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An Economic-Engineering Energy-Demand Model for the Pulp and Paper Industry

David B. Reister
Wen S. Chern
Hoang D. Nguyen

OAK RIDGE NATIONAL LABORATORY
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ENERGY DIVISION

AN ECONOMIC-ENGINEERING ENERGY-DEMAND MODEL
FOR THE PULP AND PAPER INDUSTRY
- Phase I Report -

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CONTENTS

	<u>Page</u>
ABSTRACT	v
I INTRODUCTION	1
II THE PAPERMILL INDUSTRY	3
III THE PHASE I MODEL	11
IV MODEL VALIDATION	36
V AN ENERGY DEMAND FORECAST	54
VI THE PHASE II MODEL	63
ACKNOWLEDGEMENTS	68
REFERENCES	69

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ABSTRACT

The first phase of a project to develop an economic-engineering energy demand model for the paper industry has been completed. The Phase I model has four components:

- 1) a paper demand submodel
- 2) a pulp and paper process submodel
- 3) a fuel share submodel
- 4) an energy conversion submodel

The report begins with a brief discussion of the structure and technology of the industry. After the details of the four submodels are presented, the results of the model are compared to historical data. The report concludes with a reference energy demand forecast, sensitivity analysis, and an analysis of the strengths and weaknesses of the model.

Typical results for the Phase I model are as follows. Conservation causes the growth rates for all purchased fuels to be less than the growth rate for paper production. The demand for coal grows more rapidly than the demand for petroleum but petroleum remains the dominant purchased fuel. Demand for natural gas decreases but natural gas provides more energy than coal through 1990. Conservation of steam and an increased demand for electricity cause a decrease in the growth rate of electricity produced by cogeneration and an increase in the growth rate for purchased electricity.

AN ECONOMIC-ENGINEERING ENERGY DEMAND MODEL
FOR THE PULP AND PAPER INDUSTRY
- Phase I Report -

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I. INTRODUCTION

This report describes the results of the first phase of a project to develop an economic-engineering energy demand model for the pulp and paper industry. This project is part of a program in the Energy Conservation Section of the Energy Division of the Oak Ridge National Laboratory to develop economic-engineering energy demand models for the residential, commercial, and industrial sectors. Phase I of the industrial sector research is presented in this report. Phase II of the research will be a penetration model for coal boilers and cogeneration and an improved energy demand model for the paper industry. Plans for future research include several detailed process models and a comprehensive model for the whole industrial sector.

The Phase I research, which began in the middle of the 1977 fiscal year and was completed in the 1978 fiscal year, was funded by the Federal Energy Administration's Demand Analysis Division and by the Energy Research and Development Administration's Office of Conservation Planning and Policy. (On October 1, 1977, FEA and ERDA were merged to form the Department of Energy, DOE.) The Demand Analysis Division is interested in the demand for energy in the next ten to fifteen years, in the impact of government policy on the conversion of boilers from oil and natural gas to coal, and in

the rate of penetration of cogeneration. The Office of Conservation Planning and Policy is interested in the penetration of existing technologies to conserve energy and in identifying new energy conservation ideas which need research, development, and demonstration support. Thus, the goal of the model is to estimate the impact on the demand for energy in the paper industry of government policies (conservation, conversion to coal, environmental) and programs and the penetration of new technologies.

The report begins with a brief discussion of the technology of producing paper and the structure of the industry. Section III provides a description of the Phase I model. The model has four submodels:

- 1) a paper demand submodel
- 2) a pulp and paper process submodel
- 3) a fuel share submodel
- 4) an energy conversion submodel

The information flows among the four submodels are shown in Figure 1. Given exogenous information on the level and price structure of the economy, the paper demand submodel forecasts the demand for paper products. Given the demand for paper products and exogenous information on technology, the process submodel forecasts the demand for process steam and electricity and the supply of wood by-products. Given fuel prices, the fuel share submodel forecasts the share for each type of purchased fuel. Given the demand for steam and electricity, the supply of wood by-products, the purchased fuel shares, and exogenous assumptions on technology, the energy conversion submodel forecasts demand for purchased fuel and purchased electricity.

FIG. 1. THE ENERGY DEMAND MODEL FOR THE PAPER INDUSTRY.

In section IV the results of the model are compared to historical data. Section V presents a reference energy demand projection. The report concludes with an analysis of the strengths and weaknesses of the Phase I model and a discussion of the improvements planned for the Phase II model.

The report uses the International System of Units (SI). The primary energy unit is the petajoule, PJ; $1 \text{ PJ} = 10^{15}$ joules. To measure electric energy, a secondary energy unit is the terawatt-hour, TWh; $1 \text{ TWh} = 10^9$ kilowatt-hours. The unit of mass is the teragram, Tg; $1 \text{ Tg} = 10^{12}$ grams. The unit of pressure is the megapascal, MPa; $1 \text{ MPa} = 10^6$ pascals. The unit of temperature is the degree Celsius, °C.

II. THE PAPERMILL INDUSTRY

In the Standard Industrial Classification Manual¹ the paper industry is subdivided into the seventeen sectors shown in Table 1. The

total purchased energy demand by the paper industry is shown in Table 2. In 1974, 79% of all purchased energy was consumed by integrated paper and paperboard mills² (SIC 2621 and SIC 2631). Since most of the energy is consumed to produce paper and paperboard, the Phase I model does not include energy demand to produce converted paper and paperboard products but is restricted to the energy intensive sectors which produce pulp, paper, and paperboard (SIC 2611, 2621, 2631, and 2661). We shall call these four sectors the papermill industry. In 1974 these sectors consumed 89% of all energy purchased by the paper industry. In the future, we plan to develop an energy demand model for the total paper industry.

In a previous ORNL report, Kaplan³ studied the technical aspects of the papermill industry. In particular, he studied energy use patterns, opportunities for energy conservation, and the impact of environmental protection measures. Kaplan estimates that more than ninety percent of the fuel demand in the papermill industry is for boiler fuel to produce process steam and electricity. (A small amount of fuel is consumed by lime kilns.)

Fuel is burned in boilers to produce process steam and electricity. To understand how the steam and electricity are used to produce pulp and paper, we give a brief review of the technology. (Ref. 3 contains a more detailed review.)

The primary source of pulp is wood. Wood is composed of cellulose fibers in a matrix of lignin. Each type of tree has a different type of fiber and the fibers determine the properties of the wood. In general the average length of the fibers of hardwoods is about one millimeter (mm) and the length of the fibers of softwoods is about 3 mm. Separated fibers are called pulp.

TABLE 1. THE PAPER INDUSTRY AS DESCRIBED BY THE
STANDARD INDUSTRIAL CLASSIFICATION MANUAL

Group	Industry No.	Description
261		PULP MILLS
	2611	Pulp Mills
		Establishments primarily engaged in manufacturing pulp from wood or from other materials such as rags, linters, waste paper, and straw. Logging camps operated by pulp mills, and not separately reported, are also included in this industry. Pulp mills combined with paper mills or paperboard mills, and not separately reported, are classified with the latter in Industries 2621 and 2631, respectively.
262		PAPER MILLS, EXCEPT BUILDING PAPER MILLS
	2621	Paper Mills, Except Building Paper Mills
		Establishments primarily engaged in manufacturing paper from wood pulp and other fibers, and which may also manufacture converted paper products. Pulp mills combined with paper mills, and not separately reported, are also included in this industry; where separately reported, they are classified in Industry 2611. Establishments primarily engaged in manufacturing converted paper products from purchased paper stock are classified in Groups 264 or 265.
263		PAPERBOARD MILLS
	2631	Paperboard Mills
		Establishments primarily engaged in manufacturing paperboard, including paperboard coated on the paperboard machine, from wood pulp and other fibers; and which may also manufacture converted paperboard products. Pulp mills combined with paperboard mills, and not separately reported, are also included in this industry; where separately reported, they are classified in Industry 2611. Establishments primarily engaged in manufacturing converted paperboard products from purchased paperboard are classified in Groups 264 or 265, and building board in Industry 2661.

TABLE 1. THE PAPER INDUSTRY AS DESCRIBED BY THE
STANDARD INDUSTRIAL CLASSIFICATION MANUAL
(CONTINUED)

Group	Industry No.	Description
264		CONVERTED PAPER AND PAPERBOARD PRODUCTS, EXCEPT CONTAINERS AND BOXES
	2641	Paper Coating and Glazing
	2642	Envelopes
	2643	Bags, Except Textile Bags
	2645	Die-Cut Paper and Paperboard and Cardboard
	2646	Pressed and Molded Pulp Goods
	2647	Sanitary Paper Products
	2648	Stationery, Tablets and Related Products
	2649	Converted Paper and Paperboard Products, Not Elsewhere Classified
265		PAPERBOARD CONTAINERS AND BOXES
	2651	Folding Paperboard Boxes
	2652	Setup Paperboard Boxes
	2653	Corrugated and Solid Fiber Boxes
	2654	Sanitary Food Containers
	2655	Fiber Cans, Tubes, Drums, and Similar Products
266		BUILDING PAPER AND BUILDING BOARD MILLS
	2661	Building Paper and Building Board Mills
		Establishments primarily engaged in manufacturing building paper and building board from wood pulp and other fibrous materials. Pulp mills combined with building paper and building board mills, and not separately reported, are also included in this industry; where separately reported, they are classi- fied in Industry 2611.

TABLE 2. TOTAL PURCHASED ENERGY BY THE PAPER
INDUSTRY — 1971 AND 1974

SIC	1971		1974	
	Energy (a) (PJ)	%	Energy (a) (PJ)	%
2611	113	7	109	7
2621	737	45	737	43
2631	533	32	610	36
264	102	6	105	6
265	95	6	81	5
2661	59	4	56	3
26	1640	100	1698	100

(a) The conversion factor for purchased electricity is 10.8 PJ per TWh.

Source: Reference 2

Paper is made by depositing, from a dilute water suspension of pulp, an even layer of cellulose fibers on a fine screen that permits the water to drain through but retains the intermingled fibers. This layer of fibers, removed from the screen and finally pressed and dried, becomes a sheet of paper. The characteristic qualities of the paper depend on the color, length, diameter, flexibility, strength, and other properties of the fibers used. The properties of the fibers depend on the type of tree and the pulping process.

Pulping processes are shown in Table 3. The mechanical pulping processes (groundwood and chemimechanical) have the highest yield since most of the lignin remains with the fibers. The chemical pulps are primarily cellulose fibers. Dissolving pulp is used to produce rayon; it has the lowest yield since it is produced by bleaching and refining chemical pulp. Most pulp is made by the kraft process. The kraft process produces a long fiber which produces a strong paper. (The German word for strong is kraft.)

The process structure of the papermill industry is complex; the Bureau of the Census distinguishes 30 types of paper, 26 types of paperboard, 5 types of construction paper, and 16 types of pulp. A single papermill

TABLE 3. COMMERCIAL PROCESSES FOR PULPING WOOD - 1973

Process	Yield ^(a) (%)	Production (Tg)	Percent ^(b)
Chemical			
sulfite	49	2.087	5
kraft	49	29.432	67
soda	48	0.123	0
Semichemical	80	3.509	8
Dissolving	35	1.517	4
Chemimechanical			
mason-asplund	95	2.658	6
cold soda	95	0.091	0
hot sulfide	95	0.064	0
Groundwood	93	4.366	10
TOTAL		43.847	100

(a) Yield is the fraction of the mass of the wood which remains as pulp.

(b) Percent of total production.

Source: Reference 4

can produce several types of paper and pulp. For example, the Bowaters Southern Paper Corporation papermill in Calhoun, Tennessee produces newsprint and market pulp. Newsprint is primarily a groundwood paper and 55 percent of the pulp is groundwood from softwood. Hardwood was available on their land and 15 percent of the pulp is cold soda chemimechanical from hardwood. For strength, 30 percent of the pulp is semibleached softwood kraft. Currently, the capacity of the Calhoun mill is being increased by 25 percent. Rather than increase the capacity of each of their three pulp processes by 25 percent, the managers have chosen to add a fourth process, thermo-mechanical pulp, which produces a stronger pulp than groundwood. Thus, a single papermill making a single product can use four types of pulp.

In a typical integrated papermill electricity and three process steam pressures are required. Electricity is used throughout the mill by machines and process control equipment. Process steam is used in the pulping operation, in the paper machine, and to run mechanical equipment. The pulping operation requires temperatures of 175°C to 200°C; these temperatures require saturated process steam at pressures of 1.1 to 1.3 MPa. The paper drying operation requires temperatures of 120°C to 150°C; these temperatures require saturated process steam at a pressure of 0.4 to 0.7 MPa. Many papermills use process steam to supply the energy to run blowers and other equipment; these processes require superheated process steam at a pressure of about 2.9 MPa.

The energy conversion processes at a typical papermill are shown in Figure 2. A typical papermill uses several types of boilers to produce electricity and process steam at several pressures.^{5,6,7} An integrated

FIG. 2. ENERGY CONVERSION IN A TYPICAL PAPERMILL.

papermill will have recovery boilers which burn black liquor to recover the pulp chemicals, fuel boilers which burn purchased fuel, and bark boilers which burn bark, hogged wood, and other wood by-products.

The boilers produce high pressure and high temperature steam. The actual pressure and temperature of the steam can vary substantially between papermills; for a typical integrated papermill the pressure will lie between 4 and 9 MPa and the temperature will lie between 310°C and 540°C. The pressure spectrum for all boilers in the papermill industry and for new boilers (1965-1975) is shown in Table 4. For all boilers the average pressure is 4.8 MPa and for new boilers the average pressure is 5.4 MPa, an increase of 11 percent. Although most boilers have a

TABLE 4. TOTAL STEAM BOILER CAPACITY AND NEW BOILER CAPACITY IN THE PULP AND PAPER INDUSTRY

Pressure		Total Capacity ^(a)		New Capacity ^(b)	
psig	MPa	Tg/year	%	Tg/year	%
100	0.8	54	7	7	2
200	1.5	86	11	40	10
300	2.2	29	4	18	4
400	2.9	39	5	31	8
525	3.7	59	7	26	7
725	5.1	268	35	95	25
1050	7.3	191	25	122	32
1300	9.1	45	6	45	12
TOTAL		771	100	385	100

a) Total capacity in 1975

b) Additions to capacity 1965-1975

Source: Reference 7

pressure greater than 4 MPa, 34 percent of all boilers have a pressure less than 4 MPa.

III. THE PHASE I MODEL

The Phase I model consists of four submodels. This section will describe each of the submodels. The section begins with a brief discussion of the art of model building.

There are about 800 papermills in the United States; each papermill is unique. Model building is an art; there are two schools of the art--realistic art and abstract art. A realistic model of the papermill industry might attempt to represent each of the 800 papermills. Our abstract model attempts to represent the aggregate behavior of 800 papermills by the behavior of an "average" papermill. The Bureau of the Census

collects data on 61 types of paper and 16 types of pulp; the "average" papermill of our model produces 11 types of paper from 4 types of pulp. The pressure and temperature of the steam produced by the boilers of the 800 papermills can vary substantially; the "average" papermill of the model produces high pressure and temperature steam at a single average "output enthalpy". The capital equipment of the 800 papermills has been installed over the last 50 years; the "average" papermill of the model uses the best technology available in 1974.

Since our abstract model requires so many heroic assumptions, would a realistic model be more accurate? In the debate on the merits of abstract models and realistic models, the two basic arguments in favor of abstract models are:

- 1) The data base is inadequate.

Each papermill is unique and details on inputs and outputs and operating costs are proprietary.

- 2) The industry is too complex.

Each of the 800 papermills has a chief engineer who has spent his whole career becoming aware of the technological options for his papermill. A small interdisciplinary team at a research institute cannot aspire to understanding the technologic options for energy conservation and energy conversion at 800 papermills. (We support research to improve the understanding of technological options at typical papermills.)

There are many shades of grey between the black of an abstract model and the white of a realistic model. Although a case can be argued that the current model has more detail than the current data base will support,

our goal is to continue to work on the data base and to build models which are as detailed as the data base can support.

All energy demand models must recognize the fundamental fact that energy is an intermediate good, that is, energy carriers (solids, liquids, gases, and electricity) are consumed by boilers, furnaces, and machines to produce energy services (heat and work). The structure of the Phase I model is based on the concept of energy service. The pulp and paper process submodel consumes energy services (steam and electricity) to produce paper. The energy conversion submodel consumes energy carriers to produce energy services.

During the research on the Phase I model we have allocated more of our resources to the energy conversion submodel (which is based on primary sources) than to the pulp and paper process submodel (which is based on secondary sources). There are two reasons for this allocation of resources. The first is that the research team knew more about the production of energy services than about the demand for energy services in the paper industry. The second is our conjecture that substitution between boiler fuels will have a greater impact on energy demand patterns than conservation of steam and electricity.

Since our conjecture is controversial, we shall digress for a moment to discuss it. Faced with higher prices for petroleum and/or natural gas, the manager of a papermill can reduce the demand for energy service and/or substitute a plentiful energy carrier (coal or wood) for a scarce carrier. Although the thermodynamic limit to produce paper is near zero, total purchased fuel per teragram of paper has decreased slowly from 27.2 PJ in 1947 to 21.0 PJ in 1974. Using commercial technology, coal or wood can completely substitute for petroleum and natural gas in the production

of process steam and electricity. From 1947 to 1975, the reverse process occurred; in 1947, 71% of purchased fuel was coal; by 1974, the coal share had decreased to 18%. Historically, substitution of one energy carrier for another has had a greater impact on the demand for energy carriers than reduction in the demand for energy services.

The structure of the Phase I model is shown in Figure 3. Given exogenous information on paper product prices, population, disposable

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FIG. 3. THE STRUCTURE OF THE ENERGY DEMAND MODEL OF THE PAPER INDUSTRY.

income, and gross national product, the paper demand submodel forecasts the demand for 11 types of paper products.

The pulp and paper process submodel produces 11 types of paper products using 45 process vectors. The mix of the 45 process vectors to produce the 11 types of paper products is an exogenous input to the model rather than the result of cost optimization. The output of the process model is the demand for steam and electricity and the supply of bark, and spent liquor. To introduce conservation and other forms of technological change, the output of the process model is multiplied by adjustment factors to produce the final output forecast.

Given fuel prices, the fuel share submodel forecasts the share of the purchased fuel that will be captured by each type of fuel. Given the demand for steam and electricity, the supply of bark and spent liquor, the fuel shares, and exogenous technology assumptions on energy conversion efficiencies and the amount of self-generated electricity per unit of process steam, the energy conversion submodel forecasts the demand for purchased fuel and purchased electricity.

The Paper Demand Submodel

Conceptually the economy can be divided into two parts: the papermill industry and the rest of the economy. The Phase I model consists of four submodels; three of the submodels forecast the input-output structure of the papermill industry while the fourth submodel, the paper demand submodel forecasts the demand for paper products by the rest of the economy. For example, the three papermill industry submodels forecast the amount of coal per teragram of bond paper; the demand model forecasts the demand for bond paper which determines the

total demand for coal to produce bond paper. Thus, the paper demand submodel determines the level of energy demand.

In the Phase I model there are 11 types of paper products; production data for 1972 are shown in Table 5. For the paper demand submodel, the 11 types of paper products were aggregated to 8 types; linerboard and corrugating medium become containerboard, newsprint and groundwood become groundwood, and kraft bag and packaging become packaging. To disaggregate from 8 paper types to 11 paper types, we assume that the relative shares are constant; for example, 71 percent of containerboard is linerboard.

TABLE 5. PRODUCTION OF THE 11 TYPES OF PAPER
AND PAPERBOARD IN THE MODEL - 1972 DATA

Product	Production (Tg)	Percent of Total Production
1) Linerboard	12.095	22
2) Corrugating Medium	5.012	9
3) Newsprint	3.130	6
4) Groundwood	1.187	2
5) Tissue	3.650	7
6) Boxboard	7.807	15
7) Book	5.946	11
8) Writing	3.982	7
9) Kraft Bag	3.562	7
10) Packaging	1.614	3
11) Construction	5.944	11
TOTAL	53.929	100

Source: Reference 8

Our demand model for paper products is an extension of a model developed in a 1967 study by the Forest Service.⁹ In the forest Service Model, ordinary least-squares techniques were used to estimate a relationship between aggregate paper demand and population, personal income, gross national product, and time.

To extend the forest service model, we added paper product prices to the list of explanatory variables. The eight paper products are classified into two categories: consumer products and industrial products. The consumer products are groundwood, tissue, book and writing paper; the industrial products are containerboard, boxboard, packaging, and construction paper.

For consumer products, the paper demand model is specified in log-log form as

$$\ln q_i = a_0 + a_1 \ln p_i + a_2 \ln p_j + a_3 \ln t + a_4 \ln y + e$$

where

q_i is per capita demand for paper product i ,

p_i is the wholesale price index for product i in constant dollars,

p_j is the wholesale price index for competing product j in constant dollars (Book paper competes with groundwood paper.),

y is per capita disposable income in constant dollars,

t is time, and

e is the error term.

For industrial products the demand model is specified as

$$\ln Q_i = b_0 + b_1 \ln p_i + b_2 \ln V + b_3 \ln t + e$$

where

Q_i is total demand for paper product i ,

V is the value added by the industrial sector in constant dollars, and

p_i , t , and e have the same meaning as before.

The demand models for the 8 types of paper products were estimated by Nguyen and Knight,¹⁰ using ordinary least squares and annual time series data from 1956-1975. The results are shown in Table 6.

The own price coefficients for book paper was positive and was dropped from the equation. For the other equations, the own price coefficients are negative and statistically significant at the 10 percent level or lower, indicating the significant influence of price upon paper demand. However, the price elasticities are less than unity for all paper products. Disposable income and industrial value added have large positive effects on demand.

The paper demand submodel forecasts demand for paper products; the pulp and paper process model requires the production of paper products; the difference between demand and production is imports. For all products except boxboard, we assume that imports are a constant fraction of demand because historical data show no significant decreasing or increasing trends. For boxboard, the import share was allowed to vary with time by regressing the historical data of its import share with a time-trend variable.

The demand equations have two dummy variables, D_1 and D_2 . Two different data sources were used for some of the time series data; the

TABLE 6. ESTIMATED PAPER DEMAND EQUATIONS
(t-statistics are given in parentheses)

Dependent variables	Constant	Cum price	DPI	VA	Time	Other price ^a	D ₁	D ₂	N	R ²	DW
Groundwood	12.05 ^b (3.72)	-0.223 ^d (-1.11)	1.576 ^b (5.85)		-1.440 ^b (-3.44)	0.197 ^d (1.02)			19	0.95	2.10
Tissue	-4.665 ^c (-1.47)	-0.494 ^b (-4.40)	0.475 ^c (1.82)		1.323 ^b (3.25)				20	0.98	1.30
Book	5.754 ^d (0.91)		1.480 ^b (2.85)		0.259 (-0.32)				20	0.92	1.05
Writing	8.180 ^b (3.46)	-0.773 ^c (-1.49)	1.496 ^b (6.47)				-0.267 ^b (-4.44)		20	0.98	2.02
Containerboard	4.627 ^b (3.97)	-0.490 ^c (-5.77)		0.716 ^b (5.21)	0.170 ^b (3.94)				20	0.99	0.96
Boxboard	8.139 ^b (6.17)	-0.321 ^b (-3.02)		1.044 ^b (7.30)	-0.969 ^b (-3.08)				20	0.96	2.00
Packaging	10.568 ^b (4.69)	-0.620 ^b (-3.96)		0.819 ^b (4.00)	-0.626 ^c (-1.75)		0.177 ^b (4.37)		20	0.88	1.64
Construction	5.613 ^b (1.13)	0.216 (-0.71)		0.856 ^b (3.00)				-0.278 ^b (-6.13)	20	0.90	1.78

^aWholesale price index of book paper.

^bStatistically significant at 1% level.

^cStatistically significant at 10% level.

^dStatistically significant at 20% level.

dummy variable D_1 compensates for data source differences. Construction is strongly affected by recessions; dummy variable D_2 compensates for the impact of recessions on the demand for construction paper.

The Pulp and Paper Process Submodel

The process submodel is based on the 45 process vectors defined in a recent study by Arthur D. Little.¹¹ Typical process vectors are shown in Tables 7, 8, 9, and 10. Table 7 shows a process vector for the production of unbleached kraft linerboard. The process outputs are 1.0 Tg of linerboard, 0.189 Tg of bark, and 0.860 Tg of spent liquor; the energy service inputs to the process are 8.0 Tg of steam and 0.85 TWh of electricity. This is a process vector for an integrated mill which produces and consumes unbleached kraft slush pulp as an intermediate good.

For the process vector for newsprint shown in Table 8, semibleached kraft slush pulp and groundwood slush pulp are process inputs. Since the inputs are slush pulp, the kraft pulp and groundwood pulp would be produced at the same site as the newsprint. (Pulp which is shipped from one site to another is called market pulp.) A complete description of the production of newsprint, using the process vector in Table 8,

TABLE 7. PROCESS VECTOR FOR UNBLEACHED KRAFT LINER BOARD

Factors	Coefficients (a_{ij})
Linerboard	1.000 Tg
Bark	0.189 Tg
Spent Liquor	0.860 Tg
Steam	-8.000 Tg
Electricity	-0.850 TWh

Source: Reference 11

TABLE 8. PROCESS VECTOR FOR NEWSPRINT
FROM VIRGIN FIBER

Factor	Coefficients (a_{ij})
Newsprint	1.000 Tg
Semi-bleached Kraft Slush Pulp	-0.257 Tg
Groundwood Slush Pulp	-0.778 Tg
Steam	-3.150 Tg
Electricity	-0.350 TWh

Source: Reference 11

TABLE 9. PROCESS VECTOR FOR GROUNDWOOD SLUSH PULP

Factor	Coefficients (a_{ij})
Groundwood Slush Pulp	1.000 Tg
Bark	0.176 Tg
Steam	-0.140 Tg
Electricity	-1.400 TWh

Source: Reference 11

TABLE 10. PROCESS VECTOR FOR NEWSPRINT
FROM RECYCLED NEWSPRINT

Factor	Coefficients (a_{ij})
Newsprint	1.000 Tg
Recycled Newsprint	-1.248 Tg
Steam	-3.800 Tg
Electricity	-0.700 TWh

Source: Reference 11

requires two other process vectors which produce kraft pulp, and groundwood pulp. The groundwood process vector is shown in Table 9.

In Section II we mentioned that the Calhoun newsprint mill uses three types of pulp and plans to add a fourth (groundwood, kraft, cold soda, and thermo-mechanical). We are approximating real newsprint mills by a process vector which has two pulp inputs rather than three or four and has fixed proportions (25% kraft and 75% groundwood) rather than the variable proportions found in real newsprint mills. Our rationale is that a model must simplify and approximate complex realities.

Although the Calhoun mill does not use recycled newsprint, many papermills exist which make newsprint from recycled paper. (Most recycled paper mills are located near large cities which provide a convenient source of old newspapers.) Table 10 shows a process vector for recycled newsprint.

Process vectors are a flexible tool for the description of industrial process options. An integrated industrial process which occurs in a single factory can be represented by a single vector or by several vectors. Different process vectors can produce the same product; and a single process vector can produce several products. The first 35 process vectors produce the 11 types of paper products shown in Table 5 and the other 10 vectors produce the 6 types of pulp shown in Table 11. The input-output structure of the pulp and paper process submodel is illustrated in Figure 4. The 35 paper process vectors produce paper products and consume pulp, steam, and electricity. The 10 pulp process vectors produce pulp, bark, and spent liquor and consume steam and electricity. (An integrated papermill produces both paper and slush pulp. In the process model, integrated mills are represented by both one process vector

TABLE 11. THE SIX TYPES OF PULP
IN THE PULP AND PAPER PROCESS MODEL

I. Market Pulp

A. Virgin Fiber-Bleached Kraft

1) Softwood

2) Hardwood

II. Slush Pulp

A. Virgin Fiber-Bleached Kraft

3) Softwood

4) Hardwood

B. Virgin Fiber-Softwood

5) Unbleached Kraft

6) Groundwood

Source: Reference 11

and two process vectors. When an integrated mill is represented by one vector, the vector will produce bark and spent liquor as by-products of paper production. When an integrated mill is represented by two vectors, the pulp vector will produce bark and spent liquor and the paper vector will not produce bark and spent liquor.) The net outputs of the process submodel are paper, bark, and spent liquor, while the net inputs are steam and electricity. Pulp is an intermediate good.

Mathematically, the net output for each factor, y_i , can be written

$$y_i = \sum_{j=1}^{45} a_{ij} x_j \quad i=1,21$$

		PROCESS PAPER		VECTORS PULP		NET OUTPUT	
	1	1	35	36	45		
PAPER	11	+		0		+	
PULP	12	-		+		0	
STEAM ELECTRICITY	17	-		-		-	
BARK SPENT LIQUOR	18	+		+		+	
	19						
	20						
	21						

FIG. 4. THE INPUT-OUTPUT STRUCTURE OF THE PULP AND PAPER PROCESS SUBMODEL. (PLUS DENOTES AN OUTPUT AND MINUS DENOTES AN INPUT).

where x_j is the level of operation of process j , and a_{ij} is the input or output of good i to process j (a_{ij} is positive for an output and negative for an input.).

For the 35 paper process vectors the level variables, x_j , are determined by the demand for paper products, u_k , and by the mix of the 35 process vectors required to produce each of the 11 types of paper products, that is

$$x_j = \sum_{k=1}^{11} \phi_{jk} u_k \quad j=1,35$$

where ϕ_{jk} is an exogenous matrix of mix coefficients.

Given the level variables for the 35 paper process vectors, the demand for each type of pulp, v_m , is determined by

$$v_m = \sum_{j=1}^{35} a_{mj} x_j \quad \begin{matrix} m=1,6 \\ k=m+11 \end{matrix}$$

Given the demand for each type of pulp the level variables for the 10 pulp process variables are determined by

$$x_j = \sum_{m=1}^6 \psi_{jm} v_m \quad j=35,45$$

where ψ_{jm} is an exogenous matrix of mix coefficients.

To summarize, the net output vector, y_i , depends on the matrix of process vectors, a_{ij} , and the level of operation vector, x_j . The level of operation vector depends on the demand for paper products, the mix matrix for the 35 paper process vectors, the mix matrix for the 10 pulp process vectors, and the pulp requirements of the paper process vectors.

As shown in Figure 4, the net output vector is positive for the 11 types of paper products, zero for the six types of pulp, negative for process steam, and electricity, and positive for bark and spent liquor. Given demands for paper products the process model forecasts the demand for process steam and electricity and the supply of bark and spent liquor.

We have defined a static process model; how shall we define a dynamic model? In the future (and in the past) the matrix of process vectors and the paper and pulp mix matrices will evolve. In the future we expect technological change that will conserve steam and electricity and increase the utilization of bark and spent liquor. However, since our current data base is not adequate to define the matrix of process vectors for a historical year, we are reluctant to define a sequence of process matrices for future years. For the Phase I model, we assume that the process matrix does not vary with time. We do allow the demand for paper products and the paper and pulp mix matrices to vary with time.

To bridge from the static process matrix to the dynamic behavior of the industry, we introduce row adjustment factors, $f_i(t)$, such that

$$z_i(t) = f_i(t) y_i(t) \quad i=18,21$$

and

$$y_i(t) = \sum_{j=1}^{45} a_{ij} x_j(t) \quad i=1,21$$

where $z_i(t)$ is the output of the process model, a forecast of the demand for steam and electricity and the supply of bark and spent liquor, and $y_i(t)$ is the uncorrected output of the process model which depends on the static process matrix and the dynamic level vector. The level vector is determined by the forecast of paper products and the pulp and paper mix matrices.

In Section IV of this report, the model validation section, we shall use historical data to estimate the row adjustment factors.

The values of the row adjustment factors are determined by two factors 1) alignment, and 2) technical change. The technical change factor results from conservation of steam and electricity and increased utilization of bark and spent liquor. The alignment factor results from the differences between the process matrix defined by Arthur D. Little and the actual input-output coefficients for the papermill industry. The ADL process matrix is based on engineering judgments on the I-O structure of optimum 1974 technology for a limited number of products. The actual I-O coefficients are averages over the technology in 800 papermills producing a great variety of products. The technology in the 800 papermills has been installed over the last half century. The alignment factor is needed to bridge between optimum 1974 technology and actual average technology.

In the Phase I model, we introduce energy conservation and other process changes through row adjustment factors. To study the impact of a specific process change, one could introduce a new process to the process submodel. Introduction of a new process requires an estimate of the input-output coefficients for the process, an estimate of the penetration rate for the new process, and a revision of the process mix for the old processes and the new processes.

Our model, thus, differs from the optimization model recently developed by David Pilati, et al.¹² at the Brookhaven National Laboratory (BNL). We adopted the simulation scheme rather than optimization scheme (although we could easily convert our process submodel to an optimization model) for the following reasons. First, our approach can avoid the sudden transition which can occur in optimization models. Second, our present effort put a major emphasis on the energy conversion sector in order to deal with interfuel substitution questions. Finally, the approach we used allows us to maintain the flexibility for incorporating available engineering information and judgemental factors. Of course, there is also a disadvantage of our approach. To run our model, penetration rates of new as well as existing technologies require a separate side calculation and, thus, this requires more exogenous assumptions than the BNL optimization model. The relative forecasting abilities of the BNL model and our model need further investigation.

As part of the Phase I research we have begun to evaluate the impact of the alkaline-oxygen pulping process, the Rapson effluent-free kraft process, and thermo mechanical pulping. The results of this research are outside the scope of this report and will be discussed in a subse-

quent report. However, our research on new processes illustrates that the format of the process model is flexible and can easily accept exogenous process changes.

The Fuel Share Submodel

Given fuel prices, the fuel share submodel forecasts the market share for each type of purchased fuel. If there is a sudden increase in the price of natural gas and petroleum, the optimum market shares for petroleum and natural gas would decrease and the share for coal would increase. However, the actual market share depends on the stock of boilers at the 800 papermills. Typically, a petroleum or natural gas fired boiler cannot be easily converted to burn coal;¹³ furthermore, combustion of coal requires coal handling equipment and air pollution control equipment. Rather than prematurely retire existing boilers, a paper mill will continue to burn expensive petroleum and natural gas until it is cost effective to install a new coal boiler. Thus, the actual market share will respond gradually to a sudden change in relative fuel prices.

The fuel share model is a generalization of the fuel share model for the residential and commercial sectors developed by Baughman and Joskow.¹⁴ The optimum fuel shares are given by

$$\begin{aligned} S_1^* &= A_1^* \begin{matrix} \beta_{11}^* & \beta_{12}^* & \beta_{13}^* \\ P_1^* & P_2^* & P_3^* \end{matrix} S_3^* \\ S_2^* &= A_2^* \begin{matrix} \beta_{21}^* & \beta_{22}^* & \beta_{23}^* \\ P_1^* & P_2^* & P_3^* \end{matrix} S_3^* \\ S_1^* + S_2^* + S_3^* &= 1 \end{aligned}$$

where S_1^* is the optimum share for fuel oil, S_2^* is the optimum share for coal, S_3^* is the optimum share for natural gas. The fuel shares are

measured in physical units, that is, PJ of natural gas per PJ of total purchased fuel. P_i is the price of fuel of type i measured in millions of constant 1971 dollars per PJ and A_i^* and β_{ij}^* are parameters.

The optimum fuel shares respond immediately to price changes, the observed fuel shares respond gradually to price changes. The fuel shares with a dynamic adjustment are given by:

$$S_1 = A_1 P_1^{\beta_{11}} P_2^{\beta_{12}} P_3^{\beta_{13}} \left(\frac{S_1}{S_3} \right)^{\delta}_{-1} S_3$$

$$S_2 = A_2 P_1^{\beta_{21}} P_2^{\beta_{22}} P_3^{\beta_{23}} \left(\frac{S_2}{S_3} \right)^{\delta}_{-1} S_3$$

$$S_1 + S_2 + S_3 = 1$$

where δ is a lag adjustment constant, $0 \leq \delta \leq 1$. If $\delta = 0$ the fuel shares respond immediately to price changes; as δ approaches one the response to a price change becomes increasingly slower.

Our current data base is not rich enough to estimate the lag terms in the dynamic equations for fuel shares. We have estimated the coefficients in the equations for the optimum fuel shares using state-level census data for 1971.¹⁵ The optimum fuel share elasticities are shown in Table 12. The estimated own price elasticities are all greater than -2.0 indicating a very strong response to changes in fuel prices. The cross price elasticities show that an increase in the price of natural gas will increase demand for oil, gas, and coal; while an increase in the price of oil results in greater use of coal than of natural gas.

To forecast fuel shares we use the dynamic fuel shares model. We assume a value for the lag parameter, δ , and choose the coefficients to track the optimum fuel shares, that is

$$\beta_{ij} = (1-\delta) \beta_{ij}^*$$

$$A_i = (A_i^*)^{1-\delta}$$

Since fuel boilers typically have a long lifetime (30-50 years), we expect that the adjustment will take place slowly. If δ is 0.85 the model will achieve half of its ultimate response in four years, while if δ is 0.98 the half response time is 34 years. Based on results of model validation (to be discussed in Section IV), we chose δ to be 0.94 which results in a half response time of 11 years. The coefficients for the optimum fuel shares model and for the dynamic fuel shares model for $\delta = 0.94$ are shown in Tables 13a and 13b. The price units are million 1971 dollars per PJ.

TABLE 12. MARKET SHARE ELASTICITIES
FOR THE OPTIMUM FUEL SHARE MODEL^(a)

Fuel	Price elasticities for:		
	Oil	Coal	Natural Gas
Oil	-2.545	0.835	2.466
Coal	1.643	-2.280	0.069
Natural Gas	1.016	1.218	-2.465

^{a)} 1971 data - elasticities computed at sample means

TABLE 13a. COEFFICIENTS FOR THE OPTIMUM FUEL SHARE MODEL
AND FOR THE LAGGED FUEL SHARE MODEL FOR $\delta=0.94$

Optimum Model		Dynamic Model	
Coefficient	Value	Coefficient	Value
A_1^*	11.033	A_1	1.1549
β_{11}^*	-3.561	β_{11}	-0.2137
β_{12}^*	-0.383	β_{12}	-0.0230
β_{13}^*	4.931	β_{13}	0.2959
A_2^*	0.573	A_2	0.9671
β_{21}^*	0.627	β_{21}	0.0376
β_{22}^*	-3.498	β_{22}	-0.2099
β_{23}^*	2.534	β_{23}	0.1520

TABLE 13b. 1971 FUEL SHARES AND FUEL PRICES

Fuel	Share	Price ^(a)
Oil	0.3565	0.5438
Coal	0.2027	0.4522
Gas	0.4408	0.3565

a) Million 1971 Dollars per PJ

The Energy Conversion Submodel

Most of the 800 papermills have several boilers. The boilers burn bark, spent liquor, and purchased fuels to produce steam. Some of the boilers produce saturated steam; other boilers produce superheated steam which can be expanded through a turbine to yield electricity and process steam.

The structure of the energy conversion submodel is shown in Figure 5. The variables in the submodel include all of the energy sources for the papermill industry as reported by the American Paper Institute (API).¹⁶

FIG. 5. THE ENERGY CONVERSION SUBMODEL. (THE NUMBERS IN CIRCLES ARE ENERGY CONVERSION EFFICIENCIES AND THE NUMBERS IN SQUARES ARE THE ENTHALPY OF THE STEAM OR HOT WATER IN THE MAIN LOOP.)

In the energy conversion submodel all fuel is consumed in an average boiler to produce superheated steam; the superheated steam expands in a turbine to produce electricity and process steam; process steam is used in the papermill to produce pulp and paper; condensed steam is returned to boiler to be reheated. The structure of the energy sector submodel allows process steam to be sold or purchased. In the submodel the electricity supply is provided by steam turbines, by captive hydro plants and by purchases from utilities; the electricity demand consists of demand by the process model and external sales.

All of the variables in the energy conversion submodel can be determined from historical data except the main loop steam flow, the enthalpy of the steam in each leg of the main loop, and the energy conversion efficiencies. (In Figure 5, the numbers in circles are energy conversion efficiencies and the numbers in squares are the enthalpy of the steam or hot water in the main loop.) After a careful review of the literature,^{5,6,7} we chose typical values for the energy conversion efficiencies and two of the three enthalpy values; given these parameters and data on fuel consumption and electricity generation, we can estimate the main loop steam flow and the boiler output enthalpy. An extended numerical example will illustrate the details of the calculation.

Given API data on total fuel consumption in the papermill industry and our estimates of average energy conversion efficiencies, the calculation in Table 14 yields an estimate of the total energy added to feedwater in the boiler to produce superheated steam; the results are that 2083.0 PJ of fuel yield 1509.1 PJ of process heat. (The energy conversion submodel is an approximation of reality. All fuel is burned in a boiler. No fuel is burned in lime kilns. There is no condensing power.)

TABLE 14. TOTAL FUEL CONSUMPTION
BY THE PAPERMILL INDUSTRY - 1976

Fuel Type	Gross Consumption ^(a) (PJ)	Efficiency ^(b) (%)	Net Consumption (PJ)
Coal	223.8	79	176.8
Residual Oil	513.6	83	426.3
Distillate Oil	18.6	83	15.4
Natural Gas	345.4	83	286.7
Purchased Fuel	1101.4	82 ^(c)	905.2
Bark	179.8	68	122.3
Purchased Bark	6.6	68	4.5
Spent Liquor	795.2	60	477.1
Total Fuel	2083.0	72 ^(c)	1509.1

a) Reference 16

b) Reference 6

c) Calculated Average

In 1976 the papermill industry generated 31.609 TWh (or 113.8 PJ) of electricity. If we assume a conversion efficiency of 99 percent for the turbine and generator, the generated electricity required 114.9 PJ of the superheated steam. 7.6 percent of the boiler output was required for electricity; thus, 92.4 percent of the boiler output, or 1394.2 PJ, was consumed as process steam.

We have estimated the energy content of the process steam. If we estimate average enthalpy values for the process steam and the boiler feedwater, we can estimate the main loop steam flow. After a review of the literature,^{5,6,7} we assumed that enthalpy of the process steam

is 2.74 PJ/Tg (1180 Btu per pound) and the enthalpy of the boiler feedwater is 0.58 PJ/Tg (250 Btu per pound). With these assumptions each Tg of process steam delivers 2.16 PJ to the process; consequently, if 1394.2 PJ was consumed by the process in 1976, the estimated steam flow was 645.0 Tg.

If we know the main loop flow, the boiler feedwater enthalpy, and the boiler energy gain we can estimate the boiler output enthalpy. If the feedwater enthalpy is 0.58 PJ/Tg and the feedwater flow is 645.0 Tg, the energy embodied in the feedwater is 374.8 PJ. With an energy gain of 1509.1 PJ in the boiler, the output energy is 1883.9 PJ and the output enthalpy is 2.92 PJ/Tg.

The numerical example illustrates the structure of the submodel and the assumptions required to estimate the main loop steam flow and the boiler output enthalpy. This calculation requires data on purchased fuel and by-product fuel (bark and spent liquor). The Bureau of the Census publishes data on purchased fuel but not on by-product fuel. Thus, we cannot estimate the main loop steam flow and the output enthalpy without the API data on purchased fuel and by-product fuel; the API data exists for 1972, 1975, 1976, and subsequent years.

The energy conversion submodel can determine two variables. For a historical year, the endogenous variables are the main loop steam flow and the output enthalpy. For a future year, the endogenous variables are the purchased electricity and the total purchased fuel; the fuel share model allocates the total purchased fuel to the types of fuel. For a future year the exogenous variables are the purchased fuel shares

(determined in the fuel shares model), the energy conversion efficiencies, the three enthalpies, the supply of bark and spent liquor, the demand for process steam and electricity, the amount of purchased bark and steam, the amount of sold steam and electricity, and the amount of captive hydroelectric energy. Thus, many of the most significant variables are the result of side calculations.

For a future year any of the exogenous variables can influence the demand for purchased fuel and purchased electricity. For example, energy conservation in the pulp and paper process submodel could decrease the demand for steam without changing the demand for electricity. The output enthalpy controls the amount of self-generated electricity per unit of process steam. If the demand for process steam decreases and all other exogenous variables are constant, the amount of self-generated electricity would decrease and the amount of purchased electricity would increase and the amount of purchased fuel would decrease.

A change in fuel mix or energy conversion efficiency has an impact on purchased fuel but not on purchased electricity. For example, an increase in purchased bark or an increase in combustion efficiency for spent liquor would decrease the demand for purchased fuel but would not change the demand for purchased electricity.

IV. MODEL VALIDATION

As mentioned in Section III, the pulp and paper process submodel has row adjustment factors to bridge from the static (1974) technology vectors to the dynamic behavior of the paper industry. In this section the row adjustment factors will be estimated for several historical years.

Since 1971 there have been unprecedented changes in fuel prices. The forecasts of the fuel shares model will be compared to historical data for the period 1971 to 1976.

For a historical year the energy conversion submodel is used to estimate the main loop steam flow and the boiler output enthalpy. Using data from 1972, 1975, and 1976, the energy conversion submodel will be used to estimate the steam flow for comparison with the steam demand estimate of the process submodel. Since validation of the process submodel requires input from the energy conversion submodel, we will begin with the energy conversion submodel. (We are not validating the energy conversion submodel; we are using it to estimate the main loop steam flow and the boiler output enthalpy for 1972, 1975, and 1976.)

The Energy Conversion Submodel

In the last section fuel consumption data for 1976 was used to estimate the main loop steam flow and the output enthalpy. The results of the same calculation for 1972, 1975, and 1976 are given in Tables 15, 16, and 17. Table 16 displays the total electricity supply for the papermill industry; the total supply is the sum of purchased electricity, self-generated hydroelectricity and steam electricity minus sold electricity. Similarly, Table 17 displays the total steam supply. Since supply is equal to demand, Tables 16 and 17 present estimates of the total demand for steam and electricity by the papermill industry in 1972, 1975, and 1976.

The results of the energy conversion submodel depend on several assumptions. We will discuss these assumptions after we have used the pulp and paper process submodel to estimate the demand for steam and electricity.

TABLE 15. HISTORICAL FUEL CONSUMPTION
BY THE PAPERMILL INDUSTRY

Fuel Type	Fuel Consumption (PJ) For:		
	1972	1975	1976
Coal	234.0	183.5	223.8
Distillate Oil	21.4	14.3	18.6
Residual Oil	494.4	464.0	513.6
Natural Gas	487.0	366.4	345.4
Purchased Fuel	1236.8	1028.2	1101.4
Bark	155.4	146.4	179.8
Purchased Bark	3.6	6.4	6.6
Spent Liquor	788.9	712.4	795.2
Total Fuel	2184.7	1893.4	2083.0
Net Fuel ^(a)	1598.7	1377.4	1509.0

(a) Net fuel is defined in Table 14.

Source: Reference 16

The Pulp and Paper Process Submodel

The process submodel is based on 45 process vectors defined in a recent study.¹¹ To estimate the total demand for steam in an historical year, we need to estimate the level of operation for each process; recall, that the net output for each factor, y_i , is given by

$$y_i = \sum_{j=1}^{45} a_{ij} x_j \quad i=1,21$$

TABLE 16. HISTORICAL ELECTRICITY SUPPLY
FOR THE PAPERMILL INDUSTRY

Source	1972 (TWh)	1975 (TWh)	1976 (TWh)
Purchased ^a	27.13	26.95	32.46
Sold ^b	-2.90	-3.52	-3.83
Own Hydro ^a	2.57	2.69	2.83
Own Steam ^a	29.83	28.13	31.61
Total Supply ^b	56.63	54.26	63.07

a) Reference 16

b) ORNL estimate

TABLE 17. A. HISTORICAL STEAM SUPPLY
FOR THE PAPERMILL INDUSTRY

Source	1972 (Tg)	1975 (Tg)	1976 (Tg)
Purchased ^a	8.4	6.2	6.9
Sold ^b	-1.6	-2.0	-2.1
Main Loop ^b	689.5	589.9	645.0
Total Supply ^b	696.3	594.1	649.8

B. HISTORICAL OUTPUT ENTHALPY
FOR THE PAPERMILL INDUSTRY

Parameter	1972 (PJ/Tg)	1975 (PJ/Tg)	1976 (PJ/Tg)
Output Enthalpy ^b	2.900	2.916	2.921

a) Reference 16

b) ORNL estimate

where

$$x_j = \sum_{k=1}^{11} \phi_{jk} u_k \quad j=1,35$$

$$x_j = \sum_{m=1}^6 \psi_{jm} v_m \quad j=36,45$$

$$v_m = \sum_{j=1}^{35} a_{kj} x_j \quad \begin{matrix} m=1,6 \\ k=m+11 \end{matrix}$$

Given the demand for each of the 11 types of paper products (u_k), the paper process mix matrix (ϕ_{jk}) determines the level of operation of each process which produces paper ($x_j, j=1,35$). Given the level of operation of the paper processes, the pulp demand vector (v_m) is determined by the process vectors for the paper products. Given the pulp demand vector, the pulp process mix matrix (ψ_{jm}) determines the level of operation of the pulp processes ($x_j, j=36,45$).

To estimate the quantity of pulp, spent liquor, bark, steam, and electricity for an historical year, we need to estimate the production of each of the 11 types of paper products and the pulp and paper process mix matrices.

For historical years and for forecasts, we have used constant pulp and paper process mix matrices; the matrices are shown in Tables 18 and 19. The coefficients for the paper process mix matrix were estimated using data from the Arthur D. Little study.¹¹ The ADL study was concerned with the use of recycled paper; consequently, the primary process options are the proportions of virgin fiber and recycled fiber.

Table 18 has three processes for producing linerboard (LINVE 6, LINSE 12, LINBE 18). Process LINVE 6 uses virgin fiber; process LINSE 12

TABLE 18: THE PAPER PROCESS MIX MATRIX

Product	Process ID	% Virgin Fiber	% Recycled Fiber	% Share
1. Linerboard	a) LINVE 6	100	0	78.5
	b) LINSE 12	0	100	2.1
	c) LINBE 18	80	20	19.4
2. Corrugating Medium	a) CORVE 34	85	15	27.9
	b) CORBE 46	57	43	51.1
	c) CORSE 40	100	0	21.0
3. Newsprint	a) NEWVF 6	100	0	90.8
	b) NEWSF 12	0	100	9.2
	c) NEWBF 18	67	33	0
4. Groundwood	a) PRIVF 28	100	0	83.6
	b) PRIBF 40	67	33	16.4
	c) PRISF 34	0	100	0
	d) PRIVF 46*	100	0	0
5. Tissue	a) TISVG 6	100	0	3.8
	b) TISBG 18	67	33	96.2
	c) TISSG 12	0	100	0
	d) TISVG 26*	100	0	0
5. Boxboard	a) BBDVH 10	100	0	39.2
	b) BBDSH 4	0	100	60.8
7. Writing	a) BONVI 6	100	0	44.0
	b) BONBI 18	67	33	53.6
	c) BONSI 12	0	100	2.4
	d) BONVI 24*	100	0	0
8. Book	a) BKVI 30	100	0	69.2
	b) BKVI 42	50	50	30.8
	c) BKSI 36	0	100	0
	d) BKVI 49*	100	0	0
9. Kraft Bag	a) BAGVJ 6	100	0	70.6
	b) BAGBJ 18	70	30	29.4
	c) BAGSJ 12	0	100	0
	d) BAGVJ 24*	100	0	0
10. Packaging	a) TUBVJ 28	100	0	88.4
	b) TUBBJ 40	30	70	11.6
	c) TUBSJ 34	0	100	0
11. Construction	a) RFTK 2	45	55	100.0

*This process requires market pulp

uses recycled fiber; process LINBE 18 uses a blend of 80% virgin fiber and 20% recycled fiber. For the base year, 1974, we estimate the process mix at 79% LINVE 6, 2% LINSE 12, and 19% LINBE 18.

Slush pulp is produced and consumed in an integrated papermill while market pulp is produced in an integrated papermill or a pulp mill, dried, and shipped to another papermill. Although there are small differences in the energy requirements for paper produced from slush pulp and market pulp, we have chosen to assume a zero market share for market pulp.

TABLE 19. THE PULP PROCESS MIX MATRIX

Pulp Type	Process ID	% Share
A. Market Pulp		
1) Bleached Softwood Kraft	a) MPVSWSE	70
	b) MPVSWNE	30
2) Bleached Hardwood Kraft	a) MPVHWSE	70
	b) MPVHWNE	30
B. Slush Pulp		
3) Bleached Softwood	a) SPBSWSE	100
	b) SPBSWNE	0
4) Bleached Hardwood Kraft	a) SPBHWSE	100
	b) SPBHWNE	0
5) Unbleached Softwood Kraft	a) SPUSWSE	100
6) Groundwood Slush Pulp	a) SPUGWNE	100

As shown in Table 19, the process options in the ADL report for producing each type of pulp are the same process, but adopted in two different regions (southeast or northeast); thus, they have the same requirements for steam and electricity.

Given the production of paper products in a historical year (Table 5 provides production data for 1972) and the pulp and paper process mix matrices, the pulp and paper process submodel can estimate the quantity of pulp, spent liquor, bark, steam, and electricity for an historical year; the results are shown in Table 20.

Part A of Table 20 gives historical data ($z_i(t)$); part B of Table 20 gives the unadjusted process model results ($y_i(t)$); part C of Table 20

TABLE 20. COMPARISON OF HISTORICAL DATA
WITH THE UNADJUSTED PROCESS MODEL

A. Historical Data			
Factor	1972	1975	1976
Pulp (Tg)	42.154	39.085	44.274
Spent Liquor (Tg)	53.688	49.365	55.334
Bark (Tg)	7.5512	7.3070	8.9478
Steam (Tg)	696.32	594.15	649.76
Electricity (TWh)	56.633	54.256	63.067
Paper (Tg)	53.938	47.646	54.470

B. Unadjusted Process Model Results			
Factor	1972	1975	1976
Pulp (Tg)	38.882	34.298	38.979
Spent Liquor (Tg)	29.433	26.298	29.395
Bark (Tg)	6.391	5.741	6.394
Steam (Tg)	412.95	369.788	416.172
Electricity (TWh)	45.657	41.244	46.081
Paper (Tg)	53.938	47.646	54.470

C. The Row Adjustment Factors

Factor	1972	1975	1976
Pulp	1.084	1.140	1.136
Spent Liquor	1.821	1.877	1.882
Bark	1.181	1.273	1.399
Steam	1.686	1.607	1.561
Electricity	1.240	1.315	1.369

D. Historical Input-Output Coefficients

Factor	1972	1975	1976
Pulp	.782	.820	.813
Spent Liquor	.995	1.036	1.016
Bark	.140	.153	.164
Steam	12.91	12.47	11.93
Electricity	1.050	1.139	1.158

E. Unadjusted Process Model

Input-Output Coefficients

Factor	1972	1975	1976
Pulp	.721	.720	.716
Spent Liquor	.547	.545	.540
Bark	.119	.119	.118
Steam	7.66	7.66	7.65
Electricity	.847	.854	.847

gives the row adjustment factors ($f_i(t)$). (Recall, $z_i(t) = f_i(t)y_i(t)$.) Parts D and E of Table 20 present input-output coefficients for the historical data and the unadjusted process model.

Study of Part C of Table 20 shows that the row adjustment factors are slowly varying and greater than one; thus, the 1974 technology requires less pulp, steam, and electricity than the average but also produces fewer by-products of spent liquor and bark. The largest factors are for spent liquor and steam.

Reconciling engineering estimates with statistical data is an important part of our research program. After the completion of the research on the Phase I model, we have continued to study the reasons for the large adjustment factors for spent liquor and steam. The results of our research are presented in the following paragraphs.

Energy and material balances for ten papermills which use the kraft process have been developed by J. E. Sirrine.⁵ Comparison of the amount of spent liquor per kilogram of pulp, as given in the J. E. Sirrine report and the A. D. Little report, reveals that the A. D. Little report does not include the mass of the chemicals in the spent liquor but only includes the lignin and other residues from the tree. The data in the J. E. Sirrine report yields a correction factor of 1.4, that is, for each kilogram of lignin there is 0.4 kg of chemicals. If we divide the 1976 spent liquor adjustment factor (1.882) by the chemical factor (1.4) we find an unexplained adjustment factor of 1.344.

After correction for the chemical factor, the A. D. Little report estimates 1.55 kg of spent liquor solids per kg of bleached air dry pulp and 1.36 for unbleached pulp. The average values from the

J. E. Sirrine report are 1.65 for bleached pulp and 1.44 for unbleached pulp. Thus, the average values from the J. E. Sirrine report are only about 6% higher than the corrected estimates in the A. D. Little report and this difference is much smaller than the 34% unexplained adjustment factor.

To summarize, the adjustment factor for spent liquor is about 90%. More than half of the adjustment factor can be explained by the chemical factor. To explain the residual adjustment factor, we plan further research using proprietary data from the American Paper Institute.

As noted in Section III, the estimate of total steam demand depends on several approximations. There are two approximations in the energy conversion submodel which increase the estimate of total steam demand; these are: 1) direct fuel use in lime kilns is added to boiler fuel use, and 2) a significant fraction of the steam in the main loop is used for feedwater heating and condensing power generation and is not consumed by the process.

As part of our continuing work on energy demand models for the paper industry, we have made a correction for lime kilns and feedwater heaters and developed an improved estimate of total demand for process steam. These estimates are 596.86, 489.32, and 536.63 Tg of process steam in 1972, 1975, and 1976. Using these revised estimates, the row adjustment factor for process steam in 1976 becomes 1.29, which is much smaller than the value (1.56) shown in Table 20.

For 1976 our revised adjustment factors are 1.34 for spent liquor, 1.40 for bark, 1.29 for steam, and 1.37 for electricity. The revised adjustment factors are remarkably consistent. The data supports the hypothesis that the average technology in the papermill industry may be

TABLE 21. ANNUAL GROWTH RATES
FOR THE ROW ADJUSTMENT FACTORS 1972-1976

Factor	Growth Rate (%)
Pulp	1.3
Spent Liquor	0.9
Bark	3.9
Steam	-1.9
Electricity	2.4

30% to 40% less efficient than the best technology in 1974. We plan further research to determine the differences between average technology and best technology.

The growth rates for the row adjustment factors from 1972 to 1976 are given in Table 21. What will the annual growth rates for the row adjustment factors be in the future? Conservation of mass connects paper to pulp, spent liquor, and bark. The fiber in paper comes from virgin pulp or recycled paper. The material in roundwood becomes pulp and spent liquor. There is a limit to the amount of bark and hogged wood that can be obtained per kilogram of roundwood. Sharp increases in purchased fuel prices encouraged an increased use of bark and hogged wood between 1972 and 1977 and a 4% annual increase in the amount of bark per kilogram of paper. But the 4% annual increase cannot continue indefinitely. (In 20 years, 4% annual growth yields a total growth factor of 2.2.)

The row correction factors for pulp, spent liquor, and bark cannot continue to grow at 1% or 4% but must approach zero growth rates when limits are reached. Conservation of steam should encourage a continued

decrease in steam. Conservation of electricity will be opposed by process innovations which require more electricity, the future growth rate could be positive or negative. However, these historical trends serve useful purposes for specifying the appropriate assumptions used in Section V.

The Fuel Share Model

Historical prices and fuel shares for the pulp and paper industry (SIC 26) are shown in Table 22. Expressed in constant dollars, the price of oil more than doubled between 1971 and 1974; since 1974 the oil price has decreased but the 1976 price remains at a level which is more than twice the 1971 price. The coal price nearly doubled between 1971 and 1974, increased by 18% in 1975 and decreased by 13% in 1976. The

TABLE 22. HISTORICAL PRICES AND FUEL SHARES
IN THE PULP AND PAPER INDUSTRY - SIC 26

Year	Oil	Coal	Gas
<u>A. Prices (Million 1971 Dollars per Petajoule)</u>			
1971	0.5438	0.4522	0.3565
1974	1.3380	0.8239	0.5246
1975	1.3114	0.9734	0.6998
1976	1.2402	0.8626	0.8830
<u>B. Fuel Shares</u>			
1971	0.3564	0.2027	0.4409
1974	0.4203	0.1797	0.4000
1975	0.4488	0.1705	0.3807
1976	0.4765	0.1805	0.3430

Source: Reference 2

price of natural gas increased more slowly between 1971 and 1974 but it has continued to increase; the increases were 47% between 1971 and 1974, 33% in 1975, and 26% in 1976. In addition there have been supply constraints on the availability of natural gas.

The fuel share for oil has increased steadily from 36% to 48%. The coal fuel share decreased from 1971 to 1975 before increasing slightly in 1976. The natural gas fuel share decreased steadily from 44% to 34%.

Given the prices in Table 22, the optimum fuel shares model predicts the fuel shares shown in Table 23. The coefficients in the model were estimated with 1971 data. In 1974, the model predicts a 69% share for gas because the gas price has increased much less than the prices of oil and coal. By 1976, the optimum fuel share model forecasts a share of 20% for natural gas.

The optimum fuel shares can change rapidly from year to year. The actual fuel shares are less volatile because the boilers in the paper industry can easily switch from gas to oil but cannot easily switch from oil or gas to coal. The dynamic fuel share model introduces a parameter to make the model less volatile. Natural gas fuel shares for various values of the lag parameter are shown in Table 24.

TABLE 23. OPTIMUM FUEL SHARES

Year	Oil	Coal	Gas
1971	0.3564	0.2027	0.4409
1974	0.1329	0.1787	0.6884
1975	0.3794	0.1423	0.4783
1976	0.6393	0.1593	0.2014

TABLE 24. NATURAL GAS FUEL SHARES
FOR VARIOUS VALUES OF THE LAG PARAMETER

Lag Parameter (δ)	1974	1975	1976
	Actual Shares		
	0.4000	0.3807	0.3430
	Forecasted Shares		
0	0.6884	0.4783	0.2014
0.2	0.6439	0.5172	0.2530
0.4	0.5910	0.5283	0.3167
0.6	0.5304	0.5120	0.3756
0.8	0.4638	0.4674	0.4081
0.9	0.4291	0.4342	0.4080
0.94	0.4151	0.4189	0.4042
1.0	0.3940	0.3940	0.3940

As the lag parameter increases from zero to one, the 1974 fuel share for gas decreases from 69% to a base value of 39% while the 1976 share increases from 20% to 39%. When the lag parameter is one the fuel shares cannot respond to prices; when the lag parameter is zero the fuel shares respond immediately to price changes. Since boilers have a 20 to 30 year lifetime we have chosen a value of the lag parameter (0.94) which corresponds to a half response of 11 years.

In Table 24 none of the values of the lag parameter result in a perfect match to the historical data. The best fit occurs when the lag parameter is equal to 0.98. However, if the lag parameter is 0.98 the half response time is 34 years which is too long. Since the fit to historical data is acceptable for all values of the lag parameter between 0.9 and 1.0, we have chosen the lag parameter to give a reasonable response time.

Our method of choice of the lag parameter is an example of our attempt to use both econometric information and engineering information in our energy demand models. We believe that our models will be significantly improved if we attempt to reconcile engineering and econometric information. Given the 1976 prices the optimum natural gas share is 20% which is substantially below the 1976 share and the 1976 share (34%) is substantially below the 1971 share (44%). Thus, the actual share is moving toward the optimum share.

From an engineering viewpoint, the optimum model and the historical data are not consistent with the historical prices. Natural gas is a very convenient fuel; coal is an inconvenient fuel which requires special handling equipment and air pollution control equipment; oil is not as convenient as gas but it is much more convenient than coal. In 1976 the gas price was 2% greater than the coal price and 40% less than the oil price. Given the 1976 prices, an engineer would choose natural gas as the least total cost fuel. How can an engineer explain the drop in natural gas share? A plausible hypothesis is that supply restrictions on gas forced an increased use of oil.

Another engineering insight is that a coal, oil, or gas boiler can burn oil or gas but oil and gas boilers cannot burn coal. Thus, the lag time required to substitute oil for gas can be a year or less. However, the lag time for a substitution of coal for oil and gas will depend on the lifetime of the existing oil and gas boilers. Further work is required to develop a fuel shares model that can reconcile both engineering and econometric information.

The dynamic fuel shares model responds gradually to a sudden change in energy prices but when prices change gradually the lag parameter has

a smaller influence on the forecast of the model. To illustrate this point, Table 25 shows fuel shares in the year 2000 for various values of the lag parameter. The price changes smoothly from the 1976 value to the 2000 value. When the lag parameter is 1.0, the predicted fuel shares remain at the 1976 mix. However, if the lag parameter is 0.94, the oil share is 59% which is close to the optimum share (54%). The coal share is 28% which is almost halfway on the path to the optimum share (40%). The gas share is 13% which is 70% of the way from the initial share (34%) to the optimum share (6%).

TABLE 25. FUEL SHARES IN 2000
FOR VARIOUS VALUES OF THE LAG PARAMETER

	Oil	Coal	Gas
Year	Fuel Prices ^a		
1976	1.24	0.86	0.88
2000	2.64	0.95	1.93
δ	Fuel Shares (2000)		
0	0.5401	0.3999	0.0600
0.2	0.5422	0.3969	0.0609
0.4	0.5456	0.3920	0.0624
0.6	0.5524	0.3821	0.0655
0.8	0.5708	0.3525	0.0757
0.9	0.5897	0.3101	0.1002
0.94	0.5895	0.2769	0.1336
1.0 ^b	0.4765	0.1805	0.3430

a) Million 1971 dollars per petajoule

b) Gives 1976 fuel share values

The optimum fuel shares have an elastic response to price changes. In Table 26 optimum fuel shares are given for three sets of fuel prices. Given the prices in Case 1 the oil share is 84% and the coal share is 11%. In case 2, the oil price is increased by 22% and the coal price is decreased by 23% and the oil share drops by 30% while the coal share increases by 29%.

High elasticity in combination with great uncertainty about future prices greatly increases forecasting uncertainty. If the uncertainty in fuel prices in the year 2000 is 20%, the uncertainty in fuel share is 44% for an elasticity of -2 and 73% for an elasticity of -3. Since the uncertainty in fuel prices in the year 2000 is probably greater than 20%, the uncertainty in the forecast fuel shares is very large. Even if we improve the fuel shares model by tracking investment

TABLE 26. OPTIMUM FUEL SHARES AS A FUNCTION OF PRICE
FOR THE YEAR 2000

Fuel	Case 1	Case 2	Case 3
Price ^a			
Oil	2.16	2.64	3.33
Coal	1.23	0.95	0.95
Gas	1.98	1.93	2.43
Fuel Share (%)			
Oil	84	54	45
Coal	11	40	51
Gas	5	6	4

^{a)} Million 1971 dollars per petajoule

decisions, it may be possible to forecast the total demand for residual oil, distillate oil, and natural gas but the mix between these three fuels cannot be forecast. If coal is less expensive than oil/gas, all coal boilers will burn coal and the demand for coal will be much easier to forecast than the demand for each type of oil/gas.

V. AN ENERGY DEMAND FORECAST

The Phase I energy demand model for the paper industry has four components: a paper demand submodel, a pulp and paper process submodel, a fuel share submodel, and an energy conversion submodel. The model produces a conditional forecast of energy demand by the papermill industry which depends on the exogenous values of the variables for each of the four submodels. This section begins with a discussion of the exogenous variables and concludes with a discussion of an energy demand forecast and three auxiliary forecasts which illustrate the sensitivity of the forecast to changes in the assumptions.

Assumptions

The basic assumptions used in our forecast are detailed as follows. The exogenous variables for the paper demand submodel are paper product prices, population, industrial value added, and disposable income. The growth rates for these variables are given in Table 27. Industrial value added and disposable income increase at about the same rate as the GNP in current dollars; the GNP deflator is used to obtain the growth rate for disposable income in constant dollars. Since paper product prices increase at the same rate as inflation, real paper product prices are constant.

TABLE 27. A. INPUT ASSUMPTIONS FOR THE PAPER DEMAND SUBMODEL

Variable	ANNUAL GROWTH RATES (%)			
	1976-1980	1980-1985	1985-1990	1990-2000
1) Industrial Value Added (current dollars)	11.1	10.0	8.8	8.8
2) Population	0.81	0.95	0.90	0.67
3) Disposable Income (current dollars)	10.4	8.8	7.9	7.9
4) GNP Deflator	5.8	5.3	4.8	4.8
5) Paper Prices	5.8	5.3	4.8	4.8

B. ANNUAL GROWTH RATES FOR THE ROW ADJUSTMENT FACTORS (%)

Variable	1976-1980	1980-1985	1985-1990	1990-2000
Spent Liquor	1.0	0.5	0.2	0.1
Bark	2.5	1.2	0.6	0.3
Steam	-1.6	-0.8	-0.4	-0.2
Electricity	2.0	1.0	0.5	0.2

The values of the exogenous variables used in this section are not the result of a careful study but are illustrative. The values for the growth rate of real value added and real disposable income are very important; these growth rates drive paper demand which drives energy demand. In an economy with no technological change or changes in consumption patterns, a 5% growth rate in real value added and disposable income would cause a 5% growth rate in production of paper and a 5% growth rate in energy demand.

The exogenous variables for the pulp and paper process model are the pulp and paper process mix matrices which retain the values shown in Tables 18 and 19 for all forecasts and the row adjustment factors. For the energy demand forecast the annual growth rates for the row adjustment factors are given in Table 27. Comparison with Table 21

shows that the growth rates begin at values similar to the historical values and that the growth rates gradually slow down.

The exogenous variables for the fuel share submodel are fuel prices and the key input assumption for the energy conversion submodel is the output enthalpy. These assumptions are discussed below when we describe the four cases.

The key changes in exogenous variables which produce the four forecasts are:

Case 1 - A Base-Case Energy Demand Forecast

The base case uses all the basic assumptions described above. In addition, the assumptions for fuel prices shown in Table 28 are used. Furthermore, we assume that the boiler output enthalpy, which controls the amount of electricity per unit of process steam, is fixed at the 1976 level. Case 1 features conservation of steam, increased use of solar and chemical by-product (bark and spent liquor) energy, and increased demand for electricity.

TABLE 28. ANNUAL GROWTH RATE OF FUEL PRICES
Constant Dollars
1976-2000

Fuel	Case 1 (Base Price)	Case 3 (High Price)
Oil	3.3	4.3
Coal	0.4	0.4
Gas	3.3	4.3

Case 2 - 1976 Technology

1976 technology is used in Case 2. Specifically, we assume row adjustment factors to remain at the 1976 values (instead of those shown in Table 27). Thus, in Case 2, there is less conservation of steam and less demand for solar and electricity. All other exogenous variables are the same as in Case 1.

Case 3 - High Prices For Oil And Gas

In this case, we assume higher prices of oil and natural gas than those used in the Base Case (Table 28). All other exogenous variables are the same as in Case 1.

Case 4 - More Cogeneration

In Case 4, the boiler output enthalpy is assumed to be 1% higher than the 1976 level throughout the forecast period. All other exogenous variables are the same as in Case 1.

Forecasting Results

Table 29 shows the forecasted annual growth rates for the 11 types of paper products. Since technological change and changes in consumption patterns are possible in the economy, the growth rates for production of the paper products are not uniform but range from 2.6% to 6.5%. (Demand is the sum of production and imports. Changes in imports are responsible for the small differences between the growth rates for production and demand.)

The forecasted fuel shares for the base case and for the high price case are presented in Table 30. The high prices are used for Case 3 while the base prices are used for the other three cases.

TABLE 29. PAPER PRODUCTION AND DEMAND
ANNUAL GROWTH RATE--1976-2000

Product	Production %	Demand %
1) Linerboard	4.0	4.0
2) Corrugating Medium	4.3	4.3
3) Newsprint	2.7	3.0
4) Groundwood	3.5	3.2
5) Tissue	3.4	3.3
6) Boxboard	3.0	2.8
7) Book	6.5	6.5
8) Writing	3.1	3.0
9) Kraft Bag	2.6	2.6
10) Packaging	4.6	4.5
11) Construction	3.6	3.6
Total product	3.8	3.7

TABLE 30: FUEL SHARES IN THE YEAR 2000 (%)

Fuel	Case 1 (Base Price)	Case 3 (High Price)
Oil	59	56
Coal	28	33
Gas	13	11

Since there is no feedback from fuel prices to paper product prices or to the price of steam or electricity, the demand for steam and electricity forecasted by the process model does not depend on fuel prices or the output enthalpy. Thus, Cases 1, 3, and 4 have the same demand for steam and electricity and the demand changes in Case 2. The results are shown in Figures 6 and 7. For Case 2 the demand for both steam and electricity grows at about the same rate as the demand for paper products. For Cases 1, 3, and 4, steam demand grows more slowly and electricity demand grows more rapidly than in Case 2.

The forecast of demand for purchased electricity is shown in Figure 8. The high fuel prices for Case 3 change fuel shares but do not change the demand for purchased electricity. For Case 2, the average annual growth rate for purchased electricity is the same as the rate for total electricity. For Cases 1 and 3, the growth rate for purchased electricity is higher than the growth rate for total electricity (5.3% versus 4.5%); purchased electricity grows more rapidly because steam conservation causes a decrease in cogenerated electricity. For Case 4, cogeneration causes a drop in the level of demand for purchased electricity, but the growth rate is about the same as that for Cases 1 and 3.

The forecast of demand for coal is shown in Figure 9. Cases 1 and 2 have the same fuel shares but different demands for steam; a high demand for steam results in a high demand for fuel. Cases 3 and 4 have the same steam demand as Case 1 but have higher demand for coal; for Case 3 higher prices for oil and gas cause a higher coal share; for Case 4, more cogeneration reduces demand for purchased electricity but increases the demand for coal as compared with Case 1.

FIG. 6. DEMAND FOR PROCESS STEAM.

FIG. 7. TOTAL DEMAND FOR ELECTRICITY.

The forecast of demand for natural gas is shown in Figure 10. Case 2 has a higher demand for natural gas than Case 1 due to a higher demand for steam. Case 3 has the same steam demand as Case 1 but a lower fuel share. Case 4 has a higher demand for gas due to more cogeneration than Case 1.

The forecast of demand for residual oil is shown in Figure 11. Residual oil is the primary purchased fuel for all cases. Case 2 has a higher demand for residual oil due to a higher demand for steam. Case 3 has the same steam demand as Case 1 but a lower oil share. Case 4 has a higher demand due to more cogeneration.

FIG. 10. DEMAND FOR NATURAL GAS.

FIG. 11. DEMAND FOR RESIDUAL OIL.

VI. THE PHASE II MODEL

This report concludes with a discussion of the strengths and weaknesses of the Phase I model and a brief discussion of plans for the Phase II model. This section begins with a general discussion of industrial energy demand and various methods for forecasting energy demand.

Our general goal is to develop a model for each industrial sector that will forecast energy demand and the penetration of solar energy and energy conservation technologies. Our goals are a part of the general problem of forecasting technological change in an industry. To illustrate the difficulties of developing an adequate model, we will perform the thought experiment of forecasting technological change in an industry.

Suppose we knew the demand for paper products by region for all future time. (The demand depends on the prices of paper products and the paper product prices depend on technological change. In our thought experiment we will ignore this feedback.) Demand for paper products can be satisfied by imports or by domestic production. Suppose we know the quantity and port of entry for imports of paper products. Suppose we know the cost structure of every paper mill in the country, that is we know the cost of all factors of production and the input-output coefficients for every machine in every papermill. Suppose we know the cost of all factors of production and the cost of transportation for all future time. Suppose we know the input-output coefficients for all technological options for the paper industry for all future time. Suppose all papermills cooperate to provide paper products to meet the demand at the least total cost. Suppose we know all government regulations (pollution control, land use, energy conservation, etc.) for all future time. With this long list of necessary information, we begin to be able to pose an optimization problem that would allow us to forecast technological change in the paper industry.

Theoretically, we could develop a model that would track all of the variables in our thought experiment model. However, cost structure data is proprietary and human freedom prevents us from knowing future factor cost, future technology, or future government regulations. Since a real model cannot track all of the variables in our thought experiment model, a real model must be based on incomplete information and have aggregate variables. The appropriate level of aggregation depends on the questions the model is designed to answer. A model with

more detail can respond to more detailed questions but requires more resources than a model with less detail. However, more detail usually results in less precision for each element.

Technological change models can be classified on the basis of whether the process I-O coefficients are fixed or vary in response to factor prices and investment. (Like most classification schemes there is a grey area between the black of fixed coefficients and the white of variable coefficients. If there are many process options in a fixed coefficient model the model has a variable response. In the following discussion we will contrast black and white.) Typically, an engineer prefers a fixed coefficient model and an economist prefers a variable coefficient model. A fixed coefficient model has the advantage and disadvantage that each process change can and must be identified. For example, suppose a model has two process options (A and B). Suppose process A was optimum for energy prices before 1972 and process B is optimum for energy prices after 1974. Suppose the pre 1972 capital stock used process A exclusively and after 1974 all new investment was in process B. Gradually, process B will become the dominant technology as old process A machines retire. But suppose that energy prices double in 1990 and process C is optimum for the post 1990 period. Suppose that process C has not been developed in 1974; that is, a careful engineering study has not been performed to estimate I-O coefficients. Many developers of fixed coefficient models would not include process C in their model; thus, fixed coefficient models tend to overestimate energy demand because the models do not include "speculative" new technologies. (If the models do include speculative new technologies, they may underestimate energy demand since preliminary design studies are usually overly optimistic.)

The new technology in a variable coefficient model is described by a production function or a cost function. Given a set of prices, the production function will yield the optimum technology. If the production function yields process A for 1972 prices and process B for 1974 prices, the economist is confident that the production function will yield process C for 1990 prices. Quite properly, the engineer is skeptical that the economist can predict the I-O coefficients for process C. However, the economist can answer that his approximation of process C is probably better than the engineers approximation, process B.

The Phase I model is the progeny of a collaboration between engineers and economists; naturally, two of the four submodels have fixed coefficient and two have variable coefficients. The general goal for the Phase II mode is to have all parts of the model have variable coefficients.

The paper demand submodel is a variable coefficient model which respon to changes in the economy and to changes in paper product prices. Suppose the uncertainty in our forecast of total paper demand in the year 2000 is 20%. A 20% change in paper demand will cause a 20% change in energy demand. Few conservation options will reduce energy demand by 20% by 2000. Thus, the paper demand submodel is an important part of the Phase I model. Future research will include study of regional demand patterns and study of the potential for technological change to cause a significant change in demand patterns, for example, will plastic substitute for paper or vice versa.

The pulp and paper process submodel is a fixed coefficient model. Furthermore, the process submodel has the advantage and disadvantage that the process mix is exogenous and not determined by linear programming or

another optimization method; the advantage is that the model avoids the sudden transition which can occur in optimization models; the disadvantage is that the penetration rates of new technologies require a separate side calculation. Although, we have not incorporated new technologies in the process submodel for this report, new technologies can easily be added to the process options.

In the pulp and paper process model the amount of conservation (of steam and electricity) and the demand for solar energy (spent liquor and bark) are controlled by exogenous row correction factors. Conservation and solar could be modeled by adding new processes to the model, however a switch to a variable coefficient model would be more satisfactory. The Phase II model will have variable coefficients and the penetration of new technology (conservation and solar) will depend on life cycle costs.

The fuel share submodel is a variable coefficient model in which the fuel shares respond to fuel prices with a time lag. At the end of Section IV, we discussed some of the shortcomings of the model. Further research is needed to develop a model based on both econometric information and engineering information. The Phase II fuel share model will be an integral part of the Phase II energy conversion submodel; further details on the Phase II fuel share model are discussed below.

The Phase I energy conversion submodel is a fixed coefficient model. The penetration rate for cogeneration is controlled by the exogenous boiler output enthalpy. Thus, the Phase I model cannot predict the amount of cogeneration but given a side calculation to determine the amount of cogeneration, the model can estimate the impact on energy demand of changes in the amount of cogeneration.

The Phase II energy conversion submodel will be designed to estimate the penetration of coal boilers and cogeneration. The model will be based on several options for producing process steam; the options will be differentiated on the basis of fuel type (oil/gas, coal, bark, spent liquor) and the amount of electricity produced per unit of process steam. The oil/gas boilers can burn residual oil, distillate oil, or natural gas but cannot burn coal. Demand for coal is controlled by the investment process. The model begins with stocks of each type of boiler identified by year of installation. Each year new boilers are installed and all boilers over 30 years old are retired. Investment in new boilers is allocated on the basis of life cycle costs. Penetration of coal boilers and cogeneration will occur if these technologies have lower life cycle costs than competing technologies.

The Phase I model will be useful to the Department of Energy since it can be used to evaluate the impact on energy demand of cogeneration, conversion to coal, conservation of steam and electricity, and increased use of solar energy. The Phase I model can be used to estimate potential energy savings for a cost-benefit analysis of DOE support for an energy conservation option. The Phase II model will have more behavioral detail and will require fewer exogenous assumptions.

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