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**A Technical Overview of Cogeneration:
The Hardware, The Industries, The Potential Development**

prepared for
Department of Energy
Division of Industrial Energy Conservation
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MASTER

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INTRODUCTION

Cogeneration, the simultaneous production of more than one form of useful energy, has long been used by industry as a means of producing both electric and thermal energy to meet on-site process needs. Also known as total energy systems, integrated energy systems, dual-purpose powerplants, and waste-heat utilization systems, cogeneration systems provided over 15 percent of the nation's electric energy in 1950; in recent years, however, that fraction has declined gradually to a current 5 percent.

The Department of Energy (DOE) has initiated several programs aimed at promoting energy conservation in industry. Because the by-product heat from a power-conversion process is captured for productive use in a cogeneration system, instead of exhausted to the environment as it is in a conventional powerplant, cogeneration represents an important energy-conservation technique. By cogenerating, an industrial plant can save the fuel that would have been needed to produce the amount of heat captured.

Recognizing the significant energy-savings potential offered by cogeneration, DOE has undertaken a major research, development, and demonstration (RD&D) program to investigate and promote cogeneration in industry. Resource Planning Associates, Inc. (RPA), has been working with DOE to accomplish four of the program's major objectives:

- Survey current, near state-of-the-art, and future cogeneration equipment, and identify any gaps or deficiencies
- Characterize the energy requirements of the manufacturing sectors of five of the country's most energy-intensive industries (specifically, chemical, petroleum refining, paper and pulp, textiles and food and kindred products*)
- Identify principal targets for, and barriers, to the increased market development of cogeneration systems
- Estimate the potential maximum and the probable energy savings that could be achieved in the five selected industries through cogeneration.

* These five industries were chosen not only because they are among the largest users of energy in the United States, but also because they contain a mix of plant sizes and load profiles.

In performing this study, we conducted an extensive literature search; interviewed hardware manufacturers and industrial-plant owners and operators; and visited industrial plants that are currently using cogeneration systems. In addition, we assessed the effects of economic and institutional barriers, as well as potential government actions, on the probable development of cogeneration, relying heavily on the findings of RPA's recent study of the potential for cogeneration development in six major industries, conducted for the Federal Energy Administration (FEA)¹.

Based on our research and analysis, we have estimated that the widespread application of cogeneration technology in the five industries studied could result in a maximum potential savings of 2.4 million barrels of oil equivalent per day (or a maximum incremental capacity of 140,000 MWe) by 1985. To estimate the probable level of cogeneration development, we incorporated economic, institutional, regulatory, and technical considerations into our analysis.

With a moderate degree of government incentives* and varying technology mixes (see Exhibit A), probable cogeneration development can range from 9,500 to 20,000 MWe in 1985. These incremental capacities translate into probable energy savings ranging from 0.20 to 0.60 million barrels of oil equivalent per day in 1985.

In investigating cogeneration hardware, we concentrated on three specific technologies: steam turbines, gas turbines, and diesel engines. Of these three technologies, the steam turbine is currently the most widely used in industry. Although the gas turbine and diesel engine offer even greater energy-savings potential, as a result of their high electric-to-thermal ratios, their applications has to date been limited.

One of the major barriers to the widespread application of gas turbines and diesel engines is that they generally require premium fuels. Although some gas turbines have dual-fuel capabilities (i.e., can burn either natural gas or petroleum distillates), they

1 Federal Energy Administration, The Potential for Cogeneration Development in Six Major Industries by 1985, prepared by Resource Planning Associates, Inc., Cambridge, Massachusetts, November 1977.

* Defined as: 30-percent investment tax credit (ITC); clarification of Federal Power Commission (FPC)/Public Utility Commission (PUC) jurisdiction for non-exporters; and an equitable price for export to the grid. The 20-percent ITC included in currently proposed legislation is anticipated to have a relatively small effect on market development.

Exhibit A

COGENERATION SAVINGS COMPARED TO TECHNOLOGY MIX (1985)

TECHNOLOGY MIX	TOPPING OF PROCESS STEAM	TOPPING OF PROCESS HEAT	BOTTOMING OF WASTE HEAT
Minimum saving	100 percent steam turbine	100 percent gas turbine	100 percent steam Rankine
Present	90 percent steam turbine 10 percent gas turbine	100 percent gas turbine	100 percent steam Rankine
Improved	75 percent steam turbine 15 percent gas turbine 10 percent diesel	50 percent gas turbine 50 percent diesel	50 percent steam Rankine 50 percent ORC-toluene
Highly improved	50 percent steam turbine 50 percent diesel	50 percent gas turbine 50 percent diesel	50 percent steam Rankine 50 percent ORC-toluene

are unlikely to gain wide market acceptance until they are able to burn coal-derived gases or liquids and residual oil. Currently, gas turbines are used primarily in the petroleum and chemical industries. Diesel engines are not widely used by any of the industrial sectors studied, and are not likely to gain market acceptance until they are able to burn liquefied, gasified, solvent-refined, or pulverized coal. Research is presently under way to develop gas turbines and diesel engines that have these capabilities.

In the industrial sectors studied, the back-pressure steam turbine (or extraction non-condensing turbine) matches thermal and electrical demand most accurately and is therefore the most widely used type of cogeneration hardware. One factor, however, limits the applicability of the steam turbine for small users -- it is not economically competitive with the gas turbine or diesel engine in the 5 MW-or-less power range.

General consensus among industry representatives is that federally funded research should focus on developing hardware with multi-fuel capability (including the capacity to burn non-distillate fuels); improving the operation cycle time (i.e., availability and reliability) of hardware, reducing initial capital and maintenance costs, and further developing energy storage techniques to compensate for load fluctuations. Improving the efficiencies of the various technologies seemed to be less important to industry managers. All agreed, however, that it is essential that industry be kept informed of technological advances in cogeneration hardware.

Government policy towards coal conversion will significantly affect the development of cogeneration. In general, mandatory conversion to coal is likely to encourage cogeneration by increasing the use of direct coal-fired steam turbines. However, such a policy would not maximize the potential savings available through cogeneration. If exempted from the requirement to convert plants to coal, industry would be able to use oil and gas, thus gas turbines and diesel engines, which offer greater energy savings.

In anticipation of a potential loss of their baseload, utilities are becoming more receptive to cogeneration joint ventures, and are considering both in-plant and centrally located powerplant systems. However, several important issues and concerns must be resolved if operating agreements are to be reached and market development is to proceed. These issues relate to:

- Management and operational control of equipment with assurances to industry of a reliable source of thermal energy
- Delays associated with environmental and siting regulations and procedures

- Power of state agencies to prohibit the sale of industrially generated excess power.

This final report presents the conclusions of our study in detail, supported by the methodology and data that provided the basis for our analysis. In Chapter 1, we identify plant characteristics, energy supply and demand, current and possible uses of cogeneration, and current or anticipated problems in each of the five selected industries. In Chapter 2, we identify cogeneration systems, their performance, fuel requirements, availability, and reliability, as well as the environmental consequences of hardware that has significant potential for commercialization. We cover technologies that are available, those that are close to commercialization, and those that are still in the early stages of development. In Chapter 3, we analyze the choice of specific hardware for topping of process heat and process steam, and bottoming of waste heat for the five industries. Chapter 4 contains our estimates of the maximum and the probable energy savings that would result from the increasing application of cogeneration in the five industries. Several possible technology mixes are considered.

1. INDUSTRIAL REQUIREMENTS

In this chapter, we discuss the potential for cogeneration in the chemical, petroleum refining, paper and pulp, textile, and food and kindred products industries. Our information was derived mainly from interviews with managers and visits to plants.

We chose to analyze these five industries because they were all among the ten largest energy users in the country in 1976 and because they all apparently required enough thermal and electric energy to make cogeneration an economic option. Beyond these similarities, the industries show important variations which gave us the opportunity to consider different configurations of cogeneration equipment. For example, some of the industries (e.g., petroleum refining) have a wide range of plant sizes, while others (e.g., food and kindred products) have mainly small plants. Some have relatively stable production processes, while others have frequent modifications that increase the opportunities for the introduction of new equipment.

Furthermore, while the chemical and textile industries are geographically concentrated; petroleum is somewhat dispersed; and food, and paper and pulp are widely distributed throughout the country. These differences are also important, because a widely distributed industry can minimize the effects of regional differences in energy policies or prices. Where industrial plants are concentrated in particular areas of the country, the price and availability of fuel, and environmental and regulatory controls can restrict the development of cogeneration equipment.

Our investigation of these five industries showed that managers had certain common concerns that tempered their enthusiasm for cogeneration:

- Cogeneration technology is not well known
- Fuel supplies and prices are uncertain
- Fuel flexibility will be increasingly important, and cogeneration equipment will have to demonstrate this characteristic
- Steam turbines are currently used in cogeneration systems in all five industries because they match the thermal and electrical demand more accurately than other equipment. However, steam turbines do not always satisfy the electrical demand of most plants and back up electricity must be purchased.
- Gas turbines and diesels, which would satisfy demand for electricity better than steam turbines, are perceived to be expensive to buy and operate, to require scarce or unavailable fuels, and to have restricted power levels. None of the five industries makes much use of diesels.

- Export of surplus electricity, which might make gas turbines and diesels economically more attractive, is seen to face technical, institutional, and regulatory barriers. In particular, the control of operation (plant manager vs. utility manager) is seen as an obstacle.
- Improved energy storage systems, which might also make gas turbines and diesels economically more attractive, are not yet available.
- Energy conservation measures (both for processes and house-keeping), which have recently been instituted in all five industries,* may have both positive and negative effects on the market development of cogeneration. On the one hand, managers who have recently invested in new equipment may not be ready to invest in additional equipment for cogeneration. On the other hand, where modifications have reduced thermal demand, plant load profiles may be better matched to gas turbine or diesel cogeneration systems. Furthermore, in such cases, smaller and cheaper cogeneration equipment may be adequate.
- Cogeneration may require the burning of additional fuel which (while leading to a net reduction in air emissions in the area) would lead to increased air emissions at the plant site. This increase might lead to siting and environmental problems.
- The electric grid may be the most reliable and flexible source of electricity.

All five industries show certain common trends that will affect the market development of cogeneration systems. For example, patterns of fuel consumption changed in a similar manner between 1972 and 1976. According to data from the American Manufacturing Association (see the following sections of this chapter for specific data on each industry), the use of natural gas declined considerably and was partially replaced by petroleum, the use of electricity increased, and the use of coal decreased slightly (except in the food industry). Changes will continue over the next few years: natural gas will continue to decline, but coal will almost certainly increase. The future fuel mix is hard to predict and this uncertainty is reflected in management decisions on combustion equipment.

In addition to such long-term uncertainties, all of the industries face short-term uncertainties in production processes and schedules. These fluctuations lead to mismatches between thermal and electrical demand that occur on an hourly, daily, or seasonal basis. These mismatches varied so much within each of the five industries that they must be considered on a plant-specific basis. However, mismatches generally reduce the potential for cogeneration.

* Between 1972 and 1976, the net reductions in the use of fuel in these five industries ranged from 9 to 12 percent.

Plants presently must compensate for these mismatches by going outside the cogeneration system. They can either add extraction-condensing turbines or process steam boilers; or purchase supplemental electricity from the grid.* All of these options impose an economic penalty, thus it is important to choose cogeneration hardware that best matches the thermal and electrical load at any plant.

In the rest of this section, we summarize those characteristics of the five industries that have the greatest bearing on their suitability for cogeneration. Exhibit 1-1 shows their thermodynamic and electrical profiles, expressed first as ranges of actual characteristics and then as the characterizations we selected for this study. Exhibit 1-2 shows the variation in the electric-to-thermal ratio as the demand for electricity changes. For this exhibit, we ran a regression analysis on each set of industry data (plant distribution) to obtain a smooth curve; the curve for each industry is analyzed in the sections that follow. Waste heat** profiles for each industry are shown in Exhibit 1-3.

The remaining sections of this chapter discuss the five industries individually. We discuss production processes; use of energy for process steam, process heat, and electricity; current experience with cogeneration (including problems that may have arisen); and opportunities for additional use of cogeneration. We also discuss the methodology we used for arriving at the thermodynamic and electrical variables for each industry. Finally, we consider the waste heat profiles and the changes in electric-to-thermal ratios that accompany changes in plant size.

* The integration of improved energy storage into cogeneration systems would solve some of these problems.

** Waste heat is any thermal energy rejected from a manufacturing process. At temperatures over 250°F, this energy can be captured efficiently by waste recovery equipment.

Exhibit 1-1

INDUSTRIAL CHARACTERIZATIONS

Industry	Firms Contacted	A. Avg. steam demand 10 ³ (lb/hr)	B. Avg. electric demand (MW _e)	C. Operation time (hr/wk) ¹	D. Process temp. conds. (steam) (°F)	E. Process steam pressure (PSIG)	F. Process temp. conds. (heat) (°F)	G. E/T* (10 ⁻²)	Characterization used in this study			
Chemical (SIC-28)	25	30-2,500	5-25	168	280-390	50-200	100-600 1,000-2,000	1.5-15	A. 700 D. 360	B. 40 E. 150	C. 168 F. 1,000	G. 10
Petroleum Refining (SIC-2911)	6	250-3,500	10-150	168	280-360	50-150	100-1,500	1-2.7	A. 1,000 D. 360	B. 60 E. 150	C. 168 F. 1,000	G. 2.5
Paper/Pulp (SIC-26)	10	500-2,500	15-100	168	250-360	30-150	1,500-2,000	10-30	A. 1,000 D. 360	B. 50 E. 150	C. 168 F. 1,500	G. 12
Textiles (SIC-22)	3	50-200	5-10	120-144	240-360	25-150	100-600	7-20	A. 150 D. 360	B. 6 E. 150	C. 130 F. 200	G. 15
Food (SIC-20)	4	5-180	4-12	120-168	280-345	50-125	100-1,000	1.5-25	A. 100 D. 280	B. 4 E. 50	C. 120 F. 300	G. 20

* Electric to total thermal ratio (each quantity in Btu/hr).

Source: Discussions with Industry.

INDUSTRIAL ELECTRIC DEMAND
COMPARED TO ELECTRIC-TO-THERMAL DEMAND
(Plant distribution and regression line)

Exhibit 1-3

WASTE HEAT PROFILES/1977 (10¹² Btu/yr)

Industry	Temperature range, (°F)				Total
	<150	150-300	300-600	>600	
Chemical (percent)	540 22	1,188 49	611 25	108 4	2,447 100
Petroleum (percent)	147 13	428 39	247 23	280 25	1,102 100
	<200	200-500	>500		
Paper/pulp (percent)	1,400 61	760 33	120 6		2,280 100
Textile (percent)		180 100			180 100
Food (percent)	800 74	160 15	120 11		1,080 100

CHEMICAL INDUSTRY

The chemical industry (SIC 28) is very diverse, with over 11,000 plants of 1,300 companies producing over 10,000 products. The chemical industry is divided into eight major classifications as shown in Exhibit 1-4. There are plants in almost every state, with the heaviest concentration of large plants in the West South Central Region which accounts for 16 percent of total sales. Other regions with large chemical complexes, but smaller plants, are the Middle Atlantic, East North Central, and South Atlantic which together account for 60 percent of sales.

Exhibit 1-4

CHEMICAL INDUSTRY:
FUEL AND PURCHASED POWER CONSUMPTION/1970

SIC Category	Chemicals in Group	Feedstock, Fuel, Purchased Power* (10 ¹² Btu)	Percent of Total
281	Industrial chemicals (organic/inorganic)	2,585.5	80.6
282	Plastics/synthetics	346.4	10.8
283	Drugs	54.4	1.7
284	Soaps/detergents	41.7	1.3
285	Paints, varnishes	25.7	0.8
286	Gum/wood chemicals	6.4	0.2
287	Agricultural chemicals	64.2	2.0
289	Miscellaneous chemicals (preparations, carbon black)	83.4	2.6
Total		3,207.8	100.0

* Purchased power based on 34 percent theoretical fuel efficiency.

Source: Cullihson, F.S. Review of Chemical Industry's Requirements for Energy, Chemical Marketing and Economics, Reprints, American Chemical Society, 1976.

The chemical industry used more energy than any other industry in 1976 (3.2 quads). The first two major classifications together used 92 percent of the total fuel and purchased power for the chemical industry in 1976. Through interviews with plant managers, we found that one cannot generalize about the ways in which electricity, process steam, or process heat are used in production. Exhibit 1-5 shows the types of energy used by the chemical industry in 1972 and 1976.

Exhibit 1-5

ENERGY INPUTS TO THE CHEMICAL INDUSTRY

Fuel	1972 (10 ¹² Btu)	Percent	1976 (10 ¹² Btu)	Percent
Natural Gas	1,569.6	47.2	1,310.4	40.9
Distillate Fuel Oil	30.5	0.9	54.3	1.7
Residual Fuel Oil	173.9	5.2	191.6	6.0
Coal	317.7	9.6	280.5	8.7
Electricity	696.8	21.0	769.1	24.0
Steam	133.8	4.0	144.5	4.5
Propane	17.9	0.6	13.1	0.4
Other Liquified Petroleum Gases	6.7	0.2	11.3	0.3
Coke	7.7	0.2	6.5	0.2
Other Gases	333.0	10.0	352.4	11.0
Other Liquids	26.8	0.8	60.2	1.9
Other Solids	10.0	0.3	13.9	0.4
Total	3,324.4	100.0	3,207.8	100.0

Source: Manufacturing Chemists Association, Industrial Survey of Energy Usage. Prepared for the FEA, Office of National Energy Conservation, June 1977.

In 1976 these inputs were converted into electricity, process steam and process heat in the following pattern:

<u>Energy</u>	<u>Percent</u>	<u>10¹² Btu</u>
Electricity	18.3	509
Process steam	51.2	1427
Process heat	30.5	849
TOTALS	100.0	2785

Of the five industries we studied, the chemical industry has the greatest diversity of cogeneration applications. Some chemical plants have jointly produced steam and electricity for 80 years. Steam turbine-generator sets burning coal, oil, or gas and gas turbine-generator sets burning gas or oil have been employed for process steam topping. Waste heat recovery also has been used.

Our plant surveys showed that only 13 percent of the electricity and only 11 percent of process steam are provided through cogeneration. A large number of chemical plants have steam flow demands below the level (70,000 pounds per hour) currently considered the minimum required for cogeneration. Also, some chemical plants are farther than five miles from any other industrial plant or utility, limiting the chemical plant's ability to sell steam.

These three factors constrain development of cogeneration in this industry. Load mismatch, power failures, and peak load usage further reduce the potential for topping of process steam by 15 percent.

Waste heat recovery equipment provided about 10 percent of the process steam used in the chemical industry in 1976. This heat is found primarily in cooling water and is transferred either to cooling towers or to natural bodies of water. The sources of waste heat are distillation condensers, compressor coolers, reactor cooling coils and product coolers. However, in a typical chemical plant, these sources of waste heat are small and widely dispersed.

The comparison of electric-to-thermal ratio with electric demand (see Exhibit 1-2 shows large dispersion within the industry. At the one extreme, there are large-sized plants with slowly increasing thermal demand. Gas turbines and diesels are well-suited to satisfy these plants' electric-to-thermal requirements. On the other hand, for those plants that have small electric demands, but a balanced thermal demand, the steam turbine would best meet their requirements. In general, most of the plants surveyed clustered in the range where gas turbines and diesel engines could be most attractive.

PETROLEUM REFINING INDUSTRY

Petroleum refining (SIC 2911) is one of the most complex and technically sophisticated industries in the United States. There are currently about 250 U.S. refineries, including fully integrated, highly complex plants, capable of producing a complete range of petroleum products and some petro-chemicals; as well as very simple plants, capable of producing only a small number of products. Production ranges from a few hundred barrels per day (BPD) to over 400,000 BPD. Some refineries are modern, while others contain processing units constructed over 40 years ago. The types of crude oil refined also vary greatly.

The number of refineries in the United States has decreased in the last few decades, while the average size of a refinery has increased. Few new refineries have been built in the past five years; however, changes have been made in existing refineries to reflect changing technology and product demand. Although several new facilities are planned, many such projects have been either cancelled or greatly delayed, primarily because of unresolved environmental and energy issues. The rapid increase in costs has contributed to the decline in the construction of new refineries.

Although practically every refinery has its own capacity, processing configuration, and product mix, refineries in three regions (Northeast, South, or West) do tend to have some common characteristics. Refineries in the Northeast are the only ones that extract aromatics. They also refine more fuel through desulfurizing processes and catalytic reforming than refineries elsewhere. Southern (Gulf Coast) refineries produce

more fuel through distillation than other refineries. Western refineries produce more fuel through hydrocracking and coking. Process heat is used primarily in crackers and reformers.

The distribution of input fuels is shown in Exhibit 1-6. Since 1972, the petroleum industry has increased the efficiency of its use of energy by 12 percent. In 1976, these inputs were converted to electricity, process steam, and process heat in the following pattern:

<u>Energy</u>	<u>Percent</u>	<u>10¹² Btu</u>
Electricity	2.2	74
Process steam	18.7	624
Process heat	79.1	2641
TOTALS	100.0	3339

Exhibit 1-6

ENERGY INPUTS TO THE PETROLEUM INDUSTRY

Fuel	1972*	Percent	1976**	Percent
	(10 ¹² Btu)		(10 ¹² Btu)	
Crude Oil	2.9	0.1	2.8	0.1
Distillate Oil	17.4	0.6	27.0	0.9
Residual Oil	264.4	9.1	278.5	9.7
Liquified Petroleum Gas	29.1	1.0	42.4	1.5
Natural Gas	915.4	31.5	738.2	25.6
Refinery Gas	1,060.6	36.5	1,100.0	38.2
Petroleum Coke	427.2	14.7	433.1	15.0
Coal	5.8	0.2	4.7	0.2
Purchased Steam	2.9	0.1	38.2	1.3
Purchased Electricity	180.2	6.2	214.5	7.5
Total	2,905.9	100.0	2,879.4	100.0

* Estimated-based on a sample of 51 companies which operate 93% of current U.S. petroleum refinery capacity.

** Unadjusted for product mix and processing changes.

Source: American Petroleum Institute, Industry Survey of Energy Usage, Prepared for the FEA, Office of National Energy Conservation Programs, June 1977.

From our plant surveys, we found that only 7 percent of electricity and 3 percent of process steam are produced by cogeneration. Approximately 28 percent of total process steam is generated by waste heat recovery boilers. The types of cogeneration equipment presently used include steam and gas turbine-generator sets, both with waste-heat recovery boilers. However, due to load mismatches, the potential for topping of process steam is reduced by 10 percent.

Since the construction of new refineries has slowed, cogeneration will probably be introduced only when processes are modified to account for new fuels and products. For example, by 1985, natural gas will be phased out as a refinery fuel and tetraethyl lead as a gasoline additive.

Exhibit 1-7 shows the pattern of energy use in the refining industry in 1974 and projected to 1985. Consumption of fuel and electric power is estimated to be about 18 percent higher in 1985. This increase will be due primarily to the upgrading of catalytic reformers to make unleaded gasoline.

Exhibit 1-7

PATTERN OF REFINERY ENERGY USE

	East Coast		Gulf Coast		West Coast	
	1974	1985	1974	1985	1974	1985
Crude run, 10 ³ BPD*	188	198	222	218	155	164
Purchased natural gas, BPD	2,500		5,400		6,390	
Refinery fuel, BPD						
Gas	4,810	6,990	5,450	6,880	7,190	7,500
Oil (blended)	7,210	9,640	5,350	10,700	2,140	11,690
Total fuel, BPD	14,520	16,630	16,200	17,580	15,720	19,190
Purchased steam, 10 ⁶ lb/day	5.6	5.7	0.5	0.5	0.7	0
Electricity, MWh/day	713.7	838.7	744.2	875.1	766.8	897.3

*Barrels per day

Source: U.S.E.P.A., Office of Research and Development, Environmental Considerations of Selected Energy Conserving Manufacturing Process Options: Volume IV, Petroleum Refining Industry Report, December 1976.

The comparison of electric-to-thermal ratio with electric demand (see Exhibit 1-2) shows that as electric demand increases, thermal demand also increases, but not as fast.

The trend toward larger plants means that the demand for electricity will increase faster than demands for thermal energy. Furthermore, if we project recent trends in the energy mix into the near future, we can expect an increase in the amount of coal used. On the basis of these trends, we can see that the petroleum refining industry could use cogeneration equipment with a high electric-to-thermal output ratio (i.e., gas turbines or diesel engines) that can burn coal derived products.

PAPER AND PULP INDUSTRY

The paper, pulp, and allied products industry (SIC 26) encompasses the production and sale of pulp derived from wood and other fibrous raw materials; the manufacture of paper and paperboard products from pulp and waste; and the conversion of paper and pulp into end products such as boxes, writing paper, and sanitary tissue. It is the fourth largest purchaser of electricity and fuels (and the third largest user of water) among all U.S. industries. However, it is the only U.S. industry that uses significant amounts of its waste materials as fuel.

We consider papermaking and pulping separately because the alternative pulping processes that can be used to make a given product differ considerably in energy requirements, but papermaking processes do not.

For example, about 3.5 times more energy is needed to pulp virgin fiber as is needed to pulp secondary fiber, but the energy used in making paper is about the same regardless of the kind of pulp used. Electricity and process heat are used for drying, heating and packaging in the paper and pulp mills. Also, the process steam and heat are used primarily in the chemical transformation of wood into pulp.

The amount of energy used in each of the major pulping processes is shown in Exhibit 1-8. Both unit energy requirements and total annual use (which is a function of the amount of product made by each process) are shown. The total energy required to manufacture one ton of kraft pulp is significantly greater than that required for a ton of semi-chemical or mechanical pulp. However, the purchased energy requirement for kraft pulp is significantly less than for semi-mechanical or mechanical pulp. Moreover, because kraft manufacture is by far the largest segment of the industry in terms of total production, it is also largest with respect to total annual purchased energy. Within the kraft pulping process, the integrated and market pulp segments of bleached kraft are the largest; other segments, notably unbleached kraft and dissolving kraft, are comparatively minor.

ENERGY USE FOR SLUSH PULP PRODUCTION/1974

	Unit Consumption (10 ⁶ Btu/ton)				Annual Total (10 ¹² Btu)		
	1974 Production (000 tons/yr)	Total Unit Energy ^a	Recovered Energy ^b	Purchased Energy	Total	Recovered	Purchased
I. Wood Pulp							
A. Chemical pulp - Kraft							
Bleached and semi-bleached							
Integrated	10,800	27.0	15.0	12.0	292	162	130
Market pulp, & dried transfers ^d	4,700	27.0	15.0	12.0	127	71	56
Dissolving pulp	800	32.0	17.0	15.0	26	14	12
Sub-total, bleached and semi-bleached	16,300	27.0	15.0	12.0	445	247	198
Unbleached	16,980	18.0	14.0	4.0	306	238	68
Total Kraft Pulping	33,280	23.0	15.0	8.0	751	485	266
B. Chemical pulp - other							
Sulfite							
Integrated	1,610	21.0	10.0 ^c	11.0	34	16	18
Market pulp & dried transfers ^d	700	21.0	10.0 ^c	11.0	15	7	8
Dissolving pulp	970	28.0	17.0	11.0	27	16	11
Sub-total, sulfite	3,280	23.0	12.0	11.0	76	39	37
Semi-chemical	3,790	15.0	1.0	14.0	57	4	53
Total Other Chemical Pulping	7,070	19.0	6.0	13.0	133	43	90
C. Mechanical pulp							
Groundwood (bleached & unbleached)	4,490	15.0	1.0	14.0	67	4	63
Defibrated/exploded & other	3,380	4.0	0	4.0	14	0	14
Total Mechanical Pulp	7,870	10.3	0	8.6	81	4	77
II. Waste Paper							
A. De-inking	2,200	4.0	0	4.0	9	0	9
B. Non-deinking							
Old-corrugated containers	5,700	4.0	0	4.0	23	0	23
News, mixed, pulp substitute	6,300	3.0	0	3.0	19	0	19
Total Waste Paper	14,200	3.6	0	3.6	51	0	51
Total All Wood Pulp & Waste Paper	62,420	16.3	8.5	7.8	1,016	532	484

Notes:

- a Total unit energy based on estimated existing industry average 10 percent higher than mill requirements.
- b The purchased fuel equivalent of steam and power generated from spent pulping liquors, bark, and hogged wood. Recovery efficiency for existing industry average estimated at 90 percent of new mill efficiency.
- c Recovered energy for sulfite mills based on heat recovery for 75 percent of existing paper-guide capacity and 100 percent of existing dissolving capacity.
- d No drying included. Dried transfers refer to intra-company pulp shipments of market pulp.

Source: 1974 production, Statistics of Paper and Paperboard, American Paper Institute, 1975.

Exhibit 1-9 shows the energy used in converting the intermediate product, pulp, into paper and paperboard products. Exhibit 1-10 lists the total energy use by type. Between 1972 and 1976, the energy obtained from waste wood materials increased from 41.6 percent to 44.9 percent of the total energy used.

Exhibit 1-9

ENERGY USE FOR PAPER PRODUCTION

	1973 Production (000 tpy)	Unit Consumption, (10 ⁶ Btu/ton)			Annual Total (10 ¹² Btu)		
		Steam & Extracted Power	Purchased Electricity	Total Unit Energy	Steam & Extracted Power	Purchased Electricity	Total Energy
Newsprint & uncoated groundwood	4,800	12.0	0.7	12.7	58	3	61
Printing and writing	12,000	14.0	0	14.0	168	0	168
Packaging & industrial converting	5,940	15.0	0	15.0	89	0	89
Tissue and toweling	3,900	11.0	1.5	12.5	43	6	49
Linerboard	13,200	13.0	0.5	13.5	172	7	179
Corrugating medium	5,260	12.0	1.0	13.0	63	5	68
GIS board	3,660	14.0	0	14.0	51	0	51
Recycled boxboard	5,540	14.0	4.0	18.0	78	22	100
Construction paper and board	5,130	10.0	4.0	14.0	51	21	72
All other paperboard	1,060	12.0	4.0	16.0	13	4	17
Dissolving pulp	1,770	8.0	0	8.0	14	0	14
Market pulp and transfers	5,400	8.0	0	8.0	43	0	43
Total paper, board, and machine dried pulp	67,660	12.3	1.9	14.2	843	68	911

Source: 1974 Production, Statistics of Paper and Paperboard, American Paper Institute, 1975.

Exhibit 1-10

ENERGY INPUTS TO THE
PAPER AND PULP INDUSTRY

Fuel	1972 Percent	1976 Percent
Purchased Electricity	7.3	9.6
Purchased Steam	1.7	1.6
Coal	17.4	18.4
Residual Fuel Oil	36.6	41.8
Distillate Fuel Oil	1.6	1.5
LPG	0.2	0.1
Natural Gas	36.3	28.4
Other Purchased		0.2
Energy Sold	(1.1)	(1.6)
Total	100.0	100.0

Source: American Paper Institute, Prepared
for FEA, Office of National Energy
Conservation Programs, June 1977.

In 1976, these inputs were converted to electricity, process steam, and process heat in the following pattern:

<u>Energy</u>	<u>Percent</u>	<u>10¹² Btu</u>
Electricity	11.8	201
Process steam	82.3	1401
Process heat	5.9	100
TOTALS	100.0	1702

The paper and pulp industry uses cogeneration more than any of the four industries studied. Traditional back-pressure steam turbine-generator sets and gas turbine-generator sets are the major types of cogeneration equipment presently used by the industry. Back-pressure turbines are supplemented by extraction turbines for peaking. Forty percent of the electricity and twenty percent of the processed steam used were co-generated. From our on-site interviews, we found that the potential for topping of process steam is decreased by 20 percent due to load mismatch, power failures, and peak loads.

Both the back-pressure steam turbines and the gas turbines use high pressure boilers. However, at present, these boilers cannot co-fire wood waste and coal. More research is needed on field-erected and packaged boilers that have that capability. The industry presently uses a large portion of the thermal energy in its waste streams and there is, therefore, only limited opportunity for additional bottoming of waste heat. This can be seen from the relatively low end-of-process temperatures and pressures (see Exhibit 1-3). However, future technical developments could make it possible to capture waste heat from liquid effluents.

Process load requirements for process steam and electricity are becoming more balanced. Steam demands are decreasing, due to energy conservation measures; and electric demands are increasing, due to the use of new manufacturing equipment. In addition, comparison of the electric-to-thermal ratio with the electric demand (see Exhibit 1-2) shows that as plant size increases, the thermal demand changes very little. Thus, for larger plants, gas turbines become more attractive.

TEXTILE INDUSTRY

The textile industry (SIC 22) is extremely diversified, producing a variety of fabrics and fabric blends, as well as a multitude of end products including knit apparel, yarns, and carpets. Textile plants range from highly integrated manufacturing complexes that process natural and synthetic fibers into finished products, to small, non-integrated contract plants (commission finishers) that process goods owned by other producers.

Nearly 90 percent of the U.S. textile plants are in the East and over 40 percent are in the Southeast. The rest are scattered throughout the country. The industry's basic raw materials are wool, cotton, and synthetic fibers. Wool accounts for a small and declining proportion of the materials used by the industry. Cotton is still a major raw material, but its use shows little growth. The use of manmade fibers is growing rapidly.

In transforming a fiber, the industry uses both wet and dry processes. Weaving and knitting are essentially dry processes. Wet processes include sizing, desizing, washing, dyeing, scouring, mercerizing, and bleaching. Both processes are found in most types of mills. All plants surveyed operate intermittently. Exhibit 1-11 presents an energy use profile for all segments of the textile industry.

Exhibit 1-11

**ENERGY INPUTS TO THE
TEXTILE INDUSTRY**

Fuel	1972 Percent	1976 Percent
Bituminous Coal	12.46	12.30
Anthracite Coal	.27	.19
Propane	.93	1.14
Gasoline	.06	.08
Kerosene	.04	.07
Distillate	2.65	4.22
Residual Fuel Oil	15.23	25.26
Crude	.04	
Natural Gas	38.87	25.55
Electricity	28.77	30.68
Other Energy	.68	.51

Source: American Textile Manufacturing Institute, Survey of Energy Usage, Prepared for FEA, Office of National Energy Conservation Programs, June 1977.

The textile industry is the ninth largest industrial user of energy. Four three-digit SIC categories use 66 percent of the energy used by the textile industry: cotton weaving mills, synthetic weaving mills, knitting mills, and textile finishing plants (see Exhibit 1-12). Data on energy and fiber inputs to production were submitted to the American Textile Manufacturing Association by reporting firms for 1972 and 1976. Although production was slightly higher in 1976 than in 1972, less energy was used.

In 1976, these energy inputs were converted to electricity, process steam, and process heat in the following pattern:

<u>Energy</u>	<u>Percent</u>	<u>10¹² Btu</u>
Electricity	33.7	90
Process steam	52.1	139
Process heat	14.2	38
TOTALS	100.0	267

Only 6 percent of the electricity and only 18 percent of the process steam are cogenerated. Small plants (5 MW or less) presently do very little cogenerating. The main type of cogeneration equipment found in textile plants is the back-pressure steam turbine-generator set. There is a recent trend to coal-fired boilers. Little waste heat is available for reuse since most of it is under 250°F (see Exhibit 1-3).

Exhibit 1-12

TEXTILE INDUSTRY:
FUEL AND ELECTRIC ENERGY USE/1971

SIC Code	Industry Group	Purchased Fuel (10 ¹² Btu*)	Purchased Electricity (10 ¹² Btu**)	Total (10 ¹² Btu)	Percent
221	Weaving mills cotton	30.02	57.01	87.03	16.12***
222	Weaving mills synthetic	31.39	58.52	89.91	16.65***
223	Weaving & finishing mills, wool	10.58	5.35	15.93	2.95
224	Narrow fabric mills	3.75	3.54	7.29	1.35
225	Knitting mills	48.79	32.77	81.56	15.11***
226	Textile finishing (except wool)	80.86	16.69	97.55	18.07***
227	Floor covering mills	29.68	9.68	39.36	7.29
228	Yarn & thread mills	20.13	57.89	78.02	14.45
229	Miscellaneous textile goods	23.54	20.23	43.77	8.11
22	Total textile mill products	278.42	261.45	539.87	100.0

* Converted from Census table on the basis of 1 kWh = 3,412 Btu

** Converted from Census table on the basis of 1 kWh = 10,500 Btu (energy required at the generating plant).

*** Total energy use in these categories represents more than 66 percent of textile industry energy consumption.

Source: 1972 Census of Manufacturers.

Under present conditions, intermittent operation implies the need to adjust steam and electric use to maintain high plant efficiency during periods of low steam and electric demands. From our discussions with managers, we found that load mismatch reduces the amount of steam suitable for topping applications by 50 percent.

The comparison of electric-to-thermal ratio with electric demand (see Exhibit 1-2) shows that as plant size increases, the thermal demand increases but not as much as the electric demand. Steam turbine-generators are well-matched to the textile industry's present steam and electric demands. However, for greater energy conversion efficiency and reduction in utility loads, larger plants should consider other types of cogeneration equipment. Gas turbines or diesel engines for topping of process heat could generate a significant portion of the electric demand. The industry is also investigating ways to recover rejected heat from dyeing and finishing operations.

FOOD AND KINDRED PRODUCTS

The food industry (SIC 20) uses 16.5 percent of all U.S. energy, the sixth largest amount of energy of any industrial sector in 1976. The major elements of the industry are:

- Agriculture and fishing
- Manufacturing of food and kindred products
- Wholesale trade

- Retail trade
- Consumption, involving in-home and out-of-home preparation.

We consider only the manufacturing sector.

The manufacturing sector uses steam for cooking, and electricity and heat for evaporating and drying. Most food plants do not operate continuously. They are on-line, on the average, two shifts a day, five days a week; the work schedule is longer from time to time. The range of products is diverse and the amount of energy used to produce them varies. For example, the largest energy-users are beet sugar refining, wet corn milling, and meat packing which, together, use 25 percent of the energy used for manufacturing food.

Beet sugar, wet corn milling, and meat packing remained the most intensive energy users from 1971 to 1974, but their relative positions changed, due to differing degrees of energy conservation, and differing amounts of new plant equipment. Exhibit 1-13 presents the entire set of food processing categories along with their total and relative energy use.

The types of energy used in the industry changed significantly between 1958 and 1974 (see Exhibit 1-14). Purchased fuel declined steadily from 92.0 percent of total energy used to 86.8 percent. The shift from coal and fuel oil to natural gas is evident up to 1971 and reflects the desirability and cost advantage of using natural gas over other fuels. Beginning in 1971, there was a slight shift from natural gas to fuel oil that reflects the difficulties of obtaining natural gas in some areas of the country. During the entire period, the use of electric energy increased as a percentage of total energy. Total energy use increased at an average rate of 2.7 percent per year from 1958 through 1971. From 1971 to 1976, total energy use decreased at an annual average rate of 2.3 percent per year.

In 1976, these inputs were converted to electricity, process steam, and process heat in the following pattern:

<u>Energy</u>	<u>Percent</u>	<u>10¹² Btu</u>
Electricity	20.3	142
Process steam	50.4	352
Process heat	29.3	205
TOTALS	100.0	699

The manufacturing sector of the food industry generates all of its steam in-house. In 1976, about 6 percent of all process steam and 6.3 percent of all electricity were cogenerated. The diversity of the food industry makes it difficult to generalize about the potential for additional cogeneration. However, intermittent operation makes load mismatch an important deterrent. We found from plant surveys that load mismatch reduces the potential for steam topping by 70 percent. Energy storage would help solve this problem.

Exhibit 1-13

**RANK ORDER OF SEGMENTS
OF THE FOOD INDUSTRY BY ENERGY USE /1972**

SIC	Industry	Energy use rank		1972* 10 ¹² Btu
		1974	1971	
20	Food and Kindred Products			
2063	Beet sugar	1	2	88.7
2046	Wet corn milling	2	3	63.5
2011	Meat packing plants	3	1	87.3
2082	Malt beverages	4	8	50.1
2033	Canned fruits & vegetables	5	6	52.6
2026	Fluid milk	6	5	50.5
2051	Bread, cake & related products	7	7	54.2
2075	Soybean oil mills	8	9	43.0
2062	Cane sugar refining	9	11	35.9
2037	Frozen fruits & vegetables	10	12	25.8
2048	Prepared feeds, n.e.c.	11	4	43.7
2079	Shortening and cooking oils	12	15	30.4
2099	Food preparations, n.e.c.	13	13	32.7
2077	Animal and marine fats & oils	14	10	32.9
2022	Cheese, natural & processed	15	19	21.8
2023	Condensed & evaporated milk	16	16	23.0
2032	Canned specialties	17	21	21.2
2086	Bottled and canned soft drinks	18	14	30.3
2016	Poultry dressing plants	19	17	14.5***
2085	Distilled liquor	20	18	21.4
2031	Sausage & prepared meats	21	20	21.2
2047	Pet food	22	**	14.2
2061	Raw cane sugar	23	23	14.2
2065	Confectionery products	24	22	18.2
2038	Frozen specialties	25	**	12.2
2031	Flour & other grain mill products	26	24	13.8
2034	Dehydrated food products	27	28	10.0
2052	Cookies & crackers	28	25	13.3
2095	Roasted coffee	29	26	14.2
2083	Malt	30	29	9.4
2043	Cereal breakfast foods	31	30	8.3
2074	Cottonseed oil mills	32	33	7.0
2035	Pickles, dressings & sauces	33	31	7.5
2024	Ice cream and frozen desserts	34	34	6.1
2021	Creamery butter	35	27	8.5
2066	Chocolate & cocoa products	36	37	5.1
2087	Flavoring extracts & sirups, n.e.c.	37	32	7.9
2017	Poultry and egg processing	38	**	4.4***
2091	Canned & cured seafood	39	36	6.2
2084	Wines, brandy	40	39	3.5
2092	Fresh or frozen package fish	41	40	3.7
2076	Vegetable oil mills, n.e.c.	42	38	4.1
2044	Rice milling	43	41	2.4
2097	Manufactured ice	44	35	3.2
2098	Macaroni and spaghetti	45	43	2.4
2045	Blended and prepared flour	46	42	2.6
2067	Chewing gum	47	44	3.1

* Estimated from U.S. Department of Commerce, 1972 Census of Manufacturers, November 1975.

** Because of a change of definition in the four-digit SIC code energy use for these component industries was not reported in 1971.

*** w/o transportation

Source: U.S. Department of Commerce, 1972 Census of Manufacturers, November 1975.

Exhibit 1-14

**FOOD INDUSTRY:
HISTORICAL ENERGY PROFILE**

Fuel Type	Units	1958	1962	1967	1971	1974	1976
Distillate Oil	percent	NA	4.0	6.6	7.4	8.0	6.9
Residual Oil	percent	NA	12.4	8.2	7.3	7.8	6.7
Total Fuel Oil	percent	22.4	16.4	14.8	14.7	15.8	13.6
Coal	percent	32.5	18.9	24.0	13.6	9.5	7.2
Coke and Breeze	percent	0.2	0.2	0.2	0.2	0.2	0.2
Natural Gas	percent	36.2	43.1	49.8	57.9	57.1	48.4
Other Fuels	percent	1.7	3.3	1.9	1.9	4.2	15.0
Total Purchased Fuel	percent	93.0	91.9	90.7	88.3	86.8	85.0
Net Electricity	percent	7.0	8.1	9.3	11.7	13.2	15.0
Total Purchased Fuel and Net Electricity	percent	100.0	100.0	100.0	100.0	100.0	100.0
Total Purchased Fuel and Net Electricity	10¹² Btu	766.1	802.5	899.6	1,031.3	958.8	887.0

Source: Census of Manufacturers, Fuels and Electric Energy Consumed for 1963, 1967, and 1972; unpublished Annual Survey of Manufacturers data for 1974.

The food industry is highly sensitive to power failures, as the entire production could be lost due to spoilage. Consequently, very reliable and stable sources of power and steam are required. Plant owners have told us that cogeneration hardware has been very reliable, but new hardware must meet higher load factors and have lower downtime.

The comparison of the electric-to-thermal ratio with electric demand (see Exhibit 1-2) shows that thermal demand decreases as the electric-to-thermal ratio increases. This trend suggests that gas turbines and diesels with their greater electric-to-thermal ratios could be more attractive. Appropriately-sized steam turbines would best fit those plants where the electric and thermal demands are in better balance.

2. COGENERATION SYSTEMS

The simultaneous production of electric and thermal energy requires equipment that burns fuel to produce shaft power (for mechanical work, generation of electricity, etc.) and heat. Heat or thermal energy can be used as dry heat for an industrial process or converted to steam. The equipment that makes the bulk of energy used in an industrial energy system is called a prime mover. Steam and gas turbines and diesel engines have been used as prime movers in industry since the 1920s. In recent years, most of these prime movers have operated on natural gas or petroleum fuels. The conventional industrial operation, in which thermal and electrical energy are generated separately, is shown in concept in Exhibit 2-1.

Exhibit 2-1

CONVENTIONAL INDUSTRIAL PROCESS

Steam turbine systems have been used to cogenerate steam and electricity since the turn of the century and are currently used in several industries, including the five we are concerned with in this study. Gas turbines have been used less for cogeneration in the past, but are now increasing in popularity because of their availability, small physical size, and flexibility in application. Until recently, the abundance of natural gas also favored the spread of gas turbines. Diesel engines have been used primarily for generating electricity for commercial buildings, hospitals, schools, and other small applications in this country, but are used extensively by electric utilities in Canada and Europe.

Applications

Electrical and thermal energy can be cogenerated by either or both of two techniques, topping of process steam or process heat or bottoming of processes, also called simply topping and bottoming cycles. In topping cycles, the by product steam or heat from the prime mover (which is coupled to a generator) is then used for plant processes. Topping cycles are significantly more fuel efficient than conventional systems that generate electric and thermal energy separately.

Waste heat from plant processes can be recovered and converted, using bottoming cycles such as Rankine cycles, to generate electricity. Waste heat recovery systems applied directly to gas turbine or reciprocating engine exhaust are also referred to as bottoming cycles. Bottoming cycles also save fuel when compared to conventional systems. Topping and bottoming cycles are shown schematically in Exhibit 2-2.

Exhibit 2-2

COGENERATION
SYSTEMS

The most efficient prime movers for cogeneration, diesel engines and gas turbines, produce a higher ratio of electric-to-thermal energy (E/T) than steam turbines. Diesels and gas turbines generate more electricity per unit of steam (see Exhibit 2-3) than the amount of electric power per unit of steam needed for most industrial plants. Therefore, to use the high efficiencies of diesels and gas turbines, the excess of electric power must be put to productive use, either by selling it to the utility grid, other industries or storing it for later use. The export of surplus energy is not

Exhibit 2-3

TOPPING CYCLES:
Comparison of Electrical Capacity and Process Steam Capacity

currently feasible due to institutional and regulatory barriers. Reducing these barriers would greatly increase the development of cogeneration.

In this chapter, we discuss currently available cogeneration topping and bottoming cycles in terms of major components, thermodynamic performance, fuel usage, future improvements, environmental impacts, and reliability. We cover process topping and bottoming cycles for the following prime movers:

- Steam turbine topping cycles
- Gas turbine topping cycles
- Combined gas/steam turbine topping cycles
- Diesel engines
- Rankine cycles

We also consider two near state-of-the-art technologies, fluidized bed combustion and bi-phase turbines, that are expected to improve the efficiencies and market development of cogeneration, and future technologies that show potential for cogeneration.

We based our assumptions and conclusions on an extensive literature search and on discussions with manufacturers of cogeneration hardware. We also obtained information from site visits to several industrial plants across the country. (See Chapter 3 for a complete discussion of the site visits).

CURRENT TECHNOLOGIES

Steam Turbine Topping Cycles

In recent years, the most common device for the topping of process steam has been the steam turbine. A fossil fuel-fired boiler is used to generate high pressure steam (e.g., 1000°F and 1450 psig), which is then expanded through a steam turbine-generator set to produce electricity and low pressure process steam (see Exhibit 2-4).

Exhibit 2-4

STEAM TURBINE TOPPING CYCLE

Back-pressure steam turbines* are generally used for topping because they are most efficient. Multistaged steam turbines are also used since they permit the extraction of steam at any level of pressure below inlet conditions. Inlet steam throttle conditions can range from 250 psig saturated to 1450 psig, 950°F steam. More electricity can be generated per unit of process steam under high throttle conditions, but the rate of fuel consumption per unit of process steam remains relatively constant over the range of throttle conditions. However, higher steam throttle conditions require slightly more expensive boilers, pumps, and water treatment equipment. The electricity-to-steam ratio under varying throttle conditions is shown below.

Throttle Condition	Electricity-to-Steam Ratio (kWh/10 ⁶ Btu)
1450 psig/950°F	47
850 psig/825°F	28
600 psig/750°F	24

Almost all industrial plants use packaged boilers for steam generation because they are cheaper and easier to install than field assembled boilers. Most packaged boilers cannot be used for steam turbine topping because the pressure and temperature of the steam they generate are too low. Furthermore, they are normally less efficient than field assembled boilers, and, unlike the latter, cannot usually be converted to burn coal economically. It is likely, therefore, that field assembled, coal-fired boilers will be used more and more in industry. These boilers can be designed to burn coal, residual oil, and process wastes, and are suitable for steam turbine topping cycles.

Topping of process steam by a steam turbine requires less incremental fuel per unit of power generated (approximately 4,700 Btu/kWh) than topping with gas turbines or diesel engines, but it cannot produce as much electricity per unit of process steam. The ratio of electricity-to-steam is, however, generally suitable for industrial requirements.

Small steam turbines (less than 5 MW) are significantly less efficient and cost roughly three times as much per kilowatt as large steam turbines. Small steam turbines could be used for topping in small industrial plants, however, combined gas/steam turbine cycles probably have a wider application. Research is now underway to improve the efficiency of small steam turbines and new designs are expected to be available commercially by the mid-1980's.

Increased use of steam turbines for the topping of process steam is not expected to have adverse effects on the environment except where coal is used as a fuel. Sulfur oxides are major pollutants from the burning of high sulfur coal. Fly ash is also a problem. Special emission control systems such as exhaust stack scrubbers will be required in most areas of the country where coal is burned.

* Turbines that exhaust low pressure steam.

Steam turbine technology has been available for several decades and reliability is high. Manufacturers usually recommend minor inspections annually and more detailed inspections every three years. Replacement parts are readily available and thus downtimes are usually short. Maintenance schedules need not be modified for varying throttle conditions or modes of extraction.

Gas Turbine Topping Cycles

The gas turbine is a more direct way to generate electricity than the steam turbine. Fuel, such as oil or natural gas, burned in the combustors of the turbine, heats air that has been previously compressed. The burned mixture expands through a turbine-generator set to produce electricity as shown in Exhibit 2-5.

Exhibit 2-5

GAS TURBINE TOPPING CYCLE

Gas turbines operate at higher temperatures than steam turbines, and their exhaust can be recovered in a variety of ways:

- The exhaust stream can be passed through a heat exchanger (or boiler) transferring its heat to a process fluid such as water/steam, air, or oil. Since the exhaust gas is about 18 percent oxygen by volume, additional fuel can be fired in the exhaust stream to increase initial temperatures, as required by the process.

- The exhaust stream, which is relatively clean and dry, can be used directly for heating or drying.* If lower temperatures or increased volume are desired, the exhaust stream can be mixed with ambient air. If the back pressure of the process is low, a simple inductor is all that is required to provide the dilution air. At higher back pressures, a fan is required. As in the previous case, additional fuel can be burned in the exhaust prior to the process to match various temperature requirements.
- The exhaust stream can be used for space heating or as highly preheated combustion air in boilers, oil heaters, hot gas generators, etc. This method is very efficient, since all the exhaust energy above the ambient temperature would contribute to fuel savings in the combustion device. This method has been used in the petroleum refining industry.
- The exhaust stream, (e.g., at conditions of approximately 900 psig, 830°F), can be passed through a heat recovery boiler to generate process steam.

Current gas turbine power plants operate at thermal efficiencies well below 30 percent and topping cycles have heat rates of 5,500-6,000 Btu/kWh. Optimal performance is achieved at peak rather than base loads. Significant improvement in gas turbine performance as well as fuel flexibility are expected in the near future.

Best performance and least emissions are achieved if natural gas is used as fuel. Clean light petroleum distillates (such as naphtha) also provide acceptable performance and some gas turbines are currently available with fuel flexibility. These turbines can switch without interruption from natural gas to distillates.

New fuel treatment systems will enable gas turbines to use heavier oil distillates as well. These systems remove such trace metals as sodium, potassium, and vanadium (which cause corrosion or deposits) from the crude or residual oil. The contaminated oil is washed and the clean fuel separated by centrifuging or electrostatic separation.

Gas turbines can also be modified to run on low Btu gas (approximately 100-150 Btu/SCF). In Japan, a turbine has operated on blast furnace gas for 35,000 hours and another on coke oven gas for 27,000 hours. Gasification systems that can convert any commercial grade of crude or residual fuel to low Btu gas are under development. Manufacturers recognize that future marketability will be limited unless gas turbines are adapted to burn fuels derived from coal or oil shale as they become available.

* This is important in the food industry.

High temperature, high performance gas turbines are currently limited by the materials from which they are made. Normally, excess air must be supplied in the combustors to keep the temperatures of the blades down. One method that permits firing at high temperatures is the passage of cooling air through holes in the blades. Future turbines may use film cooling and transpiration cooling (in which the cooling air passes through pores in the airfoil and into the boundary layer to insulate the blade surface from hot gas).

Improved blade and nozzle materials, such as ceramics, can also allow higher firing temperatures. A major research effort is underway to use ceramics, principally silicon, nitride, and carbide, in gas turbines, diesels, and other equipment. Ceramics tolerate higher operating temperatures (in the range of 2500°F) resulting in significant increases in heat engine efficiencies. Gas turbine thermal efficiency could increase by 10-15 percent.

We feel that we should point out that the current trends in gas turbine research may not be the most desirable. Current efforts are directed mainly at increasing performance. However, if increased operating efficiency results in higher capital cost, market development may suffer. The industrial managers we spoke to felt that gas turbines needed greater reliability and fuel flexibility more than they needed improved performance.

Use of gas turbines for cogeneration is expected to increase. Petroleum refineries and chemical plants have recently installed them. However, significant market development will be unlikely unless their fuel flexibility and performance are improved. Unless they can operate efficiently on abundant lower grade fuels, gas turbines will not sell well until coal-derived fuels are available. Thereafter, market development will depend mostly on economic factors and the availability of better energy storage systems. The primary demand is expected to be in the 5 to 100 MW range.

The effects on the environment of increased industrial gas turbine topping cycles will depend on the fuels they burn. EPA requirements will limit NOx emissions and the sulfur content of fuels. Better combustors are needed to meet new emissions levels with all fuels except lean distillates and natural gas.

Gas turbines require more frequent maintenance than steam turbines. The combustion system must receive frequent minor inspections; and bearings, rotors, etc. must be inspected at intervals ranging from 5,000 to 10,000 hours, depending upon the type of fuel and the frequency of starting. Major overhauls are required at 20,000 to 75,000 hours. The complete system or its major modules can be replaced without major disassembly on-site.

Combined Gas/Steam Turbine Topping Cycles

Combined gas/steam turbines provide greater flexibility for industrial topping of process steam than either simple gas or steam turbines. Their performance, however, can only duplicate that of separate gas turbine topping or steam turbine topping. Combined gas/steam turbine topping cycles can include special heat recovery boilers that allow the gas turbine exhaust to be used as combustion air, as shown in Exhibit 2-6.

COMBINED GAS/STEAM TURBINE TOPPING CYCLE

Additional fuel is burned in the heat recovery boiler to produce high pressure steam that is then expanded through a back-pressure steam turbine to produce low pressure process steam and electricity. The terms unfired, supplementary fired, and full fired refer to the addition of varying amounts of fuel to the heat recovery boiler for additional energy.

Because of its similarities with gas turbine and steam turbine topping, combined cycle topping was not investigated further in the study.

Diesel Engine Topping Cycles

Topping of process steam or process heat with a diesel engine provides the highest electricity-to steam ratio and is available in a range of sizes from 100 kW to 25 MW. Basic thermal efficiencies are approximately 35 percent, compared to less than 30 percent for gas and steam turbines. Heat rates are in the 6,000-7,000 Btu/kWh range, less favorable than for the other prime movers. However, electricity generation per unit of steam is twice that of gas turbines and more than 10 times that of steam turbines.

The concept of diesel topping is shown in Exhibit 2-7. The diesel engine drives an electric generator. Process steam is made in heat recovery boilers that use the engine exhaust and jacket cooling as heat sources. Diesel engines can be coupled to bottoming cycles such as Rankine cycles or bi-phase to generate additional electricity.

Exhibit 2-7

**DIESEL ENGINE
TOPPING CYCLE**

Diesels currently depend on petroleum based fuels. They can be designed to use both high distillates and low-grade crude and residual oils. Filtering and centrifuging eliminate contaminants that may cause excessive wear in the injection system and in the engine's moving parts. Research is underway on a dual-fuel diesel that can use both liquid and gaseous fuels such as propane, butane, and methane. Research has also started on the use of coal derived fuels; these will be essential to the future market development of diesels.

Ceramic pistons, cylinder liners, and heads would offer other potential benefits, such as improved efficiency, decreased fuel consumption and extended maintenance periods for diesels. Experiments on the use of ceramics in diesels have been conducted in Sweden and are beginning in this country. Ceramics can provide long life at higher pressures and temperatures.

The spread of diesel topping systems will be restrained by two major factors: first, the electricity-to-thermal ratio of diesel engines is significantly higher than most industrial plants need. Diesels will not be economically attractive unless excess electric power can be sold or stored. Second, diesels will also have to convert to more abundant coal derived fuels.

Diesel-generator sets greater than 25 MW have not been commercially available in the U.S. Large "cathedral" diesels have been used in Europe for marine propulsion and generation of electricity. The demand for large diesels may develop in this country with increased industrial incentives for cogeneration. The size of the equipment lessens the advantages of diesel units where space is a premium. Advanced, more efficient units will be lighter and smaller, and will alleviate this problem somewhat.

The environmental impact of diesel topping cycles is minimal if light distillate fuels are burned. Ceramic components will improve combustion and lower exhaust emissions. If coal is used as a fuel, sulfur oxides must be removed from the stack gas to meet emission standards.

The reliability and service life of diesel engines is high. They typically require minor maintenance at 7,000 to 10,000 hour intervals and major overhauls every 20,000 to 30,000 hours. Ceramic components, which would reduce wear on rings and cylinder liners, should extend service life.

Steam and Organic Rankine Bottoming Cycles

Steam and organic Rankine-cycle bottoming systems convert waste heat to electric and useful thermal energy. In the Rankine system, a liquid working fluid is heated and vaporized in a vapor generator at constant pressure. The hot vapor is expanded to a lower pressure in an expander, producing electric or shaft power. The turbine exhaust is then cooled and condensed at constant pressure. The condensed fluid is pressurized by a pump, preheated, and returned to the vapor generator (see Exhibit 2-8).

Exhibit 2-8

RANKINE BOTTOMING CYCLE

Bottoming cycles can be used to recover waste heat from many industrial processes and from diesel engine exhaust and jacket cooling water. Practically all of the Rankine cycle systems currently in commercial use employ steam as the working fluid. They are used for a wide variety of mechanical drive and electrical power generating purposes. These systems have thermal efficiencies from 14 to 36 percent, operate over a temperature range of 400°F to 1000°F, and are greater than 670 hp (approximately 500 kW) in size.

New Rankine cycle systems using organic working fluids are commercially available in a limited number of sizes, ranging from 3,000 to 5,000 hp (approximately 2,000 to 3,800 kW). These operate at much lower temperatures (200°F to 340°F) and so, despite their lower efficiencies (less than 13 percent), can recover waste heat more effectively.

The choice of a working fluid for Rankine cycle heat engines, depends on such factors as the temperature profile of the waste heat and the output power level. Research is being conducted on the use of organic fluids at operating temperatures up to 1000°F and efficiencies up to 20 percent. System characteristics can be improved through further development of fluids, bearing, and seals.

New working fluids or mixtures of existing fluids might reduce the need for superheating and desuperheating, thereby increasing efficiency, reducing heat transfer area, and providing chemical stability at high operating temperatures.

The effects of bottoming systems on the environment include the reduction of thermal pollution of the atmosphere. However, organic Rankine systems working fluids are generally toxic and therefore pose an environmental risk.

The maintenance requirements and reliability of bottoming cycles are generally unknown because there is little commercial experience with these systems to date. However, the technology of the component parts (expansion turbines, fluid pumps, heat exchangers, etc.) is proven and since the systems operate at lower temperatures than conventional systems, reliability is expected to be high.

NEAR STATE-OF-THE-ART TECHNOLOGIES

Fluidized-bed combustion systems and bi-phase turbine cycles are presently under full scale demonstration and will be commercially available by the early 1980's. Fluidized-bed combustion has several advantages that will enhance industrial topping cycles. Bi-phase turbines show promise for bottoming applications as a lower cost alternative to organic and steam Rankine systems.

Fluidized-Bed Combustion Systems

Fluidized-bed combustion (FBC) is an alternative to the conventional water-tube industrial boiler. Although FBC has not yet gained commercial acceptance, several advantages of the technique indicate widespread use in energy intensive industries by 1985. There are three basic FBC schemes applicable to cogeneration.

- Atmospheric pressure FBC
- Pressurized Combined Cycle FBC
- Pressurized Combined Cycle FBC with adiabatic combustion

Both atmospheric and pressurized cycle FBC techniques can be readily integrated into steam turbine and gas turbine cogeneration systems. The advantages of the FBC over conventional boilers are:

- Ability to use compliance and non-compliance (e.g., high sulfur, etc.) coal as well as other low grade fuels, e.g., wood scraps, residual oil, peat, etc.
- Effective direct capture of sulfur dioxide from the combustion of coal
- Significantly lower NO_x emissions than conventional combustion
- Relatively unobjectionable solid wastes
- Ability to be shipped in modules for simple field assembly, even for larger units.

Atmospheric fluidized-bed combustion occurs at normal atmospheric pressure in the temperature range of 1400°F to 1500°F with excess air values of 15-25 percent. The bed consists of a mixture of crushed limestone, dolomite, or inert material, and large ash particles, which is "fluidized" by a stream of air or combustion gases rising from the supporting grid beneath the bed. Steam is produced in tube bundles or water walls located in the fluidized region. Conventional steam turbines convert this steam to electrical energy (see Exhibit 2-9).

Exhibit 2-9

**ATMOSPHERIC
FLUIDIZED BED
COMBUSTION**

Pressurized combined cycle FBC uses a steam turbine and a gas turbine. Combustion occurs in a fluidized-bed unit at temperatures of 1600°F to 1800°F under pressure of 4 to 10 atmospheres. This technology reduces the size, and, thus, the cost of the combustion unit. The hot, high pressure fuel gas, existing from the combustion unit is expanded through a gas turbine to generate electric power. However, conventional steam turbines, driven by steam produced in the bed tubes, produce approximately 80 percent of the total power generated (see Exhibit 2-10).

Exhibit 2-10

**PRESSURIZED, COMBINED CYCLE
FLUIDIZED BED COMBUSTION**

A pressurized combined cycle FBC unit with adiabatic combustion has no water tubes in the combustor. A large volume of combustor air (approximately 300 percent excess air) at a pressure of 4 atmospheres is expanded through a gas turbine for generation of electric power. A low pressure steam turbine bottoming cycle also generates power. Of the total output, approximately 80 percent is due to the gas turbine and 20 percent to the steam turbine (see Exhibit 2-11).

Several large commercial FBC boilers are expected to be in operation by the late 1970s. Pressurized FBC technology is somewhat further behind, with commercial operation expected in the mid-to-late 1980s.

FBCs are expected to spread quickly because they can burn coal, including high sulfur coal, within acceptable emission standards. FBC has excellent potential for cogeneration since gas turbines and steam turbines can be used to make process steam, electricity, and process heat simultaneously.

Exhibit 2-11

**PRESSURIZED, COMBINED CYCLE
ADIABATIC FLUIDIZED BED
COMBUSTION**

Bi-Phase Turbine Bottoming Cycle

The bi-phase power system is similar to a Rankine bottoming cycle, but has several potential advantages. The bi-phase system uses a mixture of liquid and gas as a working fluid to drive a specially equipped turbine. The system features a two-phase nozzle and a rotary separator turbine that extracts work from a vapor containing a finely dispersed liquid. The high mass flow rate and low spouting velocity realize maximum efficiency at low turbine speed. A single stage bi-phase turbine achieves as much net output power at approximately 8,000 rpm as a four-stage organic Rankine turbine at 15,000 rpm or a four-stage steam turbine at 26,000 rpm.

Slower turbines can use cheaper bearings, seals, etc. The bi-phase system has a gas-to-liquid heat exchanger instead of a boiler and thus more exhaust energy is available for conversion. The available energy is greater because heat transfer is to the liquid phase. Variations of the bi-phase power cycle may allow the use of a contact heat exchanger which is cheaper than a tube-fin heat exchanger.

The bi-phase turbine may be up to 50 percent less expensive than organic or steam Rankine bottoming systems in the operating temperature range of 450°F to 1000°F. The advantages of the bi-phase turbine could result in early commercialization.

Components of the bi-phase turbine bottoming cycles are well within the state-of-the-art. Reliability is expected to be high. The cycle will reduce both air and thermal pollution.

FUTURE TECHNOLOGIES

The techniques of cogeneration discussed in previous sections of this chapter have the potential for saving large amounts of energy. Improvements in their reliability and flexibility will broaden their application. Greater fuel flexibility will make them even more attractive to industry. There are, however, other technologies, still in the earliest stages of development, that show promise of eventually finding applications in industrial cogeneration. Among the most promising of these new technologies are improved energy storage, improved Stirling cycle engines, the Lysholm expander, and advanced heat pumps.

Energy Storage Systems

Gas turbines and diesel engines are theoretically the most efficient devices for topping. However, they have a much higher electric-to-thermal ratio than is needed by most industrial processes and they are not truly efficient unless all the energy they generate can be used. Surplus electricity could be exported from the plant, but, in many cases, institutional, regulatory, and technical barriers presently preclude this option.

Such barriers may eventually be lowered, but improved energy storage might be another way to solve the problem of surplus electricity. Improved storage systems would also increase overall system reliability. There are three main objectives for energy storage:

- To improve the salability of electricity by decreasing fluctuations*
- To level loads in-plant (short term storage)
- To use in-plant at some future time (long term storage).

At present, research on storage is principally being performed by public utilities and federal agencies.

Electricity can only be stored if it is converted to some other form of energy--chemical, mechanical, thermal, etc. Current technologies for storing energy are summarized in Exhibit 2-12.

Compressed air and pumped hydro are the cheapest forms of storage for large facilities (200-2000 MW). Lead acid batteries can be used by smaller facilities, and as they improve (between now and 1985), they will be suitable in the 20 MW to 50 MW range. New designs and materials may make flywheels a good form of storage in the 20 MW to 50 MW range as well. Between 1985 and 2000, advanced batteries should raise efficiencies and lower costs considerably. Thermal storage has a longer expected life, but is more expensive. Production and storage of hydrogen will be the least efficient and most expensive technique.

* Utilities traditionally shy away from unreliable sources of electricity. Industries are unwilling to allow utilities to control operations in their plants. Energy storage systems might provide an interface acceptable to both parties.

EXPECTED TECHNICAL AND COST CHARACTERISTICS OF SELECTED ENERGY STORAGE SYSTEMS

Characteristics	Near term					Long term		
	Hydro pumped storage	Compressed air	Thermal steam	Oil	Batteries Lead acid	Advanced	Flywheel	Hydrogen storage
1. Commercial availability	Present	Present	Before 1985	Before 1985	Before 1985	1985-2000	1985-2000	1985-2000
2. Economic plant size (MWh or MW)	200-1000 MW	200-1000 MW	50-200 MW	50-200 MW	20-50 MWh	20-50 MWh	10-50 MWh	20-50 MW
3. Power related costs ^a (\$/kWh)	90-145	120-150	150-240	150-240	70-120	60-70	80-120	400-500
4. Storage related costs ^a (\$/kWh)	2-10	3-10	35-70	10-12	50-60 ^b	20-40	80-150 ^c	6-10
5. Expected life (years)	50	20-25	25-30	25-30	5-10	10-20	20-25	10-25
6. Efficiency ^d (percent)	70-75	(e)	65-75	65-75	60-75	70-80	70-85	40-50
7. Construction lead time (years)	8-12	3-12	5-12 ^f	5-12 ^f	2-3	2-3	2-3	2-3

a. Constant 1975 dollars, does not include cost of money during construction.

b. Could be considerably higher if buildings required to house batteries.

c. These numbers are very preliminary.

d. Electric energy out to electric energy in, in percent.

e. Heat rate of 4,200-5,500 Btu/kWh and compressed air pumping requirements from .58-.80 kWh (in)/kWh (out).

f. Long lead time includes construction of main power plant.

Source: Schneider, Public Service Electric and Gas Company, Near Term Energy Storage Alternatives, presented at the Near Term Energy Storage Technologies Workshop on Lead Acid Batteries, November 18, 1975.

Stirling Engine

The Stirling engine is an externally fired, multifuel, high efficiency closed cycle heat engine. Although the Stirling engine has had thermodynamic efficiencies of up to 39 percent since the late 1950s, only relatively small lightweight units for mobile power applications have been developed. Because of their potential efficiency and durability, Stirling engines are now being developed for stationary power applications.

Large Stirling engines are expected to have efficiencies in the range of 40 to 45 percent. They are expected to be clean and quiet and to operate at low speeds. They can use a variety of fuels (or thermal sources), including petroleum distillates, shale or coal distillates, methane, low Btu gas, powdered coal, waste heat, and solar energy.

Stirling engines can switch from one fuel to another without adjustment, interruption of operation, or loss of power or efficiency. The moving parts of this external combustion system are not exposed to extensive erosion because of the low gas speeds in critical parts of the system. In addition, the Stirling engine can use almost any external heat source with temperatures greater than 1000°F to drive the engine. It could be used for cogeneration as an adjunct to fluidized bed combustion and waste heat recovery systems. It is estimated that cogeneration systems using Stirling engines as the prime mover can save approximately 65 percent of the energy used in conventional generation systems.

Stirling engines have a relatively pollution-free exhaust. The NO_x content of emissions can be further reduced by recirculating part of the exhaust gas. The absence of explosive combustion, the smooth transition between maximum cylinder pressures, and the rhombic drive mechanism that establishes balanced crankcase conditions, contribute to the relative quiet operation (typically 35 to 50 percent quieter than a comparable diesel engine).

It is not anticipated that industrial Stirling engines will become commercially available before 1985. Economics, fuel availability, and environmental factors will dictate the commercial prospect for Stirling engines. Stirling engines are expected to have operational lives of over 20 years. The need for long-term investment could discourage early commercial commitment, however, longevity accentuates the overall economic advantage. Multifuel Stirling engines might be considered insurance against interruptions of petroleum supply.

Lysholm Expander

The Lysholm expander is a high temperature (greater than 2500°F), helical expansion device made of ceramic materials. It will be developed for industrial cogeneration and topping cycles for central powerplants.

The operating speeds and stresses encountered in the helical expander are an order of magnitude less than in conventional turbines. Thus, it can use durable, corrosion resistant ceramic components at high temperatures.

The expander may be driven by a direct, coal-fired Brayton topping cycle which would result in an overall thermal conversion efficiency exceeding 50 percent.

Primary application areas for the Lysholm expander are high temperature topping cycles for combined cycle electric power generation and alternatives to conventional turbines where contaminated combustion products must be tolerated. Combined with a standard steam electric powerplant cycle, a 50 MW topping cycle unit could increase the energy conversion efficiency by 20 percent.

Ceramic helical expanders are especially tolerant of a variety of fuels. They can use solid, liquid, or gaseous fuels which can be derived from coal or other sources. Air pollution must be checked by various control technologies to remove fly ash, and SOx. Exhaust gas scrubbers and precipitators will be needed for emission control as required.

The commercial potential of Lysholm expanders presently is inhibited by the materials limitation on operating temperatures, pressures, steam kinetics, etc. Assuming successful progressive development of high temperature ceramics and satisfactory solution of fabrication and design problems, the devices are expected to be commercially available by 1990.

Advanced Heat Pumps

Heat pumps can be used in industry to elevate the temperature of thermal energy in waste streams. The heat pumps can therefore be used in numerous industrial applications to reduce thermal demands by recovering and transforming low quality waste heat to usable levels.

Federally funded RD&D is presently aimed at improving component efficiencies (compressors and compact heat exchangers), lowering costs, and demonstrating reliability, specifically for use in the temperature range of interest for industrial applications.

Advanced heat pump projects being developed (including prototype design and performance evaluation tests for water-to-air and water-to-water systems), are expected to have a coefficient of performance (COP)* of 3.5 to 5.0. Present systems have demonstrated performance levels up to 3.0. This further increase in performance will make the heat pump a more attractive system. Ultimately, the widespread adoption of the heat pump will depend on how the marginal cost of recovering the available waste heat compares to the marginal cost of conventional supplemental heating techniques.

Advanced high temperature heat pumps are expected to become commercially available in the 1980s and achieve a reasonable degree of penetration in the industrial, commercial and residential markets by 1985.

* Ratio of heat output to power input to the compressor.

3. APPLICATIONS

TOPPING CYCLES

The choice of specific cogeneration technology and hardware for topping can only be made on a plant by plant basis. This is due to plant requirements for thermal and electrical energy, availability of fuel and space, and other site-specific characteristics. Steam and gas turbines and diesel engines differ in thermal and electrical output capabilities (see Chapter 2). The most energy is saved if the equipment is designed to meet in-plant thermal demands and excess electric energy is exported. Thus, energy savings are directly related to the quantity of electrical energy exported.

We compare the demands for process steam and process heat with the demand for electric energy for specific chemical, petroleum refining, paper and pulp, textile, and food processing plants in Exhibits 3-1 through 3-10. Each point represents an average daily demand for process steam or process heat and electricity. These exhibits also show estimated performance curves for steam turbine, gas turbine and diesel engine topping techniques. The performance curves represent an average of manufacturers' stated output performance characteristics. We made assumptions regarding steam pressures and temperatures and process heat temperatures for each industry application (see Exhibit 1-1).

These exhibits show which technology (steam turbines, gas turbines, or diesels), if any, has electric and process steam or process heat outputs that best fit the demands of the various plants shown. In most cases, diesels and gas turbines produce more electricity, per unit of process steam or process heat, than the plant can use. The exhibits also show the size of the surplus for any particular plant. For example, assume power generation equipment was designed to meet a plant's steam demand of 0.6×10^6 lb/hr (see Exhibit 3-1). A steam turbine would generate only 25 MW of electric power, which is 15 MW less than the plant's electric demand (40 MW). A gas turbine, however, would generate approximately 125 MW of electricity, yielding a 65 MW surplus. A diesel engine would generate approximately 290 MW, yielding a surplus of 250 MW.

Steam turbine topping best fits most plant needs in all five industries. Gas turbines best fit the process heat demands of most plants in all the industries except paper and pulp and textiles. Diesels generate the most electricity and also the greatest surplus of electricity that must be stored or sold to the utility grid.

BOTTOMING CYCLES

We evaluated various bottoming cycles for the five industrial groups. Only the chemical and the petroleum refining industries had sufficient

Exhibit 3-1

TOPPING OF PROCESS STEAM:
Comparison of Electrical Capacity and Steam Demand in the Chemical Industry

Exhibit 3-2

TOPPING OF PROCESS STEAM:
Comparison of Electrical Capacity and Steam Demand in the Petroleum Refining Industry

Exhibit 3-3

TOPPING OF PROCESS STEAM: Comparison of Electrical Capacity and Steam Demand in the Paper and Pulp Industry

Exhibit 3-4

TOPPING OF PROCESS STEAM:
Comparison of Electrical Capacity and Steam Demand in the Textile Industry

Exhibit 3-5

TOPPING OF PROCESS STEAM:
Comparison of Electrical Capacity and Steam Demand in the Food Industry

Exhibit 3-6

TOPPING OF PROCESS HEAT:
Comparison of Electrical Capacity and Thermal Energy Demand in the Chemical Industry

TOPPING OF PROCESS HEAT:
Comparison of Electrical Capacity and Thermal Energy Demand in the Petroleum Refining Industry

Exhibit 3-8

TOPPING OF PROCESS HEAT:

Comparison of Electrical Capacity and Thermal Energy Demand in the Paper and Pulp Industry

Exhibit 3-9

TOPPING OF PROCESS HEAT:
Comparison of Electrical Capacity and Thermal Energy Demand in the Textile Industry

Exhibit 3-10

TOPPING OF PROCESS HEAT:
Comparison of Electrical Capacity and Thermal Energy Demand in the Food Industry

recoverable waste heat for bottoming applications. We applied waste heat profiles of these two industries to the operating performance curves of each bottoming cycle (see Exhibit 1-3 and 3-11). The inverse heat rates used for various temperature ranges are shown below:

**Inverse Heat Rate vs. Temperature for
Various Working Fluids**

<u>Temperature</u>	<u>Inverse Heat Rate kWh/10⁶ Btu</u>				
	<u>Bi-phase turbine</u>	<u>Toluene ORC</u>	<u>Freon-11 ORC</u>	<u>Steam Rankine</u>	<u>Fluorinol-85 ORC</u>
less than 150°F	10	21	7	---	19
150°F - 300°F	17	25	20	4	23
300°F - 600°F	35	36	30	24	36
Greater than 600°F	52	53	30	46	45

The electricity output for each bottoming cycle was derived from an aggregation of the inverse heat rates times the waste heat profile. We plotted the outputs against total plant steam demand in Exhibits 3-12 and 3-13.

In both cases toluene yielded the highest output while steam Rankine was the lowest. Fluorinol 85 and the bi-phase turbine also had high performance. For the chemical industry, toluene had more than twice the output of steam bottoming. The difference is less for the petroleum industry.

These estimates are based on assumed average waste heat recovery and efficiency estimates for the industries. Specific plants may have very different waste heat profiles and any of the bottoming cycles might prove most suitable for a particular application. Nevertheless, for most applications, organic working fluids appear to be most efficient.

However, organic working fluids used in Rankine cycles and the bi-phase turbine pose serious environmental concerns that must be considered. Toluene, Fluorinol-85, Freon-11 (used in the Rankine cycle systems), and Dowtherm A (used in the bi-phase turbine) are toxic. Leakage or improper handling may be hazardous to the health and safety of workers, and improper disposal may cause environmental problems. Fluorinol-85 is a most serious hazard to workers since it is absorbed through the skin on contact. Toluene and Dowtherm A are flammable and moderately explosive. Uncontrollable release of these fluids would degrade the quality of water and possibly air. Freon-11 can break down the ozone layer of the atmosphere.

Exhibit 3-11

BOTTOMING CYCLES:
Comparison of Inverse Heat Rate and Source Gas Temperature

Exhibit 3-12

BOTTOMING CYCLES:
Comparison of Electrical Capacity and Process Steam Demand in the Chemical Industry

Exhibit 3-13

BOTTOMING CYCLES:

Comparison of Electrical Capacity and Process Steam Demand in the Petroleum Refining Industry

4. POTENTIAL SAVINGS

The purpose of this chapter is to estimate the potential maximum and probable energy savings that could be realized from cogeneration in five of the most energy-intensive industries. Thus, in looking for the upper limit, we did not consider economic or institutional constraints.*

In the following sections we describe the methodology we used to determine the potential energy savings resulting from the topping of process steam and heat and the bottoming of waste heat. We then estimate the maximum potential savings from each type of application. The sum of these figures is the maximum potential savings that are technically feasible.

However, a portion of this total will be unattainable due to the factors in each industry that inhibit the use of cogeneration. Thus, in the last section of this chapter, we estimate the probable market development as a function of these constraints, the mix of technology, and governmental incentives.

METHODOLOGY

To establish a realistic upper limit for the topping of process steam, we reduced our estimate of the total steam used in the five industries by the amount used in ways that are unsuitable for topping. These uses, which RPA determined through discussions with industrial decisionmakers, are:

- Steam consumed in power generation (e.g., pumps, compressors)
- Process steam presently cogenerated
- Process steam produced by topping cycles
- Process steam produced from waste heat recovery boilers.

There are additional constraints that might reduce the amount of steam technically suitable for cogeneration:*

- Size and geographic distribution of plants
- Plant load fluctuations
- Technical expectations of management

* Although this study does consider such barriers to cogeneration, we did not estimate their effect. That subject was treated in the RPA/FEA study.

For the purposes of this study, we assume that technological advances (e.g., better steam transmission and energy storage, etc.) would eliminate these constraints. In addition, we assume that trends towards greater use of steam (e.g., the replacement of gas dryers by steam dryers) would counterbalance any marginal change due to greater efficiencies and energy conservation efforts. We considered process changes and efficiencies, and conservation efforts in estimating the overall growth rate to forecast 1985 values. We used the same growth rates in estimating 1985 values of topping of process heat and bottoming of waste heat.

Through discussions with manufacturers of prime movers (steam and gas turbines and diesels) we determined net electrical output per unit of process steam (at specific conditions). By multiplying the estimated equivalent of the technically suitable process steam (in Btu per year) by the net power output ratio (kWh per Btu), we estimated the potential power generated.

To estimate the power generating potential of the topping of process heat, we assumed that the prime mover would be either a gas turbine or a diesel engine, with exhaust supplying energy for the industrial process. We also assumed that when the process requirement exceeded the temperature level of the exhaust stream, supplemental fuel and (in the case of diesels) air would be added. We determined the net electrical output as a function of inlet energy for each of the topping technologies. Each output ratio was multiplied by the appropriate thermal value of the temperature profile to obtain the output power for gas turbines and diesel engines. Adding these figures gave us the total output power for topping of process heat.

For the bottoming of waste heat, we determined the performance characteristics of steam Rankine cycles, organic Rankine cycles (ORCs) and bi-phase turbines as a function of source temperatures. This ratio, multiplied by the appropriate thermal value of the temperature profile, yields the output power for the various bottoming technologies.

The waste heat profiles of the paper and pulp, textile, and food and kindred products industries were generally low. Furthermore, these industries already make considerable use of the waste energy. Thus, bottoming has little potential in these industries.

To calculate energy savings for all three applications, we assumed that the cogeneration systems would be designed to satisfy thermal demand.* We also assumed that any excess electrical energy could be exported. The following algorithms relate this potential electrical output to the potential energy savings in Btu and in barrels of oil equivalent.

* In our discussions with industry and equipment manufacturers, we found this to be the principle most widely adopted.

- Topping of process steam and heat

$$\text{Savings (Btu/yr)} = P (10,000 \text{ Btu/kWh} - \text{net incremental heat rate})$$

- Bottoming of waste heat

$$\text{Savings (Btu/yr)} = P (10,000 \text{ Btu/kWh})$$

Where: $P = \text{kWh/yr}$

Net incremental heat rate (Btu/kWh)

= 4700 for steam turbine

= 5700 for gas turbine

= 6500 for diesel engine

The net incremental heat rate is an estimated average value of the five industries. It is a function of fuel type and process steam characteristics.

The algorithm to relate the potential thermal energy savings to barrels of oil per day equivalent (BPDE) is:

$$\text{Savings (BPDE)} = \text{Savings (Btu/yr)} \div 5.88 \times 10^6 \frac{\text{Btu}}{\text{bbl oil}} (365) \text{ LF}$$

Where: LF = Load or capacity factor = .9 for all industries except food and kindred products = .7

MAXIMUM POTENTIAL SAVINGS

Topping of Process Steam

We considered three types of systems for the topping of process steam: back-pressure steam turbines, gas turbines with waste heat recovery boilers, and diesel engines with waste heat recovery boilers. We assumed the following characteristics for each type of system:

- Steam turbines = $36 \text{ kWh}/10^6 \text{ Btu}$ process steam @ 850 psig/825°F throttle condition, back pressured to 150 psig (all industries but food and kindred products).
= $53 \text{ kWh}/10^6 \text{ Btu}$ process steam @ 850 psig/825°F throttle condition, back pressured to 50 psig (food and kindred products).
- Gas turbines with waste heat recovery boiler
= $175 \text{ kWh}/10^6 \text{ Btu}$ process steam, producing 150 psig process steam
= $167 \text{ kWh}/10^6 \text{ Btu}$ process steam, producing 50 psig process steam

- Diesel engine with waste heat recovery boiler
 - = 405 kWh/10⁶ Btu process steam, producing 150 psig process steam
 - = 390 kWh/10⁶ process steam, producing 50 psig process steam

The amounts of steam already used for cogeneration or for other purposes that make it unsuitable for cogeneration are shown in Exhibit 4-1. Of the estimated 3,943 trillion Btu used by the five industries in 1977, we consider 2,527 trillion Btu (64 percent) to be technically suitable for cogeneration. We estimated that in 1985, 67 percent of the total steam used (5,102 trillion Btu) will be technically suitable for cogeneration.* Exhibit 4-2 shows the total thermal energy technically suitable for cogeneration.

Exhibit 4-1

**STEAM TECHNICALLY SUITABLE FOR
TOPPING OF PROCESS STEAM (10¹² Btu/yr)**

Industry	Chemical		Petroleum refining		Paper and pulp		Textiles		Food	
	77	85	77	85	77	85	77	85	77	85
Process Steam										
Total steam use	1,427	1,882	624	772	1,401	1,838	139	155	352	455
Less steam consumed in power generation	174	143	38	31	169	134	14	11	45	37
Less on-line cogenerated process steam	151	171	15	34	236	432	15	12	27	23
Less process steam produced by topping cycles	145	119	41	41	17	19	6	6	41	41
Less process steam produced from waste heat recovery	142	214	132	184		9			8	14
Steam technically suitable for topping applications	815	1,235	398	482	979	1,244	104	126	231	340

The paper and pulp industry has proportionately and absolutely the greatest potential for topping of process steam. The textile industry has the least absolute potential, although the proportion of its process steam technically suitable for cogeneration is high (75 percent). Since textiles account for only four percent of the total steam used in the five industries, the absolute potential is small.**

* The values for steam topping presented in this report differ from, but are consistent with, those in the RPA/FEA study. That report considered additional technical constraints that reduced the value in 1977 by approximately 900 trillion Btu and in 1985 by 1,100 trillion Btu.

** RPA/FEA study showed that, when economic and other factors are considered, the potential in the textile industry is actually negligible.

Exhibit 4-2**THERMAL ENERGY TECHNICALLY SUITABLE
FOR COGENERATION (10¹² Btu/yr)**

Industry	Topping of process steam	Topping of process heat	Bottoming of waste heat	Total cogeneration
1977				
Chemical	815	849	2,447	4,111
Petroleum	398	2,641	1,102	4,141
Paper/pulp	979	100		1,079
Textile	104	38		142
Food	231	205		436
Total	2,527	3,833	3,549	9,909
1985				
Chemical	1,235	1,149	3,228	5,612
Petroleum	482	2,823	1,182	4,487
Paper/pulp	1,244	102		1,346
Textile	126	37		163
Food	340	227		567
Total	3,427	4,338	4,410	12,175

The amount of process steam found technically suitable for topping for each industry was then multiplied by the electrical output ratio of steam turbines, gas turbines, and diesel engines to arrive at the potential electrical production. Exhibit 4-3 shows that in 1977 in the five industries, steam turbines could produce approximately 95 million MWh, gas turbines could produce approximately 440 million MWh and diesels could produce 1,022 million MWh. In 1985, the values are estimated to be 129 million MWh, 597 million MWh, and 1,384 million MWh, respectively.

This potential production of electrical energy would result in the savings shown in Exhibit 4-4. The maximum total potential savings for steam turbines, gas turbines, and diesel engines are approximately 500 trillion Btu, 1,900 trillion Btu and 3,600 trillion Btu respectively in 1977; and 700 trillion Btu, 2,550 trillion Btu and 4,280 trillion Btu respectively in 1985. These values are equivalent to approximately 85 million to 610 million barrels of oil per year in 1977, and 116 million to 825 million barrels of oil per year in 1985 (see Exhibit 4-5).

Exhibit 4-3

POTENTIAL CAPACITY FOR COGENERATION (10⁶ kWh/yr)

Industry	Topping of process steam			Topping of process heat		Bottoming of waste heat		ORC R11	Steam Rankine	BI-Phase
	Steam turbine	Gas turbine	Diesel	Gas turbine	Diesel	ORC Fluorinol	ORC Toluene			
1977										
Chemical	29,300	142,600	330,000	26,700	66,900	47,200	59,800	47,600	21,200	39,800
Petroleum refining	14,300	69,700	161,200	84,900	221,700	33,900	39,000	28,700	24,900	33,600
Paper/pulp	35,200	171,300	396,500	2,500	6,300					
Textile	3,700	18,200	42,100	1,500	3,900					
Food	12,200	39,400	92,000	8,100	20,700					
Total	94,700	441,200	1,021,800	123,700	319,500	81,100	98,800	76,300	46,100	73,400
1985										
Chemical	44,500	216,000	500,200	35,200	88,500	60,700	77,100	67,700	26,100	49,800
Petroleum refining	17,400	84,400	195,200	90,800	235,000	38,300	41,600	30,700	26,700	36,000
Paper/pulp	44,900	218,000	504,600	3,000	6,500					
Textile	4,500	22,000	51,000	1,500	3,700					
Food	18,000	56,800	132,600	9,000	23,000					
Total	129,300	597,200	1,383,600	139,500	356,700	97,000	118,700	92,400	52,800	85,800

Exhibit 4-4

POTENTIAL THERMAL SAVINGS FROM COGENERATION (10^{12} Btu/yr)

Industry	Topping of process steam			Topping of process heat		Bottoming of waste heat		ORC R11	Steam Rankine	BI-Phase
	Steam turbine	Gas turbine	Diesel	Gas turbine	Diesel	ORC Fluorinol	ORC Toluene			
1977										
Chemical	155	614	1,155	115	234	472	598	476	212	398
Petroleum refining	76	300	564	365	776	339	390	287	249	336
Paper/pulp	186	737	1,388	11	22					
Textile	20	78	147	7	14					
Food	65	170	322	35	72					
Total	502	1,899	3,576	533	1,118	811	988	763	461	734
1985										
Chemical	236	929	1,750	151	309	607	771	617	261	498
Petroleum refining	92	363	683	377	822	363	416	307	267	360
Paper/pulp	237	937	1,766	12	22					
Textile	24	95	179	7	13					
Food	96	244	464	34	81					
Total	685	2,568	4,842	581	1,247	970	1,187	924	528	858

Exhibit 4-8

POTENTIAL SAVINGS FROM COGENERATION (10⁸ BPYE*)

Industry	Topping of process steam			Topping of process heat		Bottoming of process heat			Steam Rankine	BI-Phase
	Steam turbine	Gas turbine	Diesel	Gas turbine	Diesel	ORC Fluorinol	ORC Toluene	ORC R11		
1977										
Chemical	26.4	104.4	196.4	19.6	39.8	80.3	101.7	81.0	36.1	67.7
Petroleum refining	12.9	58.2	95.9	62.1	132.0	57.7	66.3	48.8	42.3	57.1
Paper/pulp	31.6	125.3	236.1	1.9	3.8					
Textile	3.4	13.3	25	1.2	2.4					
Food	11.1	28.9	54.8	6.0	12.2					
Total	85.4	330.1	608.2	90.8	190.2	138.0	168.0	129.8	78.4	124.8
1985										
Chemical	40.1	158.0	297.6	25.8	52.7	103.2	131.1	105	44.4	84.7
Petroleum refining	15.7	61.7	116.2	66.4	139.7	61.7	70.7	52.3	45.4	61.2
Paper/pulp	40.3	159.4	300.3	1.9	3.8					
Textile	4.1	16.2	30.4	1.1	2.3					
Food	16.2	41.5	78.9	6.6	13.8					
Total	116.4	436.8	823.4	101.8	212.3	164.9	201.8	157.3	89.8	145.9

* Barrels per year equivalent of oil.

Topping of Process Heat

The industries we studied all require extensive amounts of thermal energy for their processes. Applications range from heaters in the petroleum refining industry (high temperatures) to dryers and kilns in the food and textile industries (medium to high temperatures).

The thermal energy contained in the exhaust from a gas turbine or diesel engine could be used in the process either directly (e.g., for drying) or indirectly (e.g., by use of heat exchangers). For the purposes of this study, we assumed that the thermal energy would be used indirectly. We assumed that the heat transfer device would be 85 percent efficient and that the exhaust characteristics of the gas turbine would be those of air (because of the low fuel-to-air ratio) at 1000°F. For diesels, we assumed that the specific heat was equivalent to that of air, and that the exhaust stream was void of combustible oxygen and at a temperature of 800°F.

On the basis of this information, we established net electrical output per unit of input energy as a function of temperature. The following are the weighted averages for the industries in kWh per million Btu of inlet energy:

	<u>Gas Turbine</u>	<u>Diesel</u>
Chemical	31	78
Petroleum Refinery	32	83
Paper and Pulp	27	63
Textile	40	101
Food	40	100

Exhibit 4-6 shows the profile of input thermal energy required for the various processes. Exhibit 4-3 shows that in 1977 approximately 124 million MWh could be generated by employing gas turbines and 320 million generated by employing diesel engines. In 1985, these values rise to approximately 140 million and 357 million MWh respectively. We attribute approximately 90 percent of the total potential power generation to the chemical and petroleum refining industries.

Exhibit 4-6

INPUT THERMAL ENERGY FOR TOPPING OF PROCESS HEAT (10¹² Btu/yr)

Industry	Chemical		Petroleum refining		Paper and pulp		Textiles		Food	
	77	85	77	85	77	85	77	85	77	85
Process heat profile										
100-600°F	135	184	448	480			38	37	162	179
600-1000°F	28	37	1,668	1,782					43	48
1000-1500°F	501	678	525	561						
1500-2000°F	185	250			100	102				
Total	849	1,149	2,641	2,823	100	102	38	37	205	227

This potential production of electrical energy translates to the potential savings shown in Exhibit 4-4. The total potential savings for gas turbines and the diesel engines are approximately 530 trillion Btu and 1,100 trillion Btu respectively in 1977; and 580 trillion Btu and 1,250 trillion Btu respectively in 1985. These values are equivalent to approximately 90 million and 190 million barrels of oil per year in 1977; and 100 million and 210 million barrels of oil per year in 1985 (see Exhibit 4-5).

Bottoming of Waste Heat

The process exhaust thermal energy (waste heat) that is presently rejected to the environment provides an added opportunity for cogeneration. Many systems such as Rankine cycles (steam and organic) can function in a topping or bottoming mode. For this study, it was assumed that these systems as well as the bi-phase turbine would be used for bottoming. We considered three organic Rankine cycles (employing toluene, freon and fluorinol).

To determine the potential energy savings of bottoming, we developed profiles of the waste heat stream of each industry. As a result of our discussions with industry managers and our research in the sources identified in the references, we determined that of the five industries studied, only the chemical and petroleum refining industries had any real potential for bottoming. The paper and pulp, textiles, and food industries had only negligible potential. Although we did not consider the overall potential for these three industries any further, bottoming might be applicable at specific plants.

Exhibit 4-7 shows the profile of thermal energy that is considered to be suitable for the bottoming systems. To estimate the potential electrical energy that could be generated from these streams of waste heat,* we established (from various performance data), a power conversion curve as a function of source temperature. Exhibit 3-11 presents the results along with the assumptions used to establish a common base.

Exhibit 4-7

SOURCE WASTE HEAT FOR BOTTOMING (10¹² Btu/yr)

Industry	Chemical		Petroleum refining	
	77	85	77	85
Waste heat profile				
<150°F	540	731	147	159
150-300°F	1,188	1,641	428	459
300-600°F	611	709	247	265
>600°F	108	147	280	299
Total	2,447	3,228	1,102	1,182

* Although the waste streams could be employed differently (i.e., for heating or cooling), we investigated only electrical conversion.

We determined the bottoming potential on the basis of the conversions and the profiles (see Exhibit 4-3). We estimated that from approximately 46 million MWh (with steam Rankine cycles) to 99 million MWh (with toluene ORCs) could be generated in 1977. The corresponding values for 1985 are approximately 53 million MWh to 119 million MWh respectively.

The potential production of electrical energy translates to the savings shown in Exhibit 4-4. In both industrial applications, toluene organic Rankine cycles rated consistently higher than the other technologies. The steam Rankine cycle showed the least savings. The values for toluene ORCs are from approximately 1,000 trillion Btu in 1977 to 1,200 trillion Btu in 1985 and for steam Rankine cycles from approximately 460 trillion Btu in 1977 to 530 trillion Btu in 1985. The savings for the toluene ORCs are equivalent to approximately 168 million to 200 million barrels of oil per year in 1977 and 1985 respectively. For the steam Rankine cycle, we estimated the savings to be the equivalent of approximately 80 million and 90 million barrels of oil per year for 1977 and 1985 respectively (see Exhibit 4-5).

Total Maximum Cogeneration Savings Potential

In the previous sections of this chapter, we have estimated the range of the maximum potential energy savings that could be realized from topping of process steam and process heat and bottoming of waste heat, for the alternate technologies. We then summed the values for the three applications to obtain the maximum potential savings for cogeneration. However, the resulting range is dependent on the mix of technology selected (i.e., varying percentages of steam and gas turbines and diesel engines for the three applications).

For example, the use of steam turbines for topping of steam, gas turbines for topping of process heat, and steam Rankine cycles for bottoming of waste heat would yield the least savings (minimum savings technology mix) while the use of diesels and toluene organic Rankine cycles would result in the greatest (upper limit). Exhibit 4-4 indicates that the range would be approximately 1,500 trillion Btu to 5,700 trillion Btu in 1977 and 1,800 trillion Btu to 7,300 trillion Btu in 1985. Exhibit 4-8 shows that these energy savings are the equivalent of approximately 0.8 million barrels to 3.0 million barrels of oil per day in 1977 and approximately 1 million barrels to 3.9 million barrels of oil per day in 1985.

In terms of electrical generating capacity, these savings are the equivalent of 34,000 MW to 185,000 MW in 1977 and 41,000 MW to 238,000 MW in 1985. Our estimate is that the realistic maximum will be an average of these figures. Thus, we estimate that the maximum technically feasible (highly improved technology mix) will be 110,000 MW in 1977 and 140,000 MW in 1985. These values are the equivalent of approximately 1.9 million barrels of oil per day in 1977 and 2.4 million barrels of oil per day in 1985.

Exhibit 4-8

RANGE OF MAXIMUM SAVINGS FROM COGENERATION
IN EQUIVALENT BARRELS OF OIL PER DAY: 1985/1977

PROBABLE DEVELOPMENT

In this report we have focused on the technical aspects of cogeneration. Based on our assumptions, we have estimated the maximum potential savings for the five industries selected. However, regulatory, institutional and other factors can significantly reduce the willingness of industrial managers to invest in cogeneration. The presence of these barriers is indicated by the fact that managers generally require higher return on investment (ROI) for cogeneration projects than for other investments.

The main regulatory and institutional barriers to industrial cogeneration arise from difficulties in interfacing with utilities, in arranging joint ventures, and in meeting environmental requirements. Government action might eliminate or reduce these barriers.

Utility Interface

There are several basic advantages to the interconnection of an industrial cogeneration system with the utility network, however, there are also problems. The basic options are:

- For the industry to purchase standby capacity to back up its cogeneration system
- For the industry to purchase supplement power because the cogeneration system cannot meet the entire demand of the plant
- For the industry to sell surplus power to the utility
- For the industry to sell surplus power to a third party, using the utility grid for transmission ("wheeling").

However, management is concerned that standby or supplemental power contracts with utilities might not be available or might be too expensive. Furthermore, they fear that these contracts might require the cogeneration system either to deliver reserve or emergency power to the grid or to cut back power deliveries thus jeopardizing plant operations. It is not clear that industrial cogenerators will be able to obtain the price they wish from the utilities for surplus power or be allowed to wheel that power to other industrial customers.* Finally, they fear that connections with utilities may bring their operations under the purview of various regulatory bodies, such as state public utility commissions, the FPC, etc.

* In most cases, a utility itself, the state public utility commissions, or the FPC can refuse a cogenerator the right to wheel power.

Joint Ventures

Joint ventures between industry and utilities have numerous risks and uncertainties. Chief among them seems to be the number of parties that must be guaranteed adequate and reliable thermal and electrical energy. Since each potential participant has its own priorities and decisionmaking criteria, agreements would be difficult to reach.

The participation of a utility in a joint venture would facilitate construction and operation of the cogeneration system. But it might increase the likelihood of exposing the industry to unwanted regulation (see preceeding section).

Environmental Requirements

Uncertainties about environmental policy and regulations (especially the requirement for the best available technology for pollution abatement) may inhibit the spread of cogeneration systems. This would be particularly true where requirements for siting or other environmental permits might cause delays.

Because cogeneration requires the combustion of additional fuel, local air emissions will increase. This increase should, theoretically, be offset by a net reduction in emission in the area (depending upon the types of fuel already used by the industry and by the utility that supplies it with power, and the type of fuel proposed for the cogeneration system). However, pollution control equipment may be required, particularly for systems that can burn more than one type of fuel.

Estimated Development

We used the following penetration ratios* for each industry.

<u>INDUSTRY</u>	<u>PROBABLE PENETRATION RATIO</u>
Chemical	0.115
Petroleum Refining	0.132
Paper and Pulp	0.44
Textiles	<0.01
Food	0.077

We assumed that these ratios will not be influenced by a shift toward an improved technology mix (i.e., increased use of gas turbines or diesels). The resultant savings and electrical capacity values represent probable cogeneration potential without government incentives.

*The probable penetration ratios and the probable effects of government incentives were derived from the RPA/FEA study.

We estimated that with a governmental program that provides for a 30 percent investment tax credit (ITC)* clarification of FPC and Public Utility Commission (PUC) jurisdiction, an exemption from FPC/PUC jurisdiction for non-exporters of power, and an equitable purchase price for export to the grid,** market development will increase by 35 percent.

With the probable penetration ratios, we estimated the probable electrical capacity and energy savings for various technology mixes. Exhibit 4-9 shows the sensitivity of electrical capacity (i.e., potential savings) to the technology mix for 1985. A 10 percent shift to the use of gas turbines for the topping of steam results in a 20 percent increase in electrical capacity over the minimum savings technology mix (from approximately 9,200 MW to 11,000 MW). With an improved technology mix, the electrical capacity would rise to approximately 20,000 MW. With a highly improved technology mix, electrical capacity should rise to 37,000 MW.

These savings are the equivalent of approximately 0.2 million barrels of oil per day for a minimum savings technology mix, approximately 0.24 million barrels of oil per day for the present technology mix, approximately 0.4 million barrels of oil per day for an improved technology mix, and approximately 0.6 million barrels of oil per day for a highly improved technology mix. A shift toward an improved technology would double energy savings for industry and the nation; a highly improved technology mix would triple these savings.

* RPA estimated that a 20 percent ITC, as proposed in legislation currently under consideration, would result in a relatively minor impact on cogeneration market development.

** These incentives are considered to be a "medium" program in the RPA/FEA study.

Exhibit 4-9

COGENERATION SAVINGS COMPARED TO TECHNOLOGY MIX (1985)

TECHNOLOGY MIX	TOPPING OF PROCESS STEAM	TOPPING OF PROCESS HEAT	BOTTOMING OF WASTE HEAT
Minimum saving	100 percent steam turbine	100 percent gas turbine	100 percent steam Rankine
Present	90 percent steam turbine 10 percent gas turbine	100 percent gas turbine	100 percent steam Rankine
Improved	75 percent steam turbine 15 percent gas turbine 10 percent diesel	50 percent gas turbine 50 percent diesel	50 percent steam Rankine 50 percent ORC-toluene
Highly Improved	50 percent steam turbine 50 percent diesel	50 percent gas turbine 50 percent diesel	50 percent steam Rankine 50 percent ORC-toluene

APPENDIX A
ORGANIZATIONS CONTACTED

ORGANIZATIONS CONTACTED

During the course of this study, we have consulted firms that supply and use cogeneration equipment. The information gathered from the following companies was most helpful in determining the potential development of cogeneration.

SUPPLIERS

Caterpillar Tractor Co.
Delaval Turbine Inc.
General Electric Co.
International Harvester Co.
Mechanical Technology Inc.
Rolls Royce Ltd.
Sunstrand Corp.
Thermo Electron Corp.
Westinghouse Electric Corp.

USERS

Chemical

Allied Chemical Corp.
American Cyanamid Co.
Andrews Jergens Co.
Celanese Corp.
Dow Chemical Co.
E. I. Du Pont De Nemours
Hercules Inc.
Linden Chlorine Products, Inc.
Olin Corp.
PPG Industries, Inc.
Reichhold Chemicals, Inc.
Stauffer Chemical Co.
Tenneco Inc.
Virginia Chemicals Inc.

Petroleum Refining

Cities Service Co.
Indian Gas & Chemical Corp.
Shell Oil Co.
Standard Oil Co. of California
Standard Oil Co. (Ohio)
Texaco Inc.

Paper and Pulp

American Can Co.
Bergstrom Paper Co.
Beveridge Paper Co.
Champion International Corp.
Crown Zellerbach Corp.
Georgia-Pacific Corp.
Kimberly-Clark Corp.
Southland Paper Mills, Inc.
Stone Container Corp.
Weyerhaeuser Co.

Textiles

Burlington Industries, Inc.
Cone Mills Corp.
West-Point Pepperell, Inc.

Food

American Crystal Sugar Co.
General Foods Corp.
General Mills, Inc.
Holly Sugar Corp.

APPENDIX B

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