Conclusions

Potential wood fuel users would be well advised to consider combustor efficiency and moisture content of wood species available to them when they consider wood as a fuel. Of the two, moisture content is the most important.

All energy production increased over the 1967-1980 period except for anthracite coal and kerosene. Supply prices (1967 = 100), for the most part, were up at least 15 percent for the 14-year period. However, electricity, LPG, and real wood prices declined. Firewood and hardwood pulpwood stumpage prices suggest firewood sales to homeowners could have returned $6.00 dollars more on each dollar invested in stumpage for paper interests.

Total wood fuel supply potential, excluding reductions in growing stock and diversions from conventional products, amounts to 11.7 quads annually. Of this amount, 2.5 quads are classed as economic, 7.3 quads as paramarginally economic, and 1.9 quads as submarginally economic.

Prior to the 1973-1974 oil embargo, wood fuel uses declined to a record low. Since then wood fuel uses increased 40 percent, with a 240-percent residential sector price increase. In the industrial sector, increased use was more than 80 percent with a 124-percent increase in wood prices. All other energy fuels lost ground with respect to wood fuel; most other fuels used proportionately more before the embargo were used proportionately less after. Other fuel prices relative to firewood also declined.

In the commercial sector, wood fuel substitutes for oil products became economic after the 1973-1974 period. (This was a general truism in all sectors examined.) Wood was an efficient fuel choice over electricity during the 14-year period. (This too is a general truism.) Wood fuel was not, however, the most efficient fuel choice based upon life-cycle, labor, maintenance, and repair considerations. Once other factor costs were included in a comparison equation, firewood came out third best behind natural gas and bituminous coal-fired systems.

In the residential sector, a slightly different situation existed. Residential wood users maximize utility. If cost minimization is less important than recreation or physical exercise; e.g., in cutting, collecting, and stacking firewood, then wood may serve needs better than other fuels. If an individual has no alternative (income or fuel), then firewood may also be an efficient fuel. What is involved in that choice is ignoring labor associated with gathering and transporting each cord of firewood gathered and labor involved in stove tending. Distance to a firewood source and stumpage costs could change all that, however. Cost becomes prohibitive for haul distances approaching 100 miles one way. A source next door, or a short distance from home, is more efficient than paying for commercially sold fuel.

When viewed from the perspective of out-of-pocket savings, efficiency of substitution depends upon alternative income sources and the system wood will substitute for. A negative saving occurred when firewood substituted for natural gas or coal. Free firewood, transported 100 miles or more, resulted in negative savings for distillate oil substitutes, while substitutes for electricity resulted in a 6-year payback for a wood stove installation. Most residential firewood uses are secondary or supplemental uses. More than 4.0 million housing units, with natural gas systems for primary heat, used wood fuel as an alternative in 1977.

In the industrial sector, substitution potential of wood for other fuels has been strong since 1974, but ease of substitution has been weak. Little probability of substituting conventional wood products for firewood exists even though factor market cost savings were large. Strong tradition may be ignored at some point, if choice involves survival versus large volumes of unused material. Values added to veneer and lumber suggest diversion to fuel is inefficient.

Crossovers between pulp and paper industry and the residential sector is different. Production factor costs in pulp and paper have neither paced industrial factor costs nor residential firewood costs. Hardwood destined for paperboard uses may find its way to residential wood stoves. Average price differential between delivered hardwood pulpwood and firewood, $63 per cord in 1980, make crossovers worthwhile for operators. Price increases in the industry's factor markets could put hardwood out of reach of residential firewood users, but that solution would be self-defeating. Firewood price is inelastic relative to pulpwood, meaning price increases will not effect firewood consumption as much as they will affect paperboard demand. Passing a 10-percent price increase in paperboard products on to consumers will reduce overall product demand from 1 to 2 percent in the short run and 3 to 4 percent in the long run.

Few choices are open to the paperboard industry. If paperboard is to compete with firewood, it must either improve hardwood use technology, use more of the wasted wood components, or tie operators closer than ever before. Combinations of the first two alternatives are, perhaps, the most logical to pursue. The third alternative would only be a temporary solution, particularly if market slumps continue.

Firewood substitutes have been made for other fuels in the past. During the Great Depression, when wages and incomes were dramatically reduced, a large increase in wood use for cooking and heating took place. During WWII, when other fuels were diverted to the war effort, a somewhat lesser return to wood fuel uses was witnessed. The oil embargo and the recessionary period following it triggered another return to wood fuel use. As personal incomes are eroded through inflation; as industrial demand slackens for lack of consumption in product markets; as once dependable fuel supplies dwindle and their prices escalate--the search for efficient energy substitutes will continue. Wood is one such substitute.

Annual wood supply potential cannot, however, sustain large energy demands. Total annual available wood resource amounts to less than the quantity consumed by the commercial sector in 1979. At best, a return to wood is one more phenomenon of our energy use history. It can provide a small respite from shortages confronting our nation in coming years.

The substitute fuel role wood can play is as another outlet for wood products, especially during slack economic periods. It can employ part of a labor force that would otherwise be unemployed. It can also buy time; it can bridge some energy supply gaps until new technologies are perfected. At this time, however, no one is sure just what form new technologies will take: solar energy, energy from the sea, or perhaps nuclear fusion energy from hydrogen bound in water. Regardless of form or extent of new technology, wood is here now, but it is not necessarily an inexpensive alternative to other fuel choices.

Tradeoffs involved in wood use include labor, more maintenance, and more repairs. Capital investments in equipment capable of handling and delivering sufficient quantities of wood to meet demand are often much larger than similar investments for other fuels. For those industries, residences, and commercial establishments fortunate enough to have a ready and accessible wood supply, return on investments during periods of rapid inflation are sufficient to adapt a wood fuel system to their needs. For those without access to a supply, or who would otherwise tie themselves to the residue generated from a wood products industry (but not themselves part of that industry), wood fuel substitutes are most likely not economic. Using wood fuel substitutes would have to be rationalized in another way. In this situation, economic efficiency usually dictates using a non-wood alternative.

Appendices

Appendix A

Conversion Factors and Abbreviations

The preceding text used English System measurement units to conform with current convention. Each factor meets a specific purpose in the text and all factors are averages (Tillman 1978 and USDOE 1982).

Conversions from English to Metric Units

1-pound (lb) = 454 grams (gm)

1-barrel (42 gallon--bl) = 159 liters (l)

1-acre (ac) = 0.404 hectares (ha)

1-cubic foot (ft^3) = 0.03 cubic meters (m^3)

1-British thermal unit (Btu) = 252 calories (cal)

1-Btu/lb = 0.6 kilo-calories per kilogram (kcal/kg)

Abbreviations

Q = 10^{15} = 1-quadrillion (a quadrillion Btu = 1-quad).

T = 10^9

M = 10^6

k = 10^3

Quantity per Quad and Equivalent Heat per Unit

Fuel:	Quantity/Quad:	M Btu/Unit;/Unit:
Anthracite	44.1 tons	27.7/ton
Bituminous	45.1 tons	22.2/ton
Natural gas	1.0 T ft^3	0.001/ft^3
Distillate	7.2 B gallons (gal)	0.138/gal
Residual	6.7 B gal	0.150/gal
Kerosene	7.4 B gal	0.136/gal
LPG	11.4 B gal	0.088/gal
Electricity	294.1 Q k watt hours (kwh)	0.0034/kwh
Oven dry wood (OD)	62.5 M tons	16.0/ton
Green wood (30% MC)	94.3 M tons	10.6/ton
Green wood (50% MC)	128.2 M tons	7.8/ton

Wood Factors (OD)

1-ft^3 = 30.2 lb

1-ft^3 hardwood = 32.8 lb

1-ft^3 softwood = 27.3 lb

1-board foot (bdf) = 2.5 lb

1-bdf hardwood = 2.7 lb

1-bdf softwood = 2.3 lb

1-cord = 1.2 tons

1-cord hardwood = 1.3 tons

1-cord softwood = 1.1 tons

1-lb wood = 4 lb steam

1-lb wood = 8,000 Btu

Appendix B

Combustor Efficiency and Moisture Content

One effect of any combustor's efficiency, e_x, on $fuel_y$ is to inflate price, P_y, because some combustion energy is lost. (Alternatively, net heat could be reduced proportional to e_x. Note: inefficiency is $1 - e_x$.) Adjusted fuel price, P_a, is

$$P_a = P_y/e_x. \quad \text{(B.1)}$$

When the price ratio, P_r, of firewood, P_f, and some other fuel, P_y, is formed it can be adjusted for combustor efficiency as

$$P_r = (P_f/P_y)(e_f/e_y). \quad \text{(B.2)}$$

Potential heat from firewood is reduced by moisture content, MC, also; potential heat reduction due to water is usually of more consequence than combustion efficiency. It can be reflected in marginal prices per unit of heat also. Comparative firewood price, P_c, due to efficiency and moisture content is

$$P_c = P_f/(e_f[1.0000 - 0.0114\ MC]), \quad \text{(B.3)}$$

and firewood to any other fuel net price ratio, P_n, can be estimated directly as

$$P_n = (P_f/P_y)(RM), \quad \text{(B.4)}$$

where $M = 1/(1.0000 - 0.0114\ MC)$ and R is the ratio of efficiencies given in equation (B.2).

Application to firewood prices is straightforward; consider a wood stove that is 50 percent efficient, a gas heater 80 percent efficeint, and firewood containing 30 percent moisture by weight. The net price ratio, from equation (B.4), is

$$P_n = (1.6)(1.5)(P_f/P_g) = 2.4\ (P_f/P_g).$$

Appendix C

Full-tree Estimation Procedure

Firewood and other wood fuels are frequently omitted from conventional inventories (Spurr and Vaux 1976). Nevertheless, production residues are often used in products or as fuel (Glasser 1981). Residues are materials left from production processes; e.g., sawdust from a lumber mill. Residuals, which differ from residues, are tree components or whole trees left after harvest (Young 1981). Keays (1975) suggested all these components could be estimated by considering full-tree components, both residuals and residues, which included mainstem and its bark, rotten section, branches and tops, top bark, and foliage--all above a one-foot stump. Wahlgren and Ellis (1978) modified Keays' approach and reduced it to an accounting system; Carpenter used (1979) their system to simulate full-tree volumes in the Southeast. Keays' approach, modified by Wahlgren and Ellis, is generalized further and expressed algebraically in Table C.1.

An application, using 1976 inventory data (USDA 1981b) illustrates ease of use. All components are expressed as fractional components of mainstem, m (e.g., top bark is 20 percent of branches and tops--$0.2c[1 + a]m$). The approach, with one exception, is within 12 percent of a recent national inventory (USDA 1981c). Rough and rotten topwood and bark for softwood was 42 percent less than this inventory; hardwood estimates were within 16 percent.

Table C.1. Full-tree estimates.

Tree components	Expressions[a]	Sample application	
		Coefficients[b]	Volume[c]
Mainstem	m	1.00	12.50
Rotten section	am	0.30	3.75
Mainstem Bark	b(1 + a)m	0.15(1.30)	2.44
Branches and tops	c(1 + a)m	0.20(1.30)	3.25
Top Bark	0.2 c(1 + a)m	0.20(0.20)(1.30)	0.65
Foliage	d(1 + a)(1 + b)m	0.05(1.30)(1.15)	0.93
Full-tree	(1 + a)((1 + b)(1 + d) + 1.2c)m	(1.30)((1.15)(1.05) + 1.2(0.20))	23.52[d]

[a]Sources: Keays (1975) and Wahlgren and Ellis (1978).

[b]Table C.2 for salvable dead hardwood.

[c]In M ft^3: 12.5 M ft^3 of salvable dead hardwood (roundwood equivalent) was harvested for products in 1976 (USDA 1981b).

[d]12.5 M ft^3 of products leaves a net residual of 11.02 M ft^3 in full-tree components. In practice foliage would be excluded from estimates.

The method offered here uses any available commercial inventory; e.g., Table C.1 using coefficients from Table C.2 (values of the coefficients (a) through (d) for growing stock, three nongrowing stock, and saplings are included.)

Table C.2. Coefficients.[a]

	Timber classifications					
Components	Sawtimber	Poletimber	Sound cull	Rotten cull	Salvable dead	Saplings
(a) Rotten						
Softwood	0.10	0.05	0.25	0.50	0.20	0.00
Hardwood	0.20	0.10	0.30	0.50	0.30	0.00
(b) Mainstem bark						
Softwood	0.15	0.20	0.15	0.15	0.15	0.20
Hardwood	0.15	0.20	0.15	0.15	0.15	0.25
(c) Branches and tops						
Softwood	0.20	0.25	0.20	0.20	0.15	0.25
Hardwood	0.30	0.30	0.30	0.30	0.20	0.30
(d) Foliage						
Softwood	0.10	0.15	0.10	0.10	0.05	0.25
Hardwood	0.05	0.10	0.05	0.05	0.05	0.15

[a]Sources: Keays (1975) and Wahlgren and Ellis (1978). Top bark is 0.2c(1 + a) for all components.

Appendix D

Residential Firewood Price Estimates

Estimates were made by examining 21 city's newspaper classified advertisements for 1971-1980. Newspapers were chosen on an availability, geographic distribution, and population density basis. Because firewood use varies inversely with population (Lipfert 1981), cities with large populations; e.g., Chicago, New York, and San Francisco, were excluded from the survey.

To ensure finding firewood advertisements, Sunday editions following the second hard freeze were examined. Freeze data for each location were obtained from the U.S. Weather Service (NOAA 1980).

Advertised prices were recorded, adjusted to cord equivalents, and averaged. A pick-up load was a half-cord; a rick was one-third a cord; a cord was 80 ft^3 of bark and wood.

Average nominal prices are arithmetic means of adjusted advertised prices (see Table D.1). National and local average prices for 1971-1980 have an absolute range varying from 10.00 $/cord in 1971 to 126.00 $/cord in 1980. National average prices increased about 10 percent annually (standard deviations of price are also shown in Table D.1.). Average prices were extended back in time using a linear relationship between average hourly earnings in pulp and paper. (Firewood price[r=0.986] = -11.90 +13.97[wage rate]. Standard error of slope was 0.90; applications is made in Table 4.5).

Table D.1. Average firewood prices[a]

State	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
Birmingham, AL	55.00	56.00	59.00	60.00	57.00	62.64	65.00	70.67	69.09	83.00
Phoenix, AZ	47.00	42.00	59.50	51.82	61.88	75.50	69.95	78.00	98.33	112.15
Little Rock, AR	59.22	-b-	-b-	74.66	55.68	74.38	70.00	68.57	75.71	-b-
Sacramento, CA	-b-	-b-	47.23	-b-	63.75	73.64	100.83	102.24	123.06	121.64
Denver, CO	47.72	52.10	60.56	67.13	63.95	67.00	51.86	78.31	109.63	108.86
Atlanta, GA	34.67	40.00	57.78	62.14	67.78	74.55	85.38	86.82	98.73	92.86
Des Moines, IO	62.50	75.83	-b-	75.00	70.00	-b-	92.85	99.16	113.33	114.88
Wichita, KS	47.00	45.67	47.79	50.00	65.00	67.00	73.67	96.17	112.36	105.38
Lexington, KY	27.90	27.33	45.00	44.72	56.56	68.00	63.57	70.00	81.00	75.59
Portland, ME	-b-	-b-	-b-	55.00	39.67	50.00	63.33	61.14	72.78	98.00
Duluth, MN	14.50	40.00	50.95	41.00	44.44	46.80	46.67	-b-	61.00	86.25
Helena, MT	21.00	-b-	-b-	-b-	40.00	41.50	64.00	55.00	54.50	42.50
Syracuse, NY	21.50	19.00	27.46	36.60	55.33	63.80	78.20	78.29	82.07	98.42
Fargo, ND	-b-	-b-	-b-	55.00	-b-	-b-	60.00	76.00	85.00	72.20
Columbus, OH	34.00	-b-	-b-	47.27	60.00	61.67	80.56	86.88	109.36	85.00
Harrisburg, PA	36.00	-b-	-b-	56.67	-b-	57.50	69.17	72.11	82.58	85.44
San Antonio, TX	-b-	10.00	46.00	45.42	50.00	60.00	61.43	81.25	97.19	88.13
Salt Lake City, UT	38.20	47.04	64.16	57.76	67.34	64.47	68.46	78.64	109.17	126.00
Richmond, VA	38.00	-b-	50.00	53.69	55.00	63.83	79.67	67.00	98.61	97.08
Seattle, WA	35.10	27.50	54.53	45.38	40.97	51.86	60.81	71.13	82.00	91.82
Madison, WI	40.80	38.08	50.15	55.20	56.30	64.80	65.01	61.71	88.48	88.56
Average	38.83	40.04	51.44	54.45	56.35	62.57	70.02	76.95	90.67	96.38
Std. Dev.	13.34	16.92	9.19	10.37	9.54	9.58	12.85	12.57	18.52	18.94

[a]Source: Classified advertisements from local newspapers. Entries are in nominal dollars per cord.

[b]No reports were found for these years.

Bibliography

Bibliography

American Gas Association. 1980. Gas Facts, 1979. 211 pp.

American Paper Institute. 1981. estimated fuel and energy use. Memo to energy coordinators from Thomas J. Grant. 12 pp.

Barlowe, Raleigh. 1972. Land resource economics, the economics of real property. Prentice-Hall, Inc. Englewood Cliffs, NJ. 616 pp.

Baumol, William J. and Alan S. blinder. 1979. Harcourt Brace Javanovich, Inc. New York, NY. 862 pp.

Bethel, James S., et al. 1979. Energy from wood. A report to the Office of Technology Assessment, U. S. Congress. 321 pp.

Buongiorno, Joseph and Young Moo Kang. 1982 (manuscript). Econometric models of the United States demand for paper and paperboard. 12 pp. University of Wisconsin, Madison, WI 53705.

Calef, C. E. 1976. Not out of the woods. Environment. 8:17-25.

Carpenter, Eugene M. 1979. Wood fuel potential from harvested areas in the Eastern United States. USDA, For. Serv.. Res. Bull. NC-51. 14 pp.

CEA. 1981. Economic report of the president. 357pp. USGPO, Wash. DC.

Choong, Elvin T. 1974. Heat of combustion of wood and bark of sweetgum. LSU wood utilization notes. 24:1-2.

Cordell, H. Ken and Thomas W. Clements. 1979. Urban waste wood: a national perspective. USDA, For. Serv. Gen. Tech, Report SE-16. pp. 3-13.

CTA Architects. 1980. Energy Audit: aerial fire depot, Missoula MT. Project No. 2365.91, contract 53-03RG-0-9. 3 Vols.

DeVriend, Adrian J. 1978. Wood as a fuel. Univ. of Wisc. Coop. Ext. Programs. 4 pp.

EG&G, Idaho, Inc. 1978. Rules of thumb for conversion factors. 6pp.

Ekono, Inc. 1982. Wood fired boiler systems for space heating. Vol. 1. 235 pp. Bellview WA.

Ellis, Thomas H. 1978. Economic analysis of wood- or bark-fired systems. USDA, For. Serv., For. Prod. Lab. FPL No. 16. 19 pp. Madison WI.

Fege, Anne S. 1979. The Department of Energy Program: objectives and representative studies. In Soc. of Amer. For. joint Canadian Inst. of For. Proc. Pp. 129-131. St Louis MO.

Force, Jo Ellen. 1982. Understanding firewood use in Idaho. Univ. of Idaho Stn. Note: 38: 1-8.

Glasser, Wolfgang G. 1981. Potential role of lignin in tomorrow's wood utilization technologies. In For. Prod. Journ. 31: 24-29.

Grantham, John B. 1977. Anticipated competition for available wood fuels in the United States. In Fuels and energy from renewable resources. Academic Press, New York, NY. Pp 56-58.

Gramlich, Edward M. 1981. Beenfit-cost analysis of government programs. Prentice-Hall, Inc., Englewood Cliffs NJ. 273 pp.

Inman, R. E., et al. 1977. Site specific production studies and cost analysis. In Silvicultural biomass farms, Vol IV. Mitre, Tech. Report 7347: 123 pp. Washington DC.

Hatsopoulos, G. N., et al. 1978. Capital investment to save energy. In Harvard Business review, 78205: 111-122.

Hunter, Louis C. 1975. Water power in the century of the steam engine, in America's wooden age: Aspects of its early technology. Sleepy Hollow Restorations, Tarrytown NY.

Jaasma, Dennis R. and Harold A. Kurstedt, Jr. 1981. The contribution of wood combustion to national pollutant emissions (Manuscript). Dept. of Mech. Engineering, VPI, Blacksburg VA. 16 pp.

Jelinek, robert V. and David E Gushee. 1981. Synthetic fuel costs in relation to oil price. Paper presented at Ohio State-Washington Seminar on energy and national security. 47 pp.

Jones, Howard M. 1970. The age of energy. Viking Press, New york NY.

Keays, J. L. 1975. Biomass of forest residuals. In Forest Product Residuals, AICHE Symposium Series 71: 10-21.

Kelsey, Rich G., Fred Shafizadeh, and David P. Lowery. 1979. Heat content of bark, twigs, and foliage of nine species of Western conifers. USDA, For. Serv. Res. Note Int 261. 7 pp.

Koch, Peter. 1976. Material balances and energy required for manufacture of ten wood commodities. Proc. P-76-14, For. Prod. Res. Soc., Atlanta GA. Pp. 24-33.

Kogiku, K. C. 1971. Microeconomic models. Harper and Row, New York NY. 300 pp.

Lancaster, Kelvin. 1974. Introduction to modern microeconomics. Rand McNally College Pub. Co., Chicago IL. 357 pp.

Lin, Feng-Bor. 1981. Economic desirability of using wood as a fuel for steam production. For. Prod. Jour. 31:31-36.

Lipfert, Frederick W. 1981. An assessment for the air quality impact of residential wood burning (manuscript). Brookhaven Natl. Lab., Upton NY. 16 pp.

Marty, Robert J. and Henry H. Webster. 1976. The political economy of forestry. In Introduction to forestry, McGraw-Hill, New York NY. 544 pp.

Meyers, Donald L. 1978. How to do your own home insulating. Harper and Row (for Popular Science) New York NY. 170 pp.

Nicholson, Walter. 1972. Microeconomic theory. The Dryden Press, Inc., Hinsdale IL. 557 pp.

Morbark Industries, Inc. 1982. Forestry processing equipment. Big Rapids MI.

National Safety Counsel. 1979. Work injury and illness ratios. Chicago IL. 43 pp.

NOAA. 1971-80. Climatological data. USDC, Natl. Clim. Centr., Asheville NC.

Nordhaus, W. D. 1975. Proc. of the workshop on energy demand. Intnatl. Institute for applied systems analysis. Laxenburg, Austria. P. 527.

Reed, Tom and Becky Bryant. 1978. Densified biomass: a new form of solid fuel. USDOE Contract EG-77-C-01-4042 with the Solar Energy Research Institute. 30 pp.

Reynolds, R. V. and Albert H. Pierson. 1942. Fuel wood used in the United States; 1630-1930. Circ. 641: 20 pp.

Rider, Don K. 1981. Energy: hydrocarbon fuels and chemical resources. John Wiley and Son, New York NY. 493 pp.

Robinson, Jeremy. 1981. Should you buy a wood burning stove? House and Garden (February). Reprinted in Wood' n Energy (May), pp. 5-6.

Rosenburg, Nathan. 1972. Technology and American growth. Harper and Row, New York NY. Pp. 72-75.

Schurr, Sam H. and Bruce C. Netschert. 1960. Energy in the American economy. The Johns Hopkins University Press, Baltimore MD. P. 36.

_________, et al. 1979. Energy in America's future. The Johns Hopkins University Press, Baltimore MD. 555 pp.

Seidl, Robert J. 1979. Energy from wood: a new dimension in utilization. For. Prod. Journ. 29: 8-18.

Shafizadeh, Fred and William DeGroot. 1977. Thermal analysis of forest fuels. In Fuels and energy from renewable resources. Academic Press, New York NY. Pp. 93-114.

Shapiro, Andrew B. 1979. Quoted in the New York Times, May 20.

Shelton, Jay and Andrew B. Shapiro. 1978. The woodburner's encyclopedia. Vermont Crossroads Press, Waitsfield VT. 155 pp.

Smith, Nigel. 1981. Wood: an ancient fuel with a new future. Worldwatch Institute, Worldwatch pap. 42: 48 pp., Washington DC.

Smith, Norman and Thomas J. Corcoran. 1976. The energy analysis of wood production for fuel applications. In AChE Proc.: Symp. on net energetics of integrated synfuel systems, 2: 9-19.

Spurr, S. H. and H. J. Vaux. 1976. Timber: biological and economic potential. In materials: renewable and nonrenewable resources. AAAS pub. 76-4:1580-162.

Stobaugh, Robert and Daniel Yergin (Eds). 1979. Energy future. Random House, New York NY. 353 pp.

Stokes, Bruce. 1981. Wood as fuel. News release to the Washington Post, January 31. 4 pp.

Stone, R. N. 1977. Are U.S. wood supplies dependable and adequate? In Proc. For. Prod. Productivity Conf. on wood building construction, Chicago IL. 22 pp.

Tillman, David A. 1978. Wood as an energy resource. Academic Press, Inc. New York NY. 252 pp.

_________. 1981. The cost of electricity from silvicultural fuel farm based power plants (manuscript). Envirosphere Co., EBASCO Services, Inc., 27 pp., Washington DC.

U.S. Bureau of Mines. 1976. Mineral fuels and problems. Bull. 667: 15, Washington DC.

USDA. 1974. The Outlook for timber in the United States. USDA, For. Serv. For. Resource Report 20. 374 pp.

__________. 1979. Evaluation report: solid wood burning heating and cooling system, Berea Office Laboratory (unpbl. Report). USDA, For. Serv. 6 pp.

__________. 1980. Hazards make pellet fuel economically unfeasible. In Quads (a monthly publication by Forest Products Laboratory, Madison WI) 11: 1-2.

__________. 1981a. U.S. timber production, trade, consumption, and price statistics: 1950-1980. USDA, For. Serv. Misc. Pub. 1408: 1-81.

__________. 1981b. An analysis of the timber situation in the United States, 1952-2030 (review draft). USDA, For. Serv. Forest Statistics of the U. S.; 1977. Appendix 3: 1-139.

__________. 1981c. Tree biomass--a state of the art compilation. USDA, For. Serv. Gen. Tech. Report WO-33: 1-34.

USDC. 1977. Census of manufactures. Bureau of Census, Vol 2: 1-41.

__________. 1980. State, regional, and national monthly and seasonal heating degree days weighted by population. NOAA, Natl. Clim. Center, Asheville NC.

__________. 1981. Forest products review. Bureau of Industrial Economics. Vol XXXVII, No. 1, 48 pp.

USDOE. 1978. Estimated input of the 1978 UMWA contracts on the costs of mining coal.

__________. 1979a. Reduction in national requirements due to fuel switching, April 1973 to March 1978. DOE/EIA-0166, Washington DC. 25 pp.

__________. 1979b. Characteristics of the housing stock and households: preliminary findings form the national interim energy consumption survey. DOE/EIA-0199/P), Washington DC. 48 pp.

__________. 1980. Monthly petroleum product price report (February). DOE/EIA-0032(80/02). Washington DC. 15 pp.

__________. 1981a. State energy data report. DOE/EIA-0214(79). Washington DC. 579 pp.

__________. 1981b. Annual report to Congress. Volume 2, Washington DC. 234 pp.

USDOE. 1982. Monthly energy review. DOE/EIA-0035(82/06). Washington DC. 103 pp.

Wahlgren, H. Gus and Thomas H. Ellis. 1978. Potential resource availabililty with whole-tree utilization. In TAPPI 61: 37-39.

White, David E. and George E. Wilson. 1981. The cost of heating with wood. West Virginia Extension Serv. EG 10.1.10: 680-686.

Walker, Joseph E. 1966. Hopwell village: the dynamics of a nineteenth century iron-making community. University of Pennsylvania Press, Phil. PA.

Young, Harold E. Forest residues. In CRC handbook of biosolar resources, CRC Press, Inc., Boca Raton, FL. 575 pp.

Zerbe, John I. 1980. Processes change the look of wood fuel. Wood and wood products, 85: 42-43.