DOCUMENT RESUME

ED 160 374 SE 024 860

AUTHOR	Barker, James L.; And Others
TITLE	First Order Estimates of Energy Requirements for Pollution Control. Interagency Energy-Environment Research and Development Program Report.
INSTITUTION	Development Sciences, Inc., Sagamore, Mass.
SPONS AGENCY	Environmental Protection Agency, Washington, D.C. Office of Research and Development.
REPORT NO	EPA-600/7-78-022
PUB DATE	Oct 77
CONTRACT	EPA-68-01-4150
NOTE	95p.; Contains occasional light and broken type
EDRS PRICE	MF-$0.83 HC-$4.67 Plus Postage.
DESCRIPTORS	*Air Pollution Control; Energy Conservation; Environmental Criteria; Environmental Education; *Environmental Research; Environmental Technicians; *Estimated Costs; *Fuel Consumption; Government Publications; *Water Pollution Control
IDENTIFIERS	*Environmental Protection Agency

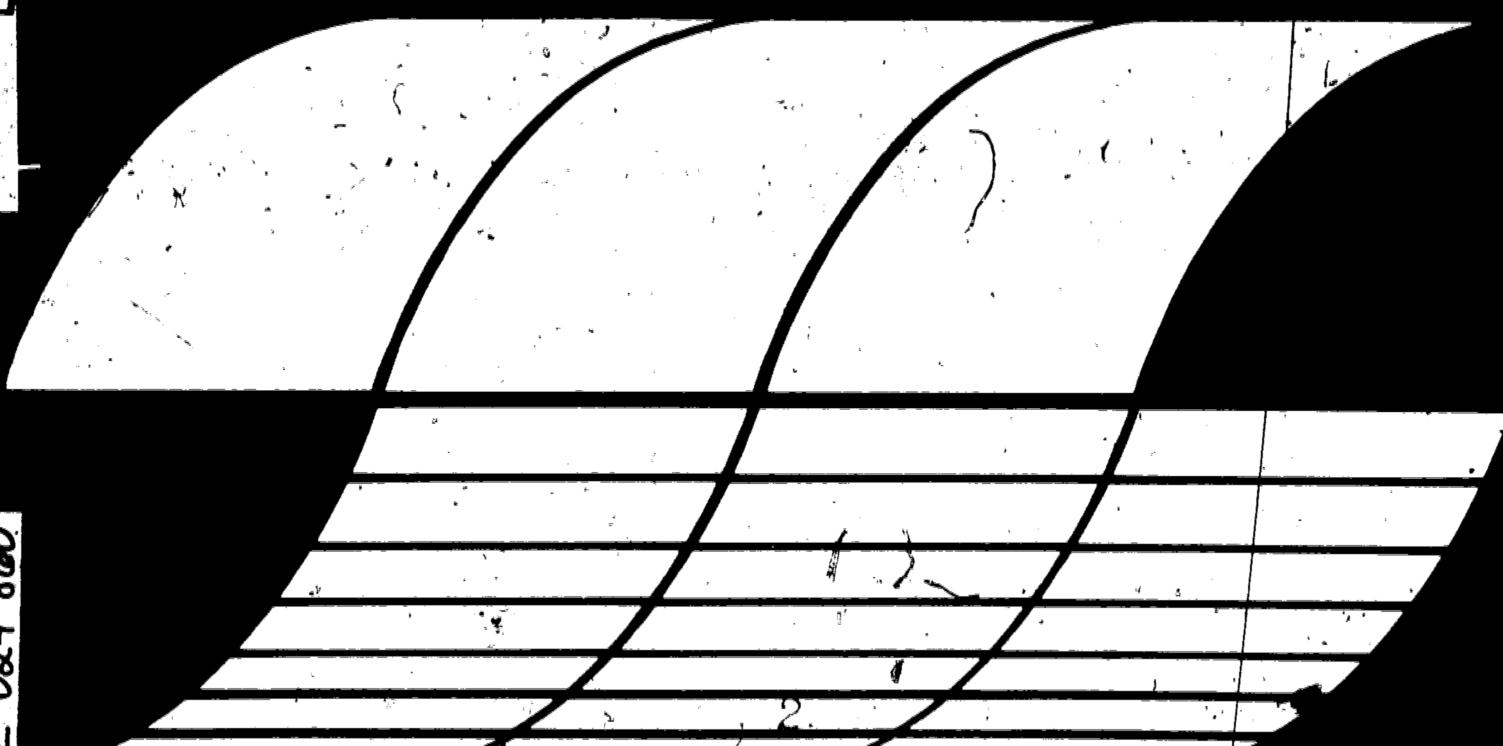
ABSTRACT

This U.S. Environmental Protection Agency report presents estimates of the energy demand attributable to environmental control of pollution from stationary point sources. This class of pollution source includes powerplants, factories, refineries, municipal waste water treatment plants, etc., but excludes mobile sources such as trucks, and automobiles, and non-point sources such as some types of farms, mines, etc. Energy requirement estimates for water pollution control and for air pollution control are discussed separately. The discussion on water pollution control energy requirements includes: (1) Industrial Water Pollution Control; (2) Control of Thermal Pollution from Electric Power Plants; and (3) Municipal Wastewater Treatment. The air pollution control energy requirement discussion deals with Industrial Air Pollution Control and with Control of SOx and Particulate Emissions from Electric Power Plants. Also included in this document is a comparison of pollution control-related energy estimates, a bibliography, and a summary. This study is a continuation of an earlier effort to estimate the energy required to meet pollution standards for stationary point sources. (Author/MR)

EPA

FIRST ORDER ESTIMATES OF ENERGY REQUIREMENTS FOR POLLUTION CONTROL

Interagency
Energy-Environment
Research and Development
Program Report



RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into nine series. These nine broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The nine series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies
6. Scientific and Technical Assessment Reports (STAR)
7. Interagency Energy-Environment Research and Development
8. "Special" Reports
9. Miscellaneous Reports

This report has been assigned to the INTERAGENCY ENERGY-ENVIRONMENT RESEARCH AND DEVELOPMENT series. Reports in this series result from the effort funded under the 17-agency Federal Energy/Environment Research and Development Program. These studies relate to EPA's mission to protect the public health and welfare from adverse effects of pollutants associated with energy systems. The goal of the Program is to assure the rapid development of domestic energy supplies in an environmentally-compatible manner by providing the necessary environmental data and control technology. Investigations include analyses of the transport of energy-related pollutants and their health and ecological effects, assessments of, and development of, control technologies for energy systems, and integrated assessments of a wide range of energy-related environmental issues.

[illegible] National Technical Informa- [illegible]

October, 1977

FIRST ORDER ESTIMATES OF ENERGY REQUIREMENTS FOR POLLUTION CONTROL

by

James L. Barker, Kenneth Maddox, James D. Westfield
and Douglas Wilcock
Development Sciences, Inc.
P.O. Box 144
Sagamore, Massachusetts 02561

Contract No. 68-01-4150

Project Officer

Steven E. Plotkin
Industrial and Extractive Processes Division
U.S. Environmental Protection Agency
Washington, D.C. 20460

Office of Energy, Minerals, and Industry
Office of Research and Development
U.S. Environmental Protection Agency
Washington, D.C. 20460

DISCLAIMER

This report has been reviewed by the Office of Energy, Minerals, and Industry, U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

FOREWORD

When this study began, we assumed that sufficient data and analysis would be available for the contractor to collect and integrate into a useful report showing the energy costs of the federal environmental protection program. We were swiftly disabused of this notion, for the following reasons:

1. Most estimates of pollution control energy costs that were examined by the contractor are difficult to accept; assumptions are not stated, methodology is poorly described, and, when the analyses could be followed, we felt that many were inadequate.

2. The federal, state and local roles in pollution control are intertwined to such an extent that it is virtually impossible to convincingly break out the federal share. In this report, therefore, energy costs are given as the total costs of all controls in a single medium (air or water) rather than for a single federal statute.

3. The longer term industry response to pollution controls is complex and involves process changes, material substitutions, and lack of compliance as well as installation of "end-of-pipe" treatments. Analyses of energy costs of pollution control, including this one, typically assume end-of-pipe treatment for most industries. This produces a conservative (high) estimate of energy costs, since process changes may allow satisfaction of environmental standards with zero energy costs and possibly with energy savings.

4. Differences in pollution control energy use from plant to plant can be large, suggesting that a disaggregated approach would greatly improve accuracy. This type of approach is beyond the resources of this study.

5. Data on the energy costs of various control alternatives is not uniformly available or is quite variable.

6. Designs of some important controls - such as flue gas scrubbers - are changing so rapidly that energy costs for future systems are highly uncertain.

The implication of these analytical difficulties is that the estimates presented here must be treated with caution. The estimates for the total national energy cost for stationary point source control are probably reasonably indicative of what will actually occur. Since the estimates are based on conservative assumptions (from EPA's viewpoint), the actual cost may be somewhat lower. On the other hand, the energy cost estimates for a single industry are subject to such substantial potential for error that they are not presented in the text. EPA's Office of Planning and Evaluation is now conducting more detailed studies of those industries that appear to be incurring, or that will incur, large energy costs for environmental controls. These industries include electric utilities, iron and steel, petroleum refining, copper and aluminum, pulp and paper, and a "miscellaneous" category covering S.I.C. codes 21 through 30. Completion of these studies should upgrade the national estimates as well as shed light on any potential for reducing these energy costs.

The estimated energy required for water and air pollution control of stationary point sources in the U.S. is two percent of the nation's energy consumption in 1977 and three percent in 1983 (Recent changes in both the Clean Air Act and the Federal Water Pollution Control Act are not considered in the analysis). This is an enormous amount of energy, over three quadrillion BTU (the equivalent of 150 million tons of coal) per year by 1983. However, to put this into perspective, the nation's energy budget is growing by about this percentage every year. Thus, if environmental controls on air and water pollution were eliminated, the net decrease in energy use would be swallowed up by growth in demand in one year.

Steve Plotkin

Steve Plotkin
Office of Energy, Minerals,
and Industry

PREFACE

This study is a continuation of an earlier effort* to estimate the energy required to meet pollution standards for stationary point sources. One objective of this investigation was to develop forecasts of national energy demands both to operate pollution control devices and to manufacture and supply materials used to build the devices. The other goal was to make it possible for others to modify or update the estimates without having to redo the entire study.

The analysis presented here used information obtained since the earlier report was published. Significant changes have occurred in the expected costs of pollution control, and these changes are reflected in the energy estimates. Furthermore, this study does not (for the most part) attempt to differentiate between the total cost for pollution control and that increment of cost directly attributable to specific federal regulations, as did the earlier study. Consequently, forecasts of energy needed to support pollution control generally are larger in this report than they were in the earlier one.

The report is divided into three major sections and two appendices:

Section 1.0 is a summary of energy requirements to control air and water pollution from industrial plants, electric power plants, and municipal wastewater treatment plants. The summary presents study results and some key assumptions and limitations that influence the results.

Section 2.0 presents the calculations by which estimates of energy to control water pollution were determined. The section is subdivided into three parts, examining energy needed for control of industrial water pollution, electric power plant thermal pollution and municipal wastewater.

Section 3.0 contains a discussion of how the estimated energy requirements for air pollution were developed. It is subdivided into an analysis of the reduction of industrial air pollution and a study of electric power plant air pollution control.

Appendix A compares the energy estimates of this report with those of the earlier study and with estimates made by other organizations.

Appendix B is a bibliography of the articles, reports, books and other source material used for the analysis.

---

* First-Order Estimates of Potential Energy Consumption Implications of Federal Air and Water Pollution Control Standards for Stationary Sources, prepared for the Environmental Protection Agency by Development Sciences Inc. July 1975, Contract No. 68-01-2498.

ABSTRACT

This report presents estimates of the energy demand attributable to environmental control of pollution from "stationary point sources." This class of pollution source includes powerplants, factories, refineries, municipal waste water treatment plants, etc. but excludes "mobile sources" - automobiles, trucks, etc. - and "non-point sources" - sources which do not produce individual effluent streams, such as some types of farms, mines, etc.

The energy requirements of pollution control arise from several sources. Energy is required to operate components of the control devices - fans, pumps, reheaters, etc. In some cases, the equipment degrades the efficiency of the process it controls, requiring additional fuel to maintain the product stream. Energy is required to mine, refine, and assemble the material components of the control equipment, transport them to the site, and install the equipment. Finally, energy is required to produce and transport materials used up in the control process - such as limestone, chlorine, etc. The calculations in this report include estimates of all of these energies, although with varying degrees of accuracy.

This report was submitted in fulfillment of Contract 68-01-4150 by Development Sciences, Inc. under the sponsorship of the U.S. Environmental Protection Agency.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES (continued)

ACKNOWLEDGEMENTS

The Project Officer for this effort has been Mr. Steven Plotkin. His advice, guidance and constructive criticisms, both of the earlier report and during this work, have been invaluable to the project team. Dr. Edwin Clark, of the Council on Environmental Quality, has been helpful throughout the study. Among many useful suggestions provided by the Municipal Construction Division of EPA, the advice of Malcolm Simmons has been particularly beneficial.

The Development Sciences Inc. Project Team Members are:

James L. Barker
Kenneth Maddox
James D. Westfield
Douglas Wilcock

The Project Team hopes that the information resulting from this study contributes positively to understanding the issues of the price and value of environmental protection.

1.0 SUMMARY

Pollution control is dependent upon the commitment of resources, and energy is among the resources necessary to install and operate devices that reduce air and water pollution. Because energy is an important resource currently in short supply in the United States, there has been concern among many regarding the energy necessary for pollution abatement. The purpose of this study was to estimate the amount of energy required to control pollution from stationary point sources.

The energy needs reported in this study are first order approximations. Although they are as accurate as existing data and time limitations would allow, the estimates do not substitute for detailed analyses of individual pollution control systems and their energy characteristics. This is particularly true in those instances where several alternative pollution control systems are being considered for a specific application. Accordingly, the results should be regarded as representing the proper magnitude of energy requirements rather than as precisely determining those requirements.

The findings of the study are that more than 1,500 trillion Btu of energy will be needed in 1977 for control of air and water pollution from stationary sources. This amounts to approximately two percent of the estimated 1977 national energy use. Within the next decade energy used for control of pollution from stationary sources is expected to nearly double to approximately 3,100 trillion Btu, which at that time will be on the order of three percent of the national energy budget.

Table 1-1 displays the results. More than two-thirds of the total energy required for pollution control, both for 1977 and 1983, will be used to mitigate the environmental impacts of industrial processing. The largest demands will be energy for industrial air pollution control, followed by demands associated with industrial water pollution. The third largest requirements will be for the control of air pollutants from electric power plants. Control of water pollution at electric power plants and new municipal wastewater treatment plants will use smaller amounts of energy.

The results of Table 1-1 include both direct and indirect energy requirements. Direct energy, in the form of fuels and electricity to operate pollution control devices, accounts for about 80 percent of the total. Indirect energy, including the energy equivalent of chemicals used in pollution control and energy used to manufacture and install pollution abatement devices, is the remaining 20 percent.

The findings presented in the table result from data and assumptions that should be carefully studied. For the most part, data were derived from estimates of pollution control costs and from projections of the numbers of facilities that would be required to meet environmental standards. Neither kind of estimate yields "hard" information that can precisely define the extent to which pollution control equipment will be installed and operated in the future. Consequently, assumptions and data sources are presented in each following section so that they can be examined directly.

TABLE 1-1. STATIONARY POINT SOURCES:
ENERGY REQUIRED FOR WATER AND AIR POLLUTION CONTROL

Sector	Energy Required (10^{12} Btu) 1977	1983
Water Pollution Control		
Industrial	479	1,079
Power Plant (Thermal)	93	156
Municipal Wastewater	*	151
Subtotal	572	1,396
Air Pollution Control		
Industrial	676	1,179
Power Plant	305	500
Subtotal	981	1,679
TOTAL STATIONARY POINT SOURCES	1,553	3,075
(APPROXIMATE % OF U.S. ENERGY CONSUMPTION)**	(2%)	(3%)

* No estimate for 1977. See discussion in Section 2.3.

** Percentages of sector (e.g., industrial) energy consumption for pollution abatement are not presented here. This is because the estimates which appear in this report include "indirect" energy, some of which is consumed by sectors other than the one reported.

Energy estimates are the major objective of this report; however, their development led to many other important findings. These discoveries concern both the process of making energy estimates and the features of pollution control sectors. They are listed below.

General

1. Statistical data on energy use in technological processes usually are not available, and this is particularly so of the new and changing technologies used for pollution control. Where energy data exist, they are often incomplete. Moreover, the rules and assumptions by which energy information is reported are often incompatible from one study to another and comparison of results is difficult.

2. The estimates made for this report are highly dependent on forecasts of pollution control costs. Various organizations and agencies disagree as to both the extent and the types of pollution control that will be required to satisfy environmental legislation, and they project different costs. As a result, energy estimates can vary, depending on underlying assumptions of the cost estimates.

3. Although pollution control energy estimates have been reported for 1977 and 1983 to correspond with the principal target years of environmental legislation (e.g. PL 92-500), maximum energy requirements may occur during other years. For example, new municipal wastewater treatment plants constructed to meet federal standards will be built throughout the 1980s and major expenditures for industrial air pollution control are expected before 1983, as are those for industrial water pollution control.

4. Indirect energy is a significant fraction of the total energy needed to support pollution control. The indirect energy is mainly due to the chemicals required as input to the abatement techniques used by the various sectors.

Water Pollution Control

5. The numbers of electric power plants that will need cooling towers is uncertain, and the uncertainty fundamentally determines the reliability of the thermal pollution control energy estimates.

6. Energy consumption to operate cooling towers at electric power plants varies with plant size, efficiency and kind. For equal units of electrical output, larger plants (with larger cooling towers) consume less energy than do smaller plants, more efficient plants are less energy consumptive than less efficient plants, and fossil fueled plants need less cooling and are less energy intensive than nuclear plants.

7. The energy intensities of municipal wastewater plants increase significantly from primary to secondary treatment levels and from secondary to tertiary treatment levels.

8. The energy cost for certain advanced methods of treating the chemical sludges from wastewater treatment plants can be partially offset by savings in indirect (chemical) energy if the method recovers useful chemicals (e.g. in the recalcination of chemical sludges to recover lime).

9. The wide variation of treatment techniques and waste stream compositions within industry (e.g. across subsectors and plant sizes) makes it difficult to develop a reliable measure of energy consumption for water pollution control. Imposition of end-of-pipe

treatment assumptions on industries which may change their production processes to reduce pollutants, to recover valuable materials, and/or to conserve energy is not always reasonable and may cause the energy estimates to be overstated.

10. There does not exist across industrial sectors a general and systematic relationship among investment in pollution control equipment, costs to operate and maintain the equipment, and energy consumption by the equipment. However, for any given sector, a coefficient relating energy consumption to capital investment is the best available basis for developing energy estimates from aggregate cost data.

11. The chemical industry will consume much more energy for water pollution control than any other industrial sector. The paper and machinery industries are the next most energy consumptive sectors.

12. The energy consumption associated with producing chemicals for industrial water pollution control devices is significant compared to the direct operating energy required.

Air Pollution Control

13. The amount of energy consumed by coal-burning power plants for stack gas scrubbers depends critically on: (a) availability of low sulfur coal; (b) the timing and extent of compliance with federal air quality standards; and (c) the timing and scope of the State Implementation Plans. There does not appear to be general agreement among federal agencies on how much low sulfur coal can be made available to the utilities by the latter 70s and early 80s.

14. The majority of the energy consumption by power plants for air pollution control will be for operation of stack gas scrubbers.

15. On a unit basis, stack gas scrubbing and using low-sulfur coal are equally energy intensive.

16. Desulfurization of residual oil at the refinery is up to 40 percent more energy intensive than stack gas scrubbing. However, for equivalent amounts of sulfur removal stack gas scrubbers cost two to three times as much as oil desulfurization units.

17. The operating energy for removal of SO_x (by limestone scrubbers) and particulates (by electrostatic precipitators) depend very little on the amount of sulfur or particulates in the stack gases (over the "normal" range of fuel qualities).

18. The energy consumed in disposing of sludges from stack gas scrubbers and in producing the limestone used by the scrubbers is insignificant compared to the energy consumed in operating the scrubbers.

19. Wet collectors are very energy intensive; their application by industry to control air pollution may result in major energy consumption/environmental quality inefficiencies.

These findings supplement the energy estimates themselves. Like the estimates however they should be reevaluated after having considered the assumptions needed to perform the analysis.

The findings indicate that detailed sector analyses are needed in order to determine more fully the energy to support pollution control. It is particularly important that the industrial sectors be studied since (a) they are the ones requiring the most energy, and (b) they have the largest variety of possible responses to effect reduction in air and water pollutants. For water pollution the chemical, paper and machinery industries are the most energy consumptive and should therefore be most closely studied; while for air pollution the primary metals, chemical and petroleum industries are the most important sectors for which to determine energy requirements.

Analyses should be made in enough depth to include accurate information on indirect energy requirements. The data on chemicals used for pollution control processes are especially critical. Indirect energy can, in some cases, significantly add to the energy requirements for pollution control.

Discussions with members of the EPA staff have revealed that efforts to refine energy data are currently underway and should result in improved estimates of the energy needed to control air and water pollution. The first order approximations reported here can therefore be compared with the findings of the more detailed study when it is finished. Until then these data serve as useful indicators of the energy resource commitments that must be made to protect air and water from stationary point source emissions.

2.0 ENERGY REQUIRED FOR WATER POLLUTION CONTROL

The 1972 Amendments to the Water Pollution Control Act mandated action to produce major reductions in the pollution of United States water resources. Since the passage of the Amendments, the EPA has been developing standards and guidelines to affect the legislative intent.

The sections that follow present the methodology, assumptions and results of investigations to determine energy required to control water pollution. Three major divisions are covered. They are:

- Water pollution abatement by industries
- Thermal pollution control by electric utilities
- Wastewater treatment by municipalities

Where possible, both direct operating and indirect energy have been determined and the results are divided accordingly.

Summary estimates for water pollution control were presented in Table 1-1.

2.1 Industrial Water Pollution Control

Since the 1972 Amendments to the Water Pollution Control Act, industry has been planning its response to the effluent guidelines published by EPA. The demands on industry to utilize by 1977 the "best practicable" technologies for controlling water pollution, and by 1983 to use the "best available" technology economically achievable, will have cost industry over $15 billion in new plant and equipment investments by 1977 and will cost $34 billion by 1983. These investments will result in major reductions in the amount of pollutants annually discharged by industry into water bodies.

Industry can reduce water pollution in one or more of three ways:

- Traditional end-of-pipe treatment of effluent to remove or reduce harmful pollutants; and/or
- Changes in production processes to reduce the quantity or types of pollutants generated; and/or
- Reuse of effluents in the production process or as inputs to another production process.

The method chosen by any particular manufacturer depends on many factors including his current production process, the age of his equipment, the size of his plant, the actions of his competitors, access to financing, the health of his business, and the characteristics of the marketplace. Although there is considerable evidence that many producers are responding to pollution regulations by altering their production processes rather than by installing relatively expensive and nonproductive end-of-pipe treatment processes, the paucity of comprehensive information about both the creative responses of some producers to pollution problems, and the unique circumstances of others who face regulations which may or may not be sensitive to their particular business situation, have caused most analysts of the impacts of the regulations to assume that all (or most) producers will install end-of-pipe treatment processes in order to meet the guidelines established for their industries.

The following subsections develop estimates of the energy consequences which accompany estimates of industrial investments for water pollution control. The data are derived largely from studies done by EPA; and because those studies focus on end-of-pipe treatment processes, the energy estimates are also primarily for end-of-pipe treatment. As such, there may be overstatements of what may actually occur once industry finalizes its responses to the 1983 standards and to the pressures of raw materials shortages and price increases.

Methodology and Assumptions

The methodology used to develop estimates of the direct and indirect energy demands for control of industrial water pollution includes five steps:

Step 1: Direct Energy Consumption Coefficients	From available data on the cost (by industry) of water pollution controls, determine direct energy consumption coefficients based on capital costs for the control techniques.
Step 2: Indirect Energy Consumption Coefficients	From the same data, determine the indirect energy consumption coefficients based on capital costs and annual consumption of chemicals.
Step 3: Investments in Water Pollution Control	From data developed by CEQ, determine expected investments for water pollution control by industry sectors.
Step 4: Direct Energy Consumption for Water Pollution Control	Using the information developed in Steps 1 and 3, estimate the direct energy consumed by all industries by multiplying the energy coefficient by the forecasted investments in control devices.

Step 5: Indirect Energy Consumption for Water Pollution Control — Using the information developed in Steps 2 and 3, estimate the energy consumed in the production of chemicals and in the construction of industrial pollution-control devices by multiplying the energy coefficients by the forecasted investments in control devices.

Thus, the methodology is based on the development of coefficients which express energy consumption as a function of investment in pollution control equipment. Although imperfect, this relationship is reasonable for making first-order estimates of energy requirements. The methodology also considers two sources of indirect energy consumption--the energy required to produce the chemicals used by pollution control devices and the energy used in the construction of control devices.

The assumptions which are necessary in order to develop the energy estimates include:

1. The detailed estimates of capital, energy and chemical costs for water pollution control by industry made by Vanderbilt University* for EPA are reasonable at least in terms of the relationship between capital cost and the two categories of operating costs.

2. The energy costs reported by Vanderbilt University are all costs for electric power.

3. Averaging of the energy coefficients from the mostly seven-digit SIC data developed by Vanderbilt to a two-digit level, and across plant sizes, produces macro energy coefficients which are representative of the industry. Industries for which Vanderbilt does not report energy costs will have energy coefficients similar to the average of all industries for which data are reported.

4. Industries for which Vanderbilt does not report types of chemicals consumed will use a mix of equal amounts of the various chemicals reported for other industries.

5. Industry will primarily employ end-of-pipe treatment for the control of water pollution.**

---

* Vanderbilt University's study of water pollution control costs was used by EPA for the 1975 "Cost of Clean Environment" report.

** Although this assumption is necessary for this analysis, evidence is mounting that some industries are moving toward process change as a method for both reducing pollutant generation and improving production efficiency and/or production economics.

6. CEQ's estimates, by industry, of investment for water pollution control are reasonable.

7. Capital expenditure is the best single indicator of energy consumption for the mix of control techniques within a particular industry.

8. Investments made through a given year (e.g. 1976) realize operating costs in the following year (e.g. 1977). Thus, investments in pollution control devices through 1976 are the basis for calculating energy consumption in 1977.

9. Capital equipment will last 20 years, and therefore the energy equivalent of capital equipment is "amortized" over a 20-year period.

Energy Demands for Industrial Water Pollution Control

The energy consumption coefficients used for this analysis were derived after a detailed analysis of typical plant data for 81 industrial sectors (at the seven-digit SIC level) and three different plant sizes. The objective of the detailed analysis of the 243 data points was to determine whether a statistically valid relationship among energy cost, capital cost and O&M cost for water pollution control existed across the industrial sectors. Because of constantly changing estimates of industry expenditures for abatement of water pollution, and because of the paucity of energy data, it was hoped that a general equation could be developed which would permit the prediction of energy cost given O&M and capital cost estimates.

The analysis proved that energy consumption for water pollution control is sector (or even plant) specific, and that generalization across sectors does not accurately predict the energy usage of any of the sectors. This finding reflects the variabilities which exist in industrial approaches to pollution control. These variabilities, in turn, reflect differences among many parameters, including waste stream composition, plant size and age, local conditions, behavior of individual decision-makers and plant engineers, and production process mixes within specific manufacturing facilities. The finding from this analysis lends support to the argument for gathering better data on the energy consumption characteristics of various abatement techniques being used or developed by industry, and for developing better forecasts of the population and processing throughput of the techniques.

The analysis of data on the 81 sectors did produce information which was useful for developing the energy estimates contained in this report. First, it was determined that, when the data on the 81 sectors were collapsed to the roughly two-digit SIC level used by CEQ for its pollution control cost estimating, the average of the individual energy cost to capital cost ratios provided forecasts of energy cost from the aggregated capital cost which were reasonably close to forecasts developed from the individual components. Second, statistical analysis showed that information on total O&M cost did not improve the predictive accuracy of the energy to capital cost ratio.

For the purposes of this study, then, it was decided to base the energy estimates on forecasts of capital expenditures by major industrial sectors and on average energy to capital ratios for the various sectors. Although this approach is crude, the results produced are likely to at least reasonably represent (in the total) the magnitude of energy consumption associated with given industrial investments in water pollution control.

The estimates of energy requirements for water pollution control are derived by converting energy cost/capital cost ratios for the industrial sectors to coefficients of the form Btu/$ capital. These coefficients are then used to calculate the sector energy consumption associated with CEQ's investment forecasts.

The investments for water pollution control by industry will be, according to CEQ:

- $15.334 billion through 1976
- $34.260 billion through 1982

Over 80 percent of these investments will occur in five (of twelve) industries:

- Chemicals (27% of total)
- Petroleum refining (17%)
- Paper and allied products (15%)
- Primary metals (12%)
- Food & kindred products (11%)

The investments in water pollution control for each industry significantly affected by Amendments to the Water Act are shown in Table 2-1. The table also shows the energy coefficients used for each industrial sector, and the resultant forecasts of direct energy consumption for 1977 and 1983. The most notable feature of the energy consumption forecasts is that although the chemicals industry is estimated to spend 27 percent of the total water pollution control investment by industry, its energy consumption is 53 percent of the total.

Direct operating energy is not the only energy requirement for water pollution control. In addition to operating energy there is energy "contained" in the chemicals and other materials used to build and supply pollution control devices. These indirect energies can sometimes be major contributors to the total energy required for pollution control.

Table 2-2 lists the energy equivalents of chemicals used for water pollution control. In order to determine the indirect energy due to chemicals, the conversion coefficients relating energy to costs (last column) were used. They were multiplied by the cost of chemicals as a fraction of total capital investment. This process is illustrated in Table 2-3. For most industries annual chemical costs are three cents per dollar of investment and the average energy/cost coefficient of 311,000 Btu/$ is used. The resulting indirect energy required for chemicals is in some industries larger than the

TABLE 2-1. ANNUAL DIRECT ENERGY REQUIRED FOR INDUSTRIAL WATER POLLUTION CONTROL

Industry	Cumulative Capital Investment (millions of 1975 $)*		Direct Energy Coefficient (1000 Btu/$)*	Direct Energy Required (10^{12} Btu)	
	1977	1983		1977	1983
Primary Metals	1,852	4,074	4.75	9	19
Machinery	809	4,809	17.54	14	84
Transportation Equipment	500	1,108	17.54	9	19
Stone, Clay and Glass	154	243	16.85	3	4
Other Durables	637	1,656	17.54	11	29
Chemicals	4,198	9,561	40.61	170	388
Textiles	374	589	17.54	7	10
Rubber	60	120	17.54	1	2
Paper	2,289	4,976	16.85	39	84
Petroleum	2,558	4,599	8.64	22	40
Food	1,665	2,126	22.03	37	47
Other Nondurables	238	339	21.65	5	9
TOTALS	15,334	34,260		326	736

* Fuel equivalent of electricity equals 10,660 Btu per kwh.

direct operating energy (compare Tables 2-2 and 2-3). The average indirect chemical energy of all industries is 37 percent of direct operating energy, and therefore it is an important part of the total energy required for water pollution control.

TABLE 2-2. ENERGY EQUIVALENTS OF SELECTED CHEMICALS

Chemical	Btu per Pound	Btu per 1975 $
Activated Carbon	12,100	173,000
Lime	2,500	342,000
Sulfuric Acid	1,400	107,000
Soda Ash	19,000	155,000
Chlorine	14,500	397,000
Methanol	14,000	599,000
Polymer	47,800	268,000
Ammonia	25,000	450,000
AVERAGE		311,000

The other kind of indirect energy, construction energy, was estimated from capital investment also. Using dollar-to-Btu conversion coefficients derived for capital equipment, and assuming 20-year life for pollution control equipment, an annual energy equivalent for construction was developed. Table 2-4 lists the indirect energy associated with construction. It can be seen by comparison with Table 2-1 that indirect energy due to construction does not add significantly to energy needed for direct operation.

Total energy requirements are obtained from the sum of direct and indirect energy for water pollution control. Table 2-5 summarizes energy requirements for the industrial sectors. According to its results, in 1977 some 479 trillion Btu will be needed to reduce industrial water pollution, and that total will more than double to 1,079 trillion Btu in 1983.

TABLE 2-3. CHEMICALS: ANNUAL INDIRECT ENERGY REQUIRED FOR INDUSTRIAL WATER POLLUTION CONTROL

Industry	Capital Investment (millions of 1975 $)		Chemical Cost Coefficient ($/$ Investment)	Chemical Energy Coefficient (1000 Btu/$)*	Chemicals: Energy Require (10^{12} Btu)	
	1977	1983			1977	1983
Primary Metals	1,852	4,074	0.030	311	17	38
Machinery	809	4,809	0.030	311	8	45
Transportation Equipment	500	1,108	0.030	311	5	10
Stone, Clay and Glass	154	243	0.030	311	1	2
Other Durables	637	1,656	0.030	311	6	15
Chemicals	4,198	9,561	0.030	173	22	50
Textiles	374	589	0.030	311	3	6
Rubber	60	120	0.136	173	1	3
Paper	2,289	4,976	0.030	311	21	46
Petroleum	2,558	4,599	0.030	311	24	43
Food	1,665	2,126	0.015	433	11	14
Other Nondurables	238	399	0.030	311	2	4
TOTALS	15,334	34,260			122	276

* Fuel equivalent of electricity equals 10,660 Btu per kWh.

TABLE 2-4.
CONSTRUCTION: ANNUAL INDIRECT ENERGY REQUIRED FOR INDUSTRIAL WATER POLLUTION CONTROL

Industry	Capital Investment (millions of 1975 $)		Construction Energy Coefficient (1000 Btu/$)*	Construction: Energy Required (10^{12} Btu)	
	1977	1983		1977	1983
Primary Metals	1,852	4,074	2	4	8
Machinery	809	4,809	2	2	10
Transportation Equipment	500	1,108	2	1	2
Stone, Clay and Glass	154	243	2	-	-
Other Durables	637	1,656	2	1	3
Chemicals	4,198	9,561	2	8	19
Textiles	374	589	2	1	1
Rubber	60	120	2	-	-
Paper	2,289	4,976	2	5	10
Petroleum	2,558	4,599	2	5	10
Food	1,665	2,126	2	3	4
Other Nondurables	238	399	2	1	1
TOTALS	15,334	34,260		31	68

*Assumed 20-year life for pollution control devices.

TABLE 2-5. ANNUAL TOTAL ENERGY REQUIRED FOR INDUSTRIAL WATER POLLUTION CONTROL

Industry	Total Energy Required (10^{12} Btu) 1977	1983
Primary Metals	30	65
Machinery	24	139
Transportation Equipment	15	32
Stone, Clay and Glass	4	7
Other Durables	18	49
Chemicals	200	456
Textiles	11	16
Rubber	3	5
Paper	65	140
Petroleum	51	92
Food	50	65
Other Nondurables	9	14
TOTAL	479	1,079

2.2 Control of Thermal Pollution from Electric Power Plants

Studies by the EPA indicate that by 1977 almost $800 million will have been spent by members of the electric utility industry on methods for controlling thermal water pollution. By 1983 it is estimated the cost will have increased to over $1.2 billion. The expenditures will be made to conform to the final guidelines on thermal pollution abatement, published by EPA. These guidelines exempt plants of certain sizes, ages, and locations, but most plants covered by the regulations will require elaborate equipment to reduce thermal impact on nearby bodies of water.

Estimates of energy that will be used to manufacture, install and operate cooling equipment are developed in the following pages. Mechanical forced-draft cooling towers have been selected as the typical control method that will be used to meet the guidelines. Plants for which cooling towers will be employed for economic rather than environmental reasons are not included in the energy estimates.

Methodology and Assumptions

The methodology employed for arriving at estimates of energy consumption by power plants for control of thermal pollution follows five steps:

Step 1: Cooling Tower Operating Energy — Determine the operating energy required for mechanical forced-draft cooling towers as a function of plant size and type.

Step 2: Capacity Requiring Cooling Towers — Determine the total generating capacity which requires cooling towers in terms of plant size and type.

Step 3: Direct Energy Consumed for Controlling Thermal Pollution — Using the information from the previous step, calculate the energy consumed by electric utilities in meeting the thermal pollution re-regulations.

Step 4: Capacity Penalty — The electricity to run the thermal pollution control equipment is supplied by the power plant. Using the estimates obtained in Step 3, estimate the capacity additions necessary and the "energy cost" of those additions.

Step 5: Materials Energy Penalty — From the estimates of capacity requiring cooling towers (Step 2), estimate the energy cost of constructing cooling towers.

The key assumptions used in the analysis include:

1. Mechanical forced-draft cooling towers are representative of devices used by utilities to control thermal pollution.

2. The operating efficiency of cooling towers increases with the size of the tower (and therefore with plant size). Consequently, energy for cooling, per unit of electricity generated, decreases as the plant size increases.

3. The energy required to operate a cooling tower is directly proportional to the amount of cooling required, which, in turn, is directly related to plant efficiency, load factor and heat loss to the atmosphere.

4. Fossil and nuclear power plant operating efficiencies, 34 percent and 32 percent respectively, will not change between 1977 and 1983. Load and capacity factors will be as was published by EPA.*

5. Estimates of generating capacity requiring cooling towers are derived from the publication listed in Step 4.

---

* Temple, Barker & Sloane, Inc. Economic and Financial Impacts of Federal Air and Water Pollution Controls on the Electric Utility Industry, Technical Report for U.S. EPA, May 1976.

6. Generating capacity will have to be added to replace that which is used for thermal pollution control. The additional generating capacity results in an energy equivalent for construction of new generating facilities.

7. The published estimated cost of cooling towers is reasonable.* The energy for cooling tower construction is 36,925 Btu/$ (I/O Sector 1103, Public Utility Construction).**

Requirements for Mechanical Forced-Draft Cooling Towers

As a result of the effluent guidelines, in 1977 some 17.21 x 10^6 kw of nuclear capacity and 56.49 x 10^6 kw of fossil capacity will have installed cooling towers. By 1983, 29.03 x 10^6 kw of nuclear capacity will require cooling towers, while 91.1 x 10^6 kw of fossil will be impacted by the guidelines.

Energy Demands for Mechanical Forced-Draft Cooling

Evaluation of the operating characteristics of forced-draft cooling towers suggests that, with 15 percent and 5 percent heat loss to the atmosphere for fossil fuel and nuclear plants respectively, the energy penalty associated with operating the devices will be (by plant size):***

ENERGY FOR OPERATING MECHANICAL FORCED-DRAFT COOLING TOWERS
(kwh per Megawatthour)

Plant Capacity	Fossil Fuel Plants	Nuclear Plants
50 Megawatt	34.2	42.2
150 Megawatt	33.2	41.0
500 Megawatt	27.0	33.4
900 Megawatt	24.0	29.6
1500 Megawatt	21.4	26.4
3000 Megawatt	18.3	22.7

* Temple, Barker & Sloan, Inc. Economic and Financial Impacts of Federal Air and Water Pollution Controls on the Electric Utility Industry, Technical Report for U.S. EPA, May 1976.

** Development Sciences, Inc., Application of Net Energy Analysis to Consumer Technologies. Report to U.S. ERDA, Contract E(49-1)-3847, Dec. 1976.

*** Jimeson, R.M; G.G. Adkins, "Waste Heat Disposal in Power Plants," Chemical Engineering Progress, Vol. 67, No. 7 (July 1971), 64.

Data on the distribution of expected cooling tower installations by plant capacity are not readily available. However, it can be assumed that the distribution of installations by size of plant will follow closely the projected distribution of new thermal power plant capacity. Analysis of Edison Electric Institute's 59th Electric Power Survey (April, 1976) indicates a plant distribution of:

DISTRIBUTION OF PROJECTED NEW
THERMAL POWER PLANT CAPACITY

(Approximate Percentages of Total New Capacity by Type of Plant)

Plant Capacity	Fossil Fuel Plants	Nuclear Plants
50 Megawatt	-	-
150 Megawatt	6%	-
500 Megawatt	62%	-
900 Megawatt	24%	58%
1,500 Megawatt and Greater	8%	42%
	100%	100%

The weighted average operating energy for cooling towers, calculated by combining the two previous tables, is 26.2 kwh per megawatt hour for fossil plants, and 28.3 kwh per megawatt hour for nuclear plants. These estimates include the energy required to operate the cooling equipment as well as some losses in turbine efficiency caused by back pressure. Given the generation for each plant type in 1977 and 1983, the operating energy penalty is 91 x 10^{12} Btu in 1977 and 153 x 10^{12} Btu in 1983.

Energy Demands for Capacity Replacement

In the case of nuclear generation the operating energy penalty is 2.8 percent of input energy while for fossil fuel generation the energy penalty is 2.5 percent. Consequently, the capacity penalty is assumed to be 2.8 percent and 2.5 percent for nuclear and fossil plants, respectively.

Given the required capacity additions (equal to the percent capacity penalty multiplied by capacity affected), the 1975 cost of that additional capacity, the energy intensity of construction [measured in Btu/$(1975)], and an assumed 20-year life for the equipment, the capacity penalty is estimated for 1977 to be 0.9 x 10^{12} Btu and for 1983 to be 1.5 x 10^{12} Btu.

Materials Energy Estimate

The materials energy estimate is based on cooling tower installation costs of $5.77 per kilowatt capacity (1975 dollars).* Using the energy intensity of construction, the materials energy equivalent is 16×10^{12} Btu for 1977 and 26×10^{12} Btu for 1983. Amortizing over 20 years, the annual materials energy total for 1977 is 0.8×10^{12} Btu and for 1983 is 1.3×10^{12} Btu.

Summary of Results

The energy for meeting thermal water pollution regulations both in 1977 and 1983 is summarized in Table 2-6. Major energy requirements are those for direct operating energy; the capacity penalty and materials energy equivalents make up only a small fraction of the total. The energy for controlling thermal water pollution from electric power plants increases by 67 percent, from 93 trillion Btu in 1977 to 156 trillion Btu in 1983.

* Temple, Barker & Sloane, Inc., Economic and Financial Impacts of Federal Air and Water Pollution Controls on the Electric Utility Industry, Technical Report for U.S. EPA, May 1976, page III-24. The $5.77 per kilowatt is the cost for new units. While the cost for retrofits is more than four times as great, it was assumed that the new unit cost is most representative for the energy calculation.

TABLE 2-6. DIRECT AND INDIRECT ANNUAL ENERGY REQUIRED FOR POWER PLANT FORCED-DRAFT COOLING TOWERS: 1977 AND 1983

Type	Energy Required (10^{12} Btu) 1977	1983
Fossil Fuel		
Operating Energy	67	107
Capacity Penalty	1	1
Materials Energy	1	1
Subtotal	69	109
Nuclear Fuel		
Operating Energy	24	46
Capacity Penalty	-	1
Materials Energy	-	-
Subtotal	24	47
All Plants		
Operating Energy	91	153
Capacity Penalty	1	2
Materials Energy	1	1
Total	93	156

2.3 Municipal Wastewater Treatment

Local governments have been collecting and treating sewage as a matter of course for many years. In 1976, approximately 75 percent of the United States' population was served by sewer systems, and more than 90 percent of the collected sewage was treated in either a primary or secondary treatment plant before discharge to the water or land. However, the Amendments to the Water Pollution Control Act require higher average levels for treating sewage wastes so that additional facilities will be needed.

According to estimates derived from EPA's 1976 Survey of Needs for Municipal Wastewater Treatment Facilities, almost $27 billion will have to be spent to bring all treatment plants into conformity with the standards called for by the Amendments. Nearly $10 billion will be spent to build secondary treatment plants, and the remaining $17 billion will be used to construct tertiary treatment facilities.* As the complexity of treatment increases from secondary to tertiary processes, costs and operating energy go up dramatically.

* The basis for these estimates is an unpublished analysis by CEQ of the 1976 "Needs" data. DSI recognizes that results of the Needs Survey are difficult to interpret and that certain of the data appear to contradict actual and likely practices at the local level. Some of these data problems will be alleviated when EPA has received and analyzed the plans prepared under Section 208 of PL 92-500.

In the pages that follow estimates are developed to determine both direct and indirect energy associated with improvement in municipal wastewater treatment.

Methodology and Assumptions

Energy estimates were made using a four-step methodology.

Step 1: Amount of Treatment Required	Determine the number and size of new treatment facilities that will be required to meet water pollution standards. Calculate total flow rates through new plants.
Step 2: Mix of Treatment Plants	Determine the distribution of levels and types of treatment that will be added in order to conform to the standards.
Step 3: Treatment Unit Energy Characteristics	Determine the direct and indirect energy required to treat a unit flow of wastewater for each type of treatment in Step 2.
Step 4: Total Energy Required to Meet Wastewater Treatment Standards	From the flow rates through new plants (Step 1) and the energy characteristics for unit flow (Step 3), calculate total direct and indirect energy for wastewater treatment.

The methodology is based on simplifying the mix of plant sizes, designs, levels and types of treatment, and costs to a few representative units. It requires five key assumptions. They are:

1. "Needs Survey" data give good estimates of communities requiring added treatment facilities.

2. Plant size can be estimated from the population of the community served, using a flow rate of 100 gallons per person per day.

3. The energy requirements of sewage treatment facilities are directly proportional to the plant size, so that unit treatment characteristics apply to all plants regardless of size.

4. Unit processes can be determined from standard 30 million gallon per day plants described in a recent EPA report.*

---

* Energy Conservation in Municipal Wastewater Treatment, prepared for EPA by Culp, Wesner and Culp, 1976.

5. Future secondary treatment processes will be activated sludge, oxidation ponds and trickling filter, in the ratio of 5/3/2, respectively.*

The DSI staff is concerned about the validity of these assumptions. For example, it is not clear that the "Needs Survey" accurately projects future sewage treatment requirements (assumption 1) nor can much confidence be placed in a linear relationship between plant size and energy characteristics (assumption 3). However, within the constraints imposed by this project, the assumptions are thought to be acceptable. Numbers of new treatment plants are probably overestimated; the energy required per unit of wastewater flow, using a large 30 MGD plant that is likely more efficient per unit than is the average mix of plants, is probably underestimated. Thus, the errors resulting from these assumptions at least partly cancel each other, and energy estimates are probably in the proper range of magnitude.

Needs Survey data are not exactly attributable to the year 1983. Many of the plants listed may be built later in the 1980s. However, it has been assumed that energy estimates for all new facilities apply to 1983.

The number and size of new treatment facilities were estimated from data of the 1976 Survey of Needs for Municipal Wastewater Treatment Facilities. Table 2-7 shows approximations for populations of communities served by new treatment facilities, for numbers of new facilities needed by treatment level, and for costs of those additions.

TABLE 2-7. ESTIMATES OF NEW WASTEWATER TREATMENT UNITS BY SIZE AND LEVEL OF TREATMENT

Community Size (thousands)	Number of Units			Costs (billions of 1976 $)
	Primary	Secondary	Tertiary	
0 - 2.5	9,670	13,070	3,570	12
2.5 - 5.0	800	1,620	520	2
5.0 - 15	800	1,830	650	3
15 - 25	210	500	170	2
25 - 50	180	410	130	2
50 - 100	100	240	90	2
100	80	220	90	5
TOTAL	11,840	17,890	5,220	27*

* Individual costs do not sum to total cost due to independent rounding.

Average community sizes were assumed to be half the range shown in the table, and plant size in gallons per day was estimated as 100 times the

* This ratio of treatment methods is based on the aforementioned unpublished analysis by CEQ of 1976 "Needs Survey" data.

community population. So, for example, it is estimated that 9,670 communities of 1,250 people each will need new 125,000 gallon per day primary treatment units, for a total requirement of (9,670 x 125,000 gallons per day) 1.2 billion gallons per day of new primary treatment capacity. Similar calculations for each size and type of treatment yield the following results:

Treatment Level	New Treatment Capacity Required (billion gallons per day)
Primary	5.4
Secondary	11.7
Tertiary	4.2

The 11.7 billion gallons per day of secondary treatment capacity is divided into 5.85 billion gallons per day of activated sludge treatment, 3.51 billion gallons per day of oxidation pond treatment, and 2.34 billion gallons per day of trickling filter treatment, according to the assumed distribution 5/3/2, respectively.

The end of this section contains four process schematics (Figures 2-1 through 2-4) and four tables (Tables 2-9 through 2-12) that describe standard 30 million gallon per day treatment plants. The tables were used to obtain operating and chemical energy estimates for wastewater treatment. Data from the four tables were divided into primary, secondary and (for Activated Sludge with Nitrification, Chemical Clarification, Filtration and Carbon Adsorption) tertiary treatment level processes. Operating and chemical energy requirements were then scaled to meet the capacity needs listed above.

Energy is used in the construction and maintenance of wastewater treatment facilities. An estimate of the "indirect" energy requirements can be obtained by converting the costs of facilities to energy equivalents. Estimating techniques have been developed to make cost-to-energy conversions,* and these were applied to the costs reported in Table 2-7.

The conversion factor for wastewater treatment facilities was determined to be 34,830 Btu per dollar in constant 1976 dollars. Multiplying by the facilities' cost ($27 billion) results in total energy requirements of approximately 940 trillion Btu. Facilities were "amortized" over 20 years, yielding a yearly energy requirement of 47 trillion Btu.

Table 2-8 shows both direct and indirect energy required for wastewater treatment. Although the indirect energy from the use of chemicals is not large compared to direct operating energy, the energy equivalent of treatment plants and equipment contributes substantially to the total. Together the chemical and "construction" energies are 57 percent as large as the direct energy. The total annual energy required for new wastewater treatment facilities will be 151 trillion Btu, according to the estimates reported in Table 2-8.

* A discussion of the estimating techniques can be found in Application of Net Energy Analysis to Consumer Technologies, prepared for ERDA by DSI, December 1976. Appendix A contains dollar-to-energy conversion factors for each of 357 economic sectors, including the public utility construction sector used for estimates in this study.

TABLE 2-8. ANNUAL ENERGY REQUIREMENTS
FOR MUNICIPAL WASTEWATER TREATMENT: 1983*

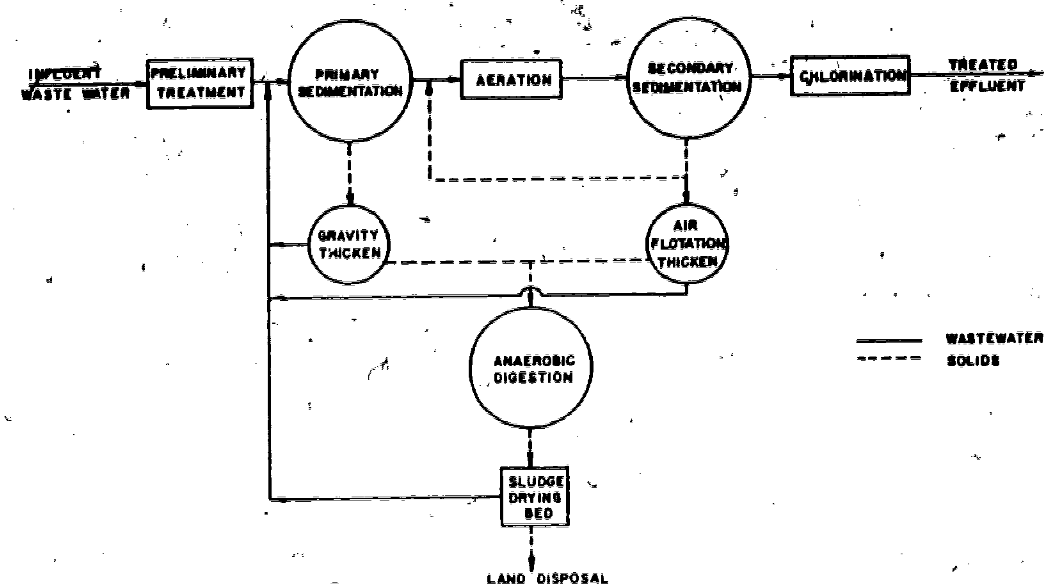
Treatment Level	Energy Requirements (10^{12} Btu**) Direct	Chemical	Construction	Total
Primary	6	4	***	10
Secondary				
Trickling Filter	4	-	***	4
Activated Sludge	23	-	***	23
Oxidation Ponds	6	-	***	6
SUBTOTAL	33	-	***	33
Tertiary	57	4	***	61
TOTAL OPERATING	96	8	***	104
Energy Equivalent of Facilities			47	47
GRAND TOTAL	96	8	47	151

* Nominal date

** Electricity was converted to Btu at 10,660 Btu per kwh

*** Estimated for grand total only

FIGURE 2-1. ACTIVATED SLUDGE WITH ANAEROBIC DIGESTION



PROCESS SCHEMATIC

Source: Culp, Wesner and Culp.

TABLE 2-9. ACTIVATED SLUDGE WITH ANAEROBIC DIGESTION

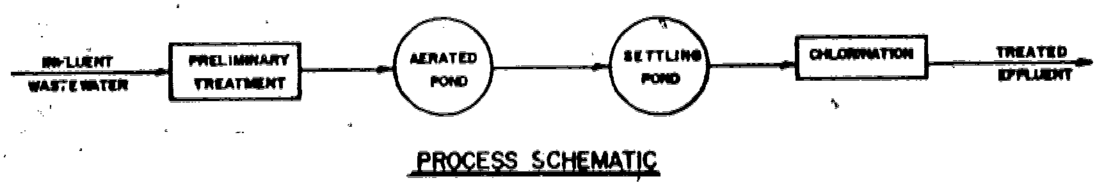
30 mgd PLANT CAPACITY

Process	Primary Energy Required: Thousand kwh/yr	Primary Energy Required: Million Btu/yr	Secondary Energy Required: Thousand kwh/yr
Treatment Processes			
Raw Sewage Pumping*	470		
Preliminary Treatment*	102		
Bar Screen*			
Comminutor*			
Grit Removal Aerated*			
Primary Sedimentation-Circular*	30		
Aeration-Mechanical	4,900		
Secondary Sedimentation	250		
Chlorination*	290		1,828
SUBTOTAL*	6,042		1,828
Gravity Thicken**	8		
Air Flotation Thicken**	1,250		
Anaerobic Digestion**	1,500	31,755	
Sludge Drying Bed**	15	150	
Land Disposal-Truck		1,400	
SUBTOTAL	2,773	33,305	
Building Heat*		500	
Building Cooling*	100		
SUBTOTAL	100	500	
TOTAL TREATMENT PROCESSES	8,915	33,805	1,828

* Primary treatment
** Fifty percent primary, 50 percent secondary treatment

Source: Culp, Wesner, and Culp

FIGURE 2-2. OXIDATION PONDS



Source: Culp, Wesner and Culp.

41

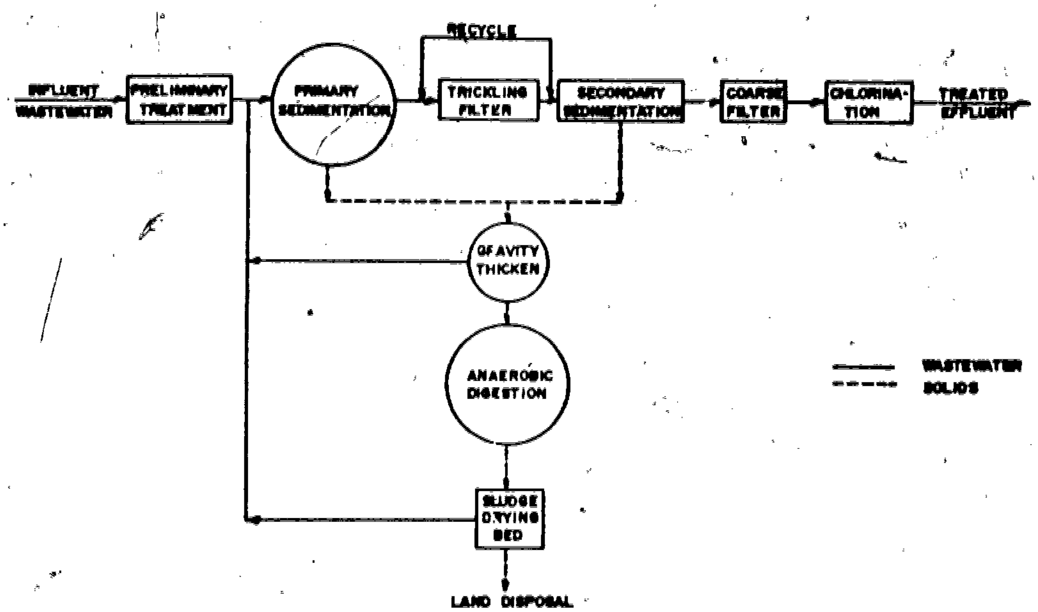
TABLE 2-10. OXIDATION PONDS

30 mgd PLANT CAPACITY

Process	Total Energy Required	
	Thousand kwh/yr	Million Btu/yr
Primary Energy		
Raw Sewage Pumping	470	
Preliminary Treatment Bar Screen Comminutor	22	
Aerated Pond	7,400	
Chlorination	290	
TOTAL PRIMARY ENERGY	8,182	
Secondary Energy		
Chlorine	1,828	
TOTAL PRIMARY AND SECONDARY	10,010	

Source: Culp, Wesner and Culp.

FIGURE 2-3. TRICKLING FILTER WITH COARSE FILTRATION



PROCESS SCHEMATIC

Source: Culp, Wesner and Culp.

TABLE 2-11. TRICKLING FILTER (ROCK MEDIA) WITH COARSE FILTRATION 30 mgd PLANT CAPACITY IN SOUTHERN UNITED STATES

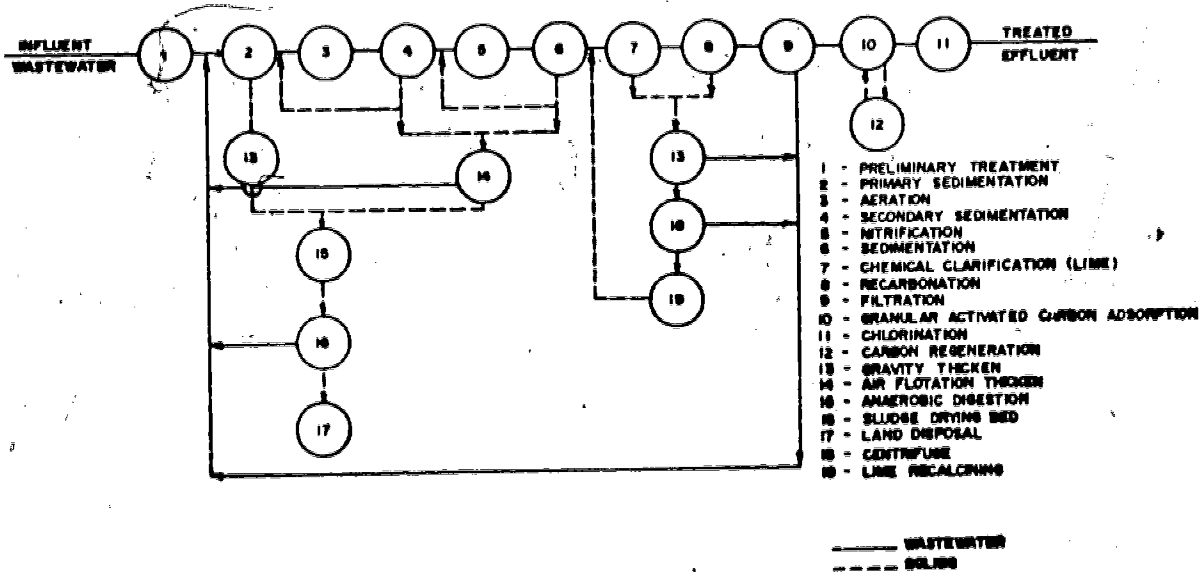
Treatment Processes	Primary Energy Required		Secondary Energy Required
	Thousand kwh/yr	Million Btu/yr	Thousand kwh/yr
Raw Sewage Pumping*	470		
Preliminary Treatment *	23		
Bar Screen*			
Comminutor*			
Grit Removal--Nonaerated*			
Primary Sedimentation Circular*	30		
Trickling Filter--High Rate, Rock Media	1,500		
Secondary Sedimentation	35		
Coarse Filter	930		
Chlorination*	290		1,828
SUBTOTAL	3,278		1,828
Gravity Thicken**	8		
Aerobic Digestion**	1,000	31,755	
Drying Bed**	15	150	
Land Disposal--Truck**		1,400	
SUBTOTAL	1,023	33,305	
Building Heat*		500	
Building Cooling*	100		
SUBTOTAL	100	500	
TOTAL TREATMENT PROCESS ENERGY	4,401	33,805	1,828

* Primary Treatment

** 50 percent Primary, 50 percent Secondary Treatment

Source: Energy Conservation in Municipal Wastewater Treatment. Prepared for EPA by Culp, Wesner and Culp, 1976.

FIGURE 2-4. ACTIVATED SLUDGE WITH NITRIFICATION, CHEMICAL CLARIFICATION, FILTRATION AND CARBON ADSORPTION



PROCESS SCHEMATIC

Source: Culp, Wesner and Culp.

TABLE 2-12. ACTIVATED SLUDGE - TERTIARY, 30 mgd PLANT CAPACITY IN NORTHERN UNITED STATES

Process	Total Energy Required	
	Thousand kwh/yr	Million Btu/yr
Primary Energy		
Raw Sewage Pumping	470	
Preliminary Treatment	102	
Bar Screen		
Comminutor		
Grit Removal--Aerated		
Primary Sedimentation--Rectangular	52	
Aeration--Mechanical	4,900	
Secondary Sedimentation	250	
Nitrification--Suspended Growth	4,500	
Nitrification Sedimentation	330	
Chemical Clarification (Lime) & Recarbonation	6,700	
Filtration--Gravity	670	
Chlorination	290	
SUBTOTAL	18,264	
Thicken--Primary Sludge	8	
Flotation Thicken	1,250	
Anaerobic Digestion	1,500	57,000
Sludge Drying Bed	15	150
Land Disposal--Truck		1,400
SUBTOTAL	2,773	58,550
Thicken--Chemical Sludge	15	
Centrifuge	2,121	
Lime Recalcination	900	150,000
SUBTOTAL	3,036	150,000
Building Heating		1,500
Building Cooling	7	
TOTAL PRIMARY ENERGY	24,080	210,050
Secondary Energy		
Lime		25,080
Chlorine	1,828	
TOTAL SECONDARY ENERGY	1,828	25,080
TOTAL PRIMARY AND SECONDARY ENERGY	27,736	235,130

Source: Culp, Wesner and Culp

3.0 ENERGY REQUIRED FOR AIR POLLUTION CONTROL

The 1970 Amendments to the Clean Air Act call for actions to reduce air pollution in the United States. The two sections that follow present estimates of energy needed to comply with provisions of the Amendments. They are divided into:

- Control of industrial air pollution
- Control of SO_x and particulate emissions from electric power plants.

Only stationary point sources of pollution are considered in these sections and in this report.

3.1 Industrial Air Pollution Control

It is estimated that by 1977 members of industry will have spent more than $16 billion on air pollution control equipment and that by 1983 more than $28 billion will have been committed. These investments are intended to result in major reductions in air pollution by industrial processes.

As in their approaches to water pollution control, industrial firms are seeking other than end-of-pipe techniques for meeting air quality standards. In-plant process changes, including reuse of recovered pollutants and generation of valuable by-products from components of emission streams, are in competition with end-of-pipe techniques when and where economic conditions favor them.

The following pages develop estimates of the energy consumption implications of forecasts of investments for control of industrial air pollution. These estimates are imprecise, first because the cost estimates on which they are based generally assume end-of-pipe control of pollutants; and second, because of scarcity of detailed operating data to support the cost estimates.

Methodology and Assumptions

The methodology employed for arriving at estimates of the direct energy requirements for industrial air pollution control includes five steps:

Step 1: Mix of Control Devices	From available (preliminary) data developed by Battelle for EPA,* determine the mix of pollution control devices to be invested in by industry.

* Battelle provided EPA with total O&M and capital cost data by control device and air regulation for a number of industrial sectors as part of EPA's efforts in improving estimates of the cost of environmental regulations.

Step 2: Operating Energy/Capital Cost of Devices — For the major air pollution control techniques, develop information on the annual operating energy required by a typical device and on the installed (capital) cost of the device.

Step 3: Energy Consumption Coefficients — For each of the devices analyzed in Step 2, calculate energy consumption coefficients, using annual operating energy and capital cost as the bases for the coefficients.

Step 4: Investments in Air Pollution Control — Using the results of Step 1 and data published by CEQ* on the investments by industry in air pollution control equipment, determine the pattern of investments for air pollution control by control device.

Step 5: Direct Energy Consumption for Air Pollution Control — Using the data developed in Steps 3 and 4, estimate the direct energy consumption by all industries for air pollution control by multiplying the energy coefficients by the forecasted investments in each device.

Thus, the methodology uses operating data from typical devices, and a forecast of device population, to arrive at a national estimate of energy requirements for industrial air pollution control.

The assumptions used to develop the energy estimate are:

1. The preliminary data developed by Battelle on investments by device are representative of the mix of air pollution control devices which will be employed by industry in the 1977-1983 time frame.

2. The data published in 1969 by HEW (National Air Pollution Control Administration) on the operating characteristics and costs of various devices for controlling particulates is relevant to the time frame for this analysis, with appropriate adjustments for inflation. The relationships among energy consumption, capital costs (adjusted to current prices), and device capacity presented in the HEW report are thus assumed to be stable into the early 1980s, and technological change in control devices is thus assumed to have a minimal impact on the energy consumption and the first cost of the devices.**

3. The CEQ forecasts of investments for pollution control by industry are reasonable.

4. Industry will control air pollution primarily through end-of-pipe control techniques.

---

* See Environmental Quality - 1976, the Seventh Annual Report of the Council on Environmental Quality.

** See Control Techniques for Particulate Air Pollutants, U.S. Department of Health, Education and Welfare, January 1969.

5. The energy coefficients of devices other than those for which coefficients were developed from engineering data can be reasonably set at the average of those analyzed.

6. Capital investments made through the end of one year are the basis for operating costs in the next year. Thus, investments through 1976 are used to calculate energy consumption from operations in 1977.

Investments in Industrial Air Pollution Control

Table 3-1 lists CEQ's estimates of the capital investments for industrial air pollution control for 1977 and 1983. The investments are spread over a number of industries, although the primary metals, chemicals and petroleum sectors will require the largest investments at 34 percent, 17 percent and 13 percent, respectively, of the total industrial investment.

TABLE 3-1. TOTAL CAPITAL INVESTMENT FOR AIR POLLUTION CONTROL (Millions of 1975 Dollars)

	1977	1983
Primary Metals	5,601	9,026
Machinery	728	1,488
Transportation Equipment	545	1,012
Stone, Clay and Glass	1,643	2,947
Other Durables	838	1,848
Chemicals	2,803	4,257
Textiles	-	-
Rubber	150	300
Paper	1,294	2,543
Petroleum	2,183	3,739
Food	573	1,078
Other Nondurables	142	475
TOTAL	16,500	28,749

Analysis of Battelle data indicates that almost 86 percent of industries' investments in air pollution control will be for five devices:

- Lime/limestone scrubbers (38.5% of total investments)
- Baghouses and fabric filters (25.5%)
- Wet collectors (13.2%)
- Electrostatic precipitators (5.8%)
- Acid plants (2.9%)

The remaining investment is divided among various other control techniques, including CO boilers, interstate adsorption, tail gas scrubbers, etc. Table 3-2 shows the investments of Table 3-1 divided among the five major control devices. It has been assumed that all industrial investments can be approximated by the five major devices.

TABLE 3-2. INVESTMENT BY INDUSTRY IN AIR POLLUTION CONTROL DEVICES

	Fraction of Total	Capital Investment (Millions of 1975 Dollars)	
		1977	1983
Electrostatic Precipitators	0.058	957	1,667
Wet Collectors	0.132	2,178	3,795
Lime/Limestone Scrubbers	0.385	6,353	11,068
Fabric Filters	0.255	4,208	7,331
Acid Plants	0.029	478	834
Other	0.141	2,326	4,054
TOTAL	1.000	16,500	28,749

Energy Demands for Industrial Air Pollution

Analysis of data from HEW, as well as data developed for other sections of this study, yields the following representative direct operating energy coefficients for the five major air pollution control techniques:

	Capacity or Flow Rate Through Collector	Typical (or Average) Installed Cost ($ 10^3)	Typical (or Average) Btu/year (10^9)	Energy/Capital Cost (1976) 10^3 Btu/$
Electrostatic Precipatators	100,000 acfm	265	1.46	5.49
Wet Collectors	20,000 acfm	32	3.03	93.41
Limestone Scrubbers	Based on installations on power plants ranging from 200 to 1000 MW	7288	233.20	32.00
Fabric Filters	300,000 acfm	466	13.15	28.23
Acid Plant	Based on 100,000 ton per year copper plant	19695	808.00	41.03
AVERAGE				40.03

Table 3-3 shows the results when these coefficients are combined with the investment forecasts. Wet collectors, with 13 percent of the investment, consume about 30 percent of the annual operating energy. Lime and limestone scrubbers are less energy intensive, but because they are a larger share of total investment (38.5 percent), they also consume approximately 30 percent of all direct energy. Total direct operating energy will be 643 trillion Btu in 1977 and 1,121 trillion Btu in 1983.

Indirect energy for air pollution control consists of the energy required to fabricate and to build pollution control devices. According to DSI estimates,* approximately 40,000 Btu are required for every (1976) dollar of capital investment for pollution control devices. The equipment is assumed to last 20 years, which results in an annual coefficient of 2,000 Btu/$.

Table 3-4 shows the indirect energy needed to support air pollution control by industry. The energy is small compared to direct operating energy.

Table 3-5 summarizes the energy required to manufacture, install and operate industrial air pollution control devices. The totals are 676 trillion Btu and 1,179 trillion ~~Btu~~ for 1977 and 1983, respectively.

* Estimates of the energy equivalents of equipment are discussed in Application of Net Energy Analysis to Consumer Technologies, Appendix A, prepared for ERDA by DSI, December 1976. Pollution control devices were assumed to have average Btu/dollar conversion factors.

TABLE 3-3. DIRECT ENERGY REQUIRED FOR INDUSTRIAL AIR POLLUTION CONTROL

Control Technique	Fraction of Total	Capital Investment (Millions of 1975 $)		Direct Energy Coefficient (1000 Btu/$)	Direct Energy Required (10^{12} Btu)	
		1977	1983		1977	1983
Electrostatic Precipitators	0.058	957	1,667	5.49	5	9
Wet Collectors	0.132	2,178	3,795	93.42	203	355
Lime/Limestone Scrubbers	0.385	6,353	11,068	32.00	203	354
Fabric Filters	0.255	4,208	7,331	28.23	119	207
Acid Plants	0.029	478	834	41.03	20	34
Other	0.141	2,326	4,054	40.03	93	162
TOTAL	1.000	16,500	28,749		643	1,121

TABLE 3-4. INDIRECT ENERGY REQUIRED FOR INDUSTRIAL AIR POLLUTION CONTROL

Control Technique	Capital Investment (Millions of 1975 $)		Construction: Energy Coefficient (1000 Btu/$)	Construction: Energy Required (10^{12} Btu)	
	1977	1983		1977	1983
Electrostatic Precipitators	957	1,667	2	2	3
Wet Collectors	2,178	3,795	2	4	8
Lime/Limestone Scrubbers	6,353	11,068	2	13	22
Fabric Filters	4,208	7,331	2	8	15
Acid Plants	478	834	2	1	2
Other	2,326	4,054	2	5	8
TOTAL	16,500	28,749		33	58

TABLE 3-5. TOTAL ENERGY REQUIRED FOR INDUSTRIAL AIR POLLUTION CONTROL

Control Technique	Total Energy Required (10^{12} Btu) 1977	1983
Electrostatic Precipitators	7	12
Wet Collectors	207	363
Lime/Limestone Scrubbers	216	376
Fabric Filters	127	222
Acid Plants	21	36
Other	98	170
TOTAL	676	1,179

3.2 Control of SO_x and Particulate Emissions from Electric Power Plants

The Council on Environmental Quality estimates that, as a result of the Clean Air Act Amendments of 1970, the electric utility industry will have invested about $8.9 billion in new plant and equipment for air pollution control by the end of 1982. These incremental capital expenditures will be for devices which limit the amount of particulates and sulfur oxides (SO_x) which escape into the atmosphere from the burning of oil or coal in utility boilers.

Oil- and coal-burning utilities will control particulates primarily through the use of electrostatic precipitators. SO_x emissions control is more complicated:*

1. SO_x can be removed from the power plant stack gases by scrubbers; and/or

2. The utilities can burn low sulfur fuels; and/or

3. Fuel producers can remove sulfur from their output at the point of mining or refining.

Any air pollution control method which requires a utility (or a refiner) to install and operate additional equipment as part of his production process will result in additional consumption of energy to operate the equipment and to provide any chemicals needed for the control process.

* Not included are methods such as tall stacks, intermittent control systems and supplementary control systems--none of which (alone) satisfy the ultimate requirements of the Clean Air Act.

The following subsections develop estimates of the additional energy required to make it possible for electric utilities to meet federal standards for SO_x and particulate emissions.

Methodology and Assumptions

The methodology used for estimating the energy consumed in order to reduce power plant-generated air pollutants to acceptable levels has twelve major steps:

Step 1: Precipitator and Scrubber Operating Energy as Percent of Plant Output	For the two power plant-based pollution control techniques (electrostatic precipitation and stack gas scrubbing), determine the energy required to operate the devices as a function of plant generating capacity.
Step 2: Required SO_x Removal from Flue Gas	Determine the required fraction of SO_x removal from the flue gas as a function of fuel heating value and weight percent sulfur.
Step 3: Chemicals Required/Sludge Produced by Scrubber	Determine the limestone and water needed, and sludge produced, by scrubbers as a function of fuel heating value and weight percent sulfur.
Step 4: Energy Per Ton to Produce Limestone and Dispose of Sludge	Determine the energy needed to produce and transport a unit (ton) of lime or limestone, and the energy consumed per ton to transport and dispose of sludge in a landfill.
Step 5: Residual Oil Desulfurization Operating Energy per Barrel	Determine the operating energy required per barrel of residual oil desulfurized (including the energy needed to produce the required amount of hydrogen for the desulfurization unit) as a function of weight percent sulfur in the residual oil and the resultant required fraction of sulfur removal.
Step 6: Power Plant Capacity and Fuel Mix in 1977 and 1983	Determine the predicted characteristics of power plants in 1977 and 1983, including generating capacity by type of fuel used.
Step 7: Coal and Oil Supply and Quality in 1977 and 1983	Determine the predicted supply, source and quality (sulfur content, heating value) of residual oil and coal for electric utilities in 1977 and 1983.

Step 8: Population of Control Devices

From the information produced in Steps 6 and 7, determine for 1977 and 1983:

a. the total megawatts of power generating capacity which will have to burn coal that exceeds the maximum acceptable sulfur content and therefore require stack gas scrubbers;

b. the total coal-burning capacity that will require western low sulfur coal;

c. the total amount of residual oil that requires desulfurization;

d. the total megawatts of fossil fuel burning capacity which will require electrostatic precipitators.

Step 9: Direct and Indirect Energy Consumed for Controlling Power Plant Air Pollution

Using the unit data developed from Steps 1-5 and the requirements forecasts developed in Step 8, determine the energy consumed in 1977 and 1983 for:

a. operating power plant electrostatic precipitators and limestone scrubbers;

b. producing limestone for the stack gas scrubbers;

c. disposing of the sludges produced by the scrubbers;

d. ransport of western low sulfur coal;

e. desulfurizing residual oil.

Step 10: Capacity Penalty

The operation of scrubbers and precipitators requires electricity that must come from capacity additions. Using the estimates obtained in Step 9, estimate the necessary capacity additions and then determine the energy cost of those additions.

Step 11: Capacity Penalty, Low Sulfur Coal

Because of the lower heating value of low sulfur coal (supplied principally from the Northern Great Plains) power plant capacity is derated. Estimate the capacity derating and the energy cost of replacing that capacity.

Step 12: Materials Energy

From the estimates of capacity requiring scrubbers and precipitators (Step 8) estimate the energy cost of constructing scrubbers and precipitators.

Thus, the methodology employed is based on developing a set of unit data for the various air pollution control techniques, and then applying the data to predicted requirements for each technique. Although the methodology falls far short of a more comprehensive materials flow approach, it does include consideration of energy consuming activities which occur prior to, and after, the operation of a control device itself.

Various assumptions are made at each step of the analysis. Some of the more important assumptions are:

1. Limestone scrubbing will be the dominant technique for removing SO_x from power plant flue gases over the time frame of 1975-1983. Low sulfur coal use will emerge by 1983 as the second most used control technique.

2. Electrostatic precipitators and Venturi scrubbers will be used for removing particulates from power plant flue gases over the 1976-1983 period. It is assumed that when Venturi scrubbers are used in combination with SO_2 scrubbers, the operating energy requirements over and above the energy for the SO_2 scrubbers are negligible. It is further assumed that all oil-fired capacity will use electrostatic precipitators.

3.*Over the range of sulfur and particulate removal normally required for power plants, neither scrubber nor precipitator operating energy varies significantly as the percent SO_x of particulates change.** (The validity of this assumption has not been verified for low-sulfur coal with high ash content. Thus, operating energies for precipitators on plants burning low-sulfur coal may be somewhat understated. This understatement is partly offset by the assumption that all oil-fired capacity will have precipitators.)***

4.*Scrubber and precipitator operating energies are direct (but different) functions of plant generating capacity. The ratios of operating energy to plant capacity for the devices are constant over the range of capacities covered in this analysis.

5. Limestone is the only chemical required in significant quantities for power plant air pollution control.****

---

* These assumptions were verified in part through analysis of available data from other studies.

** TVA report PB No. 183908, Sulfur Oxide Removal from Power Plant Stack Gas: Use of Limestone in Wet-scrubbing Process.

*** A further source of overstatement of the energy consumed for removing pollutants from flue gases is the assumption that the control device will be sized to handle the entire flow of gases. In practice, many control systems will be designed so that part of the gases will bypass the scrubber or precipitator. The feasibility of this design practice depends on the particular circumstances at a specific site.

**** DSI studies of operating scrubbers indicate that the predominant scrubbing technique uses limestone. Hittman Associates (Intermittent Versus Constant SO_2 Controls for Retrofit of Existing Coal-Fired Power Plants) similarly conclude that "the limestone slurry scrubbing system was chosen because it presently (1976) accounts for the largest percentage of installed megawatt capacity with FGD systems."

6. The sludge from limestone scrubbers will be disposed of (without drying) in a sanitary landfill at some distance from the power plant.*

7. **The operating energy for desulfurizing residual oil should include the energy needed to produce hydrogen for the desulfurization unit. The total operating energy increases nonlinearly as the sulfur content of the residual oil increases.

8. The efficiencies of fossil fuel plants will be constant over the 1975-1983 time frame, with fossil fuel plant efficiency at 34 percent and nuclear plant efficiency at 32 percent.

9. Total power generation, generating capacity by fuel type, and consumption of fuels by electric utilities in 1977 and 1983 will be as reported by EPA.***

10. The published estimated cost of scrubbers and precipitators is reasonable.*** The energy for scrubber and precipitator construction is 40,256 Btu/$ (1975).****

11. Total energy requirements attributable to United States air pollution regulations should be estimated. Consequently, energy used to desulfurize residual oil refined in foreign countries is included as well as energy required for domestic operations.

Coal-Fired Power Plants' Control Strategies

The energy penalties for three different control strategies for coal-fired power plants are presented in the following pages. Estimates were made for construction, installation and operation of limestone scrubbers, transportation and utilization of low sulfur coal, and construction, installation and operation of electrostatic precipitators. In the case of the precipitators, the estimates cover some coal-burning capacity and all oil-burning capacity.

The control strategies for coal-fired power plants are given in Tables 3-6 and 3-7 for 1977 and 1983, respectively. The coverage assumptions are derived from Economic and Finanaical Impacts of Federal Air and Water Pollution Controls on the Electric Utility Industry, Technical Report, Exhibit III-9 and a personal communication from James Ferry, U.S. EPA, on October 4, 1976. Estimates of the capacity utilizing coal are from the same report, Exhibit II-4.

---

* According to information from TVA (James Crowe, Tennessee Valley Authority, Personal Communication, November 1976), sludge is frequently disposed of in clay-lined ponds. However, this disposal technique will likely be unacceptable except as a short-term measure. Because of the uncertainties concerning improved methods for sludge disposal, this report does not include provisions for the energy required for (for example) sludge drying, recalcination, land reclamation or incineration.

** The assumptions were verified in part through analysis of available data from other studies.

*** Temple, Barker & Sloane, Inc., Economic and Financial Impacts of Federal Air and Water Pollution Controls on the Electric Utility Industry, Technical Report for U.S. EPA, May 1976, Page III-24.

**** Development Sciences Inc., Ibid.

TABLE 3-6. COAL-FIRED POWER PLANT COVERAGE ASSUMPTIONS AND CONTROL STRATEGY FOR COMPLIANCE WITH CLEAN AIR ACT: 1977 (10^6 kw)

Problem/Control Strategy	Pre-1974 Units	1974-76 Units	1977 Units	Total
Particulate Control				
Precipitators	61.3	18.2	5.0	84.5
Venturi Scrubbers*	21.1	11.5	6.7	39.3
SO_2 Control				
Scrubbers	42.9	11.5	6.7	61.1
Washing and Blending	37.2	-	-	37.2
Medium Sulfur Coal	21.8	11.4	-	33.2
Western Low Sulfur Coal	1.4	2.2	5.0	8.6

* Venturi scrubbers are installed in combination with SO_2 scrubbers

Sources: Temple, Barker & Sloane, Inc., Ibid, Table III-9; Personal Communication from J. Ferry, EPA, October 1976.

TABLE 3-7. COAL-FIRED POWER PLANT COVERAGE ASSUMPTIONS AND CONTROL STRATEGY FOR COMPLIANCE WITH CLEAN AIR ACT: 1983 (10^6 kw)

Problem/Control Strategy	Pre-1974 Units	1974-76 Units	Post-1976 Units	Total
Particulate Control				
Precipitators	61.3	18.2	54.6	134.1
Venturi Scrubbers*	21.1	11.5	52.4	85.0
SO_2 Control				
Scrubbers	42.9	11.5	52.4	106.8
Washing and Blending	37.2	-	-	37.2
Medium Sulfur Coal	21.8	11.4	-	33.2
Western Low Sulfur Coal	1.4	2.2	54.6	58.2

* Venturi scrubbers are installed ir ination with SO_2 scrubbers

Sources: Temple, Barker & Sloane, Inc., Ibid, Table III-9; Personal Cummunication from J. Ferry, EPA, October 1976.

Low Sulfur Coal - 1977

In 1977 power plants of 8.6 x 10^6 kw capacity will burn low sulfur coal. With a load factor of 55 percent for coal-fired power plants,* plants burning low sulfur coal will generate 41.4 x 10^9 kwh. Assuming a power plant efficiency of 34 percent, input energy to the power plants is 417.4 x 10^{12} Btu.

One of the energy penalties for utilizing western low sulfur coal is the operation of precipitators for control of particulates. The operating energy, capacity and materials energy penalties for those precipitators are calculated in a later section of this report.

There is a five percent capacity penalty** for pre-1977 power plants due to boiler derating associated with burning low sulfur western coal. Applying this penalty to the 3.6 x 10^6 kw burning low sulfur coal at a replacement cost (1975 dollars) of $211/kw* and using an energy cost of 36,925 Btu/$ gives a capacity penalty of 1.4 x 10^{12} Btu. When amortized over 20 years, the capacity penalty converts into an annual energy cost of .07 x 10^{12} Btu. Note that this is an upper limit on the capacity penalty; if excess capacity exists it can be brought online and the capacity penalty is diminished.

The major energy penalty associated with the utilization of low sulfur coal is the energy to transport the coal from the Northern Great Plains to the areas of consumption. Most coal-burning utilities in the United States are located in four regions: the Middle Atlantic region, the East North Central region, the South Atlantic region and the East South Central region. Transportation of coal from the Northern Great Plains to these regions implies a substitution of the low sulfur coal for traditional supplies. It is estimated that average transportation distances for the low sulfur coal will be 1,575 miles, and that the coal will supplant the traditional average transportation distance of 575 miles. Approximately 76 percent of the ton-miles of delivered western coal will be by rail (at an energy cost of 680 Btu/ton-mile); the remaining 24 percent will be by water (at an energy cost of 378 Btu/ton-mile), to give a weighted energy cost of 607.5 Btu/ton-mile.*** This compares with a weighted energy cost of 595.4 Btu/ton-mile for the current transport mix.

---

* Temple, Barker & Sloane, Inc., Economic and Financial Impacts of Federal Air and Water Pollution Controls on the Electric Utility Industry, Technical Report for U.S. EPA, May 1976.

** Pedco-Environmental Specialists, Inc., Particulate and Sulfur Dioxide Emission Control Cost Study of the Electric Utility Industry, Preliminary Draft for U.S. EPA, Contract 68-01-1900.

*** Mahoney, James et al; Energy Consumption of Environmental Controls: Fossil Fuel, Steam Electric Generating Industry, Draft Report prepared by Environmental Research & Technology, Inc., for U.S. Department of Commerce, January 1976.

In 1977 22.44 x 10^6 tons of low sulfur coal will be burned. Because of its relatively low heating value (9,300 Btu/lb, vs. 11,800 Btu/lb average for the high sulfur coal it replaces), the 22.44 x 10^6 tons will be substituting for 17.69 x 10^6 tons of high sulfur coal that would have been burned in the absence of air pollution regulations. This western low sulfur will be transported 1,575 miles at an energy cost of 607.5 Btu/ton-mile, giving a transportation energy cost of 21.47 x 10^{12} Btu.

The net transportation energy cost is found by subtracting the cost of transporting high sulfur coal from the gross energy cost of 21.47 x 10^{12} Btu for low sulfur coal. The 17.69 x 10^6 tons of high sulfur coal is transported a distance of 575 miles at a cost of 595.4 Btu/ton-mile. Thus the transport energy for traditional supply sources is 6.06 x 10^{12} Btu. The new transport cost for substituting low sulfur coal for high sulfur is 21.47 x 10^{12} minus 6.06 x 10^{12} Btu, or 15.41 x 10^{12} Btu.

Low Sulfur Coal - 1983

In 1983, 58.2 x 10^6 kw of coal-fired capacity will burn western low sulfur coal, generating 280.4 x 10^9 kwh. Power plant fuel input will be 2814.7 x 10^{12} Btu.

As in the 1977 case, the capacity penalty applies only to those units constructed prior to 1977. Thus the capacity affected is 3.6 x 10^6 kw, implying a capacity penalty of 1.4 x 10^{12} Btu, or .07 x 10^{12} Btu per year.

The major energy penalty associated with using low sulfur coal will again be the energy to transport coal. In 1983, 151.33 x 10^6 tons (at 9,300 Btu/lb) will have to be transported 1,575 miles, implying an energy cost of 144.79 x 10^{12} Btu. This supplants the shipment of 119.27 x 10^6 tons shipped 575 miles at an energy cost of 40.83 x 10^{12} Btu. The transportation increment is thus 103.96 x 10^{12} Btu.

Flue Gas Desulfurization - 1977

Energy penalties for flue gas desulfurization are divided into three categories:

1. An "energy penalty" associated with operating the scrubber. This consists of both the direct energy consumed in scrubber operation and the indirect energy to mine and transport limestone and to transport sludge to a disposal site.

2. A capacity penalty to reflect the additional capacity required to replace capacity used to generate the electricity to run the scrubber. It has been assumed that this penalty will equal the direct operating energy penalty. This places an upper bound on the capacity penalty

which may be reduced by, for example, using excess steam for stack gas reheat or using oil to run a fan or pump. The capacity penalty in this case may be less than the energy penalty.*

3. A materials energy penalty associated with the construction of the scrubbers.

Data on the operating characteristics of limestone scrubbers indicate that their energy requirements are approximately 3.5 percent** of a coal burning power plant's fuel input. This percentage has been found for a range of plant sizes from 200 to 1000 megawatts and for coal sulfur content of from 2 to 5 percent. In 1977 61.1×10^6 kw will use scrubbers. Assuming a load factor of 55 percent and an efficiency of 34 percent, input energy is $2,955.05 \times 10^{12}$ Btu. Thus the direct operating energy penalty is 103.48×10^{12} Btu.

The indirect energy consumption consists of limestone extraction and transportation and sludge disposal. In 1977 5.778×10^6 tons of limestone will be required. At an extraction energy of 75,000 Btu/ton,*** the energy penalty is 0.43×10^{12} Btu. The 5.778 tons are assumed trucked an average distance of 100 miles, at 1,165 Btu/ton-mile, incurring an energy penalty of 0.67×10^{12} Btu. For sludge disposal it was assumed that truck transportation to a land-fill site twenty miles from the power plant would consume an average of 1,165 Btu/ton-mile, or 46,600 Btu/ton of sludge. Equipment oeprations at the fill site are assumed to consume 129,000 Btu/ton of sludge. Sludge generation in 1977 is $13,045 \times 10^6$ tons, implying a disposal energy consumption of 2.29×10^{12} Btu.

The capacity penalty is assumed equal to the energy penalty of 3.5 percent. If 61.1×10^6 kw will require scrubbers in 1977, capacity loss will total 2.14×10^6 kw. The energy requirement to replace this lost capacity will be 16.67×10^{12} Btu, based on a 1975 replacement cost of $211 per kilowatt**** and an energy cost for public utility construction (I/O Sector 11.03) of 36,925 Btu/$.***** When this replacement energy cost is amortized over twenty years, the annual cost is 0.83×10^{12} Btu.

---

* Pedco-Environmental Specialists, Inc., Particulate and Sulfur Dioxide Emission Control Cost Study of the Electric Utility Industry, Preliminary Draft of U.S. EPA, Contract 68-01-1900.

** As indicated in the text, 3.5 percent is derived from Development Sciences Inc. data on power plant operation. There is a considerable variation in the range of estimates. PEDCO gives a direct operating energy penalty of 1.8 percent, with a range of 1.1 to 4.4 percent. Energy Consumption of Environmental Controls: Fossil Fuel, Steam Electric Generating Industry Draft Report uses 5.5 percent, with a range derived from a literature survey, of 1.5 to 9.5 percent. The 3.5 percent penalty is supported primarily from data developed by TVA.

*** Colorado School of Mines Research Institute, Mineral Industries Bulletin, V. 18 Number 4, July 1975, p.12, Table 5.

**** Temple, Barker & Sloane, Inc., Economic and Financial Impacts of Federal Air and Water Pollution Control on the Electric Utility Industry, Technical Report for U.S. EPA, May 1976.

***** Development Sciences Inc., Application of Net Energy Analysis to Consumer Technologies, Report to U.S. ERDA, Contract E(49-1)-3847, December 1976.

Of the 61.1 x 10^6 kw using scrubbers in 1977, 42.9 x 10^6 kw will be retrofits. The average cost of the retrofits (based on \$86.83/kw for combined SO_2 and Venturi scrubbers, and \$70.27/kw for SO_2 scrubbers only) is estimated to be \$78.40/kw.* The remaining scrubbed capacity will have scrubbers installed at a cost of \$72.06/kw. Construction energy, at 40,256 Btu/\$, will be 188.2 x 10^{12} Btu. Amortizing over 20 years gives a value of 9.41 x 10^{12} Btu as the annual materials energy penalty.

Flue Gas Desulfurization - 1983

The analysis of the energy penalty associated with flue gas desulfurization is analagous to that for 1977. Capacity of 106.8 x 10^6 kw will be scrubbed, with 42.9 x 10^6 kw being retrofits and the remaining 72.8 x 10^6 kw being new installations.

The direct operating energy penalty (3.5 percent), applied to an input energy of 5162.3 x 10^{12} Btu, is 180.79 x 10^{12} Btu. Limestone extraction (9.95 x 10^6 tons) requires 0.75 x 10^{12} Btu, while transport requires 1.16 x 10^{12} Btu. Sludge disposal (22.47 x 10^6 tons) requires 3.95 x 10^{12} Btu.

Replacement of 3.5 percent of the scrubbed 106.8 x 10^6 kw at a cost of \$211 kw implies a capacity energy penalty of 29.14 x 10^{12} Btu, or 1.46 x 10^{12} Btu annually when amortized over 20 years. Materials energy for the construction of scrubbers, 42.9 x 10^6 kw of which will be retrofit at a cost of \$78.40/kw, will be 320.76 x 10^{12} Btu. Amortizing this value over 20 years gives an annual materials energy penalty of 16.04 x 10^{12} Btu.

Precipitators - 1977

As noted at the beginning of the section, all oil capacity and some coal capacity (See Table 3-6) will use precipitators. For 1977, 84.5 x 10^6 kw of coal capacity and 87.4 x 10^6 kw of oil capacity will be equipped with precipitators. As in the scrubber analysis, there are three sources of energy penalties associated with using a precipitator:

1. A direct energy penalty to run the precipitators.

2. A capacity penalty because of electrical consumption to run the precipitators.

3. A materials energy penalty associated with the construction and installation of the capital equipment.

* Temple, Barker & Sloane, Inc., Economic and Financial Impacts of Federal Air and Water Pollution Controls on the Electric Utility Industry, Technical Report for U.S. EPA, May 1976.

Analysis of precipitator operation indicates that there is a direct energy penalty of approximately 0.2 percent to operate a typical device. Given an efficiency of 34 percent for both the oil- and coal-fired plants and load factors of 51.3 percent for oil and 55 percent for coal, the operating energy penalty is 16.06 x 10^{12} Btu.

Capacity derating of 0.2 percent will be applied to 84.5 x 10^6 kw of coal capacity and 87.4 x 10^6 kw of oil capacity. At a replacement cost of $211/kw for coal and $220/kw for oil, the capacity penalty will be 2.70 x 10^{12} Btu. Amortizing this amount over 20 years gives an annual energy cost for capacity additions of 0.14 x 10^{12} Btu.

In 1977, 79.5 x 10^6 kw of coal capacity and 83.8 x 10^6 kw of oil capacity will be retrofit with precipitators. An additional 5.0 x 10^6 kw of new coal capacity and 3.6 kw of new oil capacity will also require precipitators. At a capital cost of $45.50/kw for retrofits and $56/kw for new installations and an energy cost of 40,256 Btu/$, the materials energy penalty in 1977 will be 318.5 x 10^{12} Btu. Amortizing over 20 years gives an annual charge, applicable to 1977, of 15.93 x 10^{12} Btu.

Precipitators - 1983

As for 1977, all oil capacity (93.2 x 10^6 kw) and 134.1 x 10^6 kw of coal capacity (Table 3-7) will require precipitators.

An operating energy penalty of 0.2 percent applied to the affected oil and coal capacity implies a penalty of 21.38 x 10^{12} Btu. A similar capacity penalty of 0.2 percent, with coal construction cost of $211/kw and oil construction cost of $220/kw, carries an energy penalty of 3.64 x 10^{12} Btu, or 0.18 x 10^{12} Btu per year. A materials energy penalty of 443.39 x 10^{12} Btu, amortized over 20 years, gives an annual penalty for the construction of precipitators of 22.17 x 10^{12} Btu.

Residual Oil Desulfurization - 1977

For both years, two residual oil desulfurization cases are developed. Case I considers only domestically refined oil, while the second case estimates the energy cost of desulfurization of all residual oil, whether foreign or domestically refined. In both cases estimates are made of operating energy requirements for the desulfurization process.

Case I: Data from Mineral Industry Surveys (June 1976) indicates that for the first half of 1976 50.8 percent of all residual oil will be domestically refined. Of the domestic product, the following breakdown by weight percent sulfur holds:

TABLE 3-8. PERCENT OF DOMESTICALLY REFINED RESIDUAL OIL BY WEIGHT PERCENT SULFUR

Weight Percent Sulfur	Percent of Product
0 - 0.5	26.26
0.51 - 1.0	23.29
1.01 - 2.0	24.48
>2.0	25.97

For 1977, utility consumption is 644.4 x 10^6 bbls of residual oil, 327.36 x 10^6 bbls of which will be domestically refined. For the domestically refined product the following breakdown by weight percent sulfur will hold:

TABLE 3-9. BARRELS OF DOMESTICALLY REFINED PRODUCT BY WEIGHT PERCENT SULFUR

Weight Percent Sulfur	Average Percent Sulfur	10^6 Barrels
0 - 0.5	0.25	85.96
0.51 - 1.0	0.75	76.24
1.01 - 2.0	1.5	80.14
>2.0	3.5	85.02
	TOTAL	327.36
	TOTAL REQUIRING DESULFURIZATION	241.40

Given desulfurization operating energies* of 0.072 x 10^6 Btu per barrel for residual oil with sulfur content between 0.5 and 1.0 percent, of 0.336 x 10^6 Btu per barrel for residual with sulfur content between 1.0 and 2.0 percent, and 0.516 x 10^6 Btu per barrel for residual with sulfur content greater than 2 percent, the following energy is required for domestic residual desulfurization in 1977:

* Sources from which operating energies were derived are: Van Dressen, R.P. and Rapp, L.M. Residual Oil Desulfurization in the Ebullated Bed, Seventh World Petroleum Congress Proceedings, Vol. 4, p. 261-274; Hydrocarbon Processing, September 1970, pp 210, 211, 213, 214, 224, 226; Blume, J.H. et al. Remove Sulfur from Fuel Oil at Lowest Cost, Hydrocarbon Processing, Sept. 1969, p. 131; Alpert, S.R., et al. Oil and Gas Journal, Feb. 7, 1966.

TABLE 3-10. ENERGY REQUIREMENTS FOR RESIDUAL DESULFURIZATION: 1977 ($\times 10^{12}$ Btu)

Weight Percent Sulfur		Energy Requirements
0.51 - 1.0		5.49
1.01 - 2.0		26.93
> 2.0		43.87
	TOTAL	76.29

Case II: Case II assumes that the energy penalty for desulfurization of both domestically refined and foreign refined residual oil is relevant to an analysis of the impact of U.S. environmental regulations. Mineral Industry Surveys (June 1976) gives the breakdown, by weight percent sulfur, for all residual refined in the first half of 1976. Those percentages are assumed to hold for 1977. The following table presents both the percentage breakdown and actual quantity refined, by category, in 1977:

TABLE 3-11: PERCENT OF PRODUCT AND BARRELS REFINED, BY WEIGHT PERCENT SULFUR: 1977

Weight Percent Sulfur	Percent Product in Category		Barrels Refined ($\times 10^6$ 1977
0 - 0.5	31.61		203.76
.51 - 1.0	22.42		144.47
1.01 - 2.0	19.86		127.98
> 2.0	26.10		168.19
		TOTAL	644.4
	TOTAL REQUIRING DESULFURIZATION		440.64

Given desulfurization operating energies equal to those of Case I, Table 3-12 presents operating energy requirements for 1977 for desulfurization of all high sulfur residual fuel oil.

TABLE 3-12. ENERGY REQUIREMENTS FOR RESIDUAL DESULFURIZATION: 1977
($x\ 10^{12}$ Btu)

Weight Percent Sulfur	Operating Energy (10^6 Btu/bbl)		Energy Requirements (10^{12} Btu)
0.51 - 1.0	0.072		10.40
1.01 - 2.0	0.336		43.00
$\geq$ 2.0	0.516		86.79
		TOTAL	140.19

Residual Oil Desulfurization 1983

As for 1977, two cases are developed. Case I presents the operating energy requirements for desulfurization of domestically refined residual, while the second case treats all residual oil.

Case I: For 1983 it is posited that utility consumption will be 680.2 x 10^6 barrels.* Of this total 50.8 percent, or 345.54 x 10^6 barrels, will be domestically refined. The same breakdown, by weight percent sulfur, as given for 1977 is assumed to hold. Thus, the following table presents operating energy for residual desulfurization in 1983:

TABLE 3-13. DOMESTIC RESIDUAL DESULFURIZATION OPERATING ENERGY: 1983
($x\ 10^{12}$ Btu)

Weight Percent Sulfur	Barrels Refined ($x10^6$)	Operating Energy (10^6 Btu/bbl)		Operating Energy Requirements ($x10^{12}$ Btu)
0 - 0.5	90.73	-		-
0.51 - 1.0	80.48	.072		5.79
1.01 - 2.0	84.59	.336		28.42
>2.0	89.74	.516		46.31
	345.54		TOTAL	80.52

* Temple, Barker & Sloane, Inc., Economic and Financial Impacts of Federal Air and Water Pollution Controls on the Electric Utility Industry, Technical Report for U.S. EPA, May 1976

Case II: The percent of product by category that was given in Case II for 1977 is assumed to hold in 1983. Table 3-14 summarizes the 1983 results.

TABLE 3-14. RESIDUAL DESULFURIZATION OPERATING ENERGY: 1983 ($x10^{12}$ Btu)

Weight Percent Sulfur	Barrels Refined ($x10^6$)	Operating Energy (10^6 Btu/bbl)	Operating Energy Requirements ($x10^{12}$ Btu)
0 - 0.5	215.01		-
0.51 - 1.0	152.50	.072	10.98
1.01 - 2.0	135.09	.336	45.39
>2.0	177.53	.516	91.61
		TOTAL	147.98

Summary of Energy Estimates for Power Plant Air Pollution Control

The energy requirements of meeting air pollution regulations are summarized in Tables 3-15 and 3-16 for 1977 and 1983, respectively. Of particular interest are the relative energy requirements for meeting sulfur regulations: the energy penalty for low sulfur coal is about 1.8×10^6 Btu per kilowatt, while the energy penalty for flue gas desulfurization is about 2.2×10^6 Btu per kilowatt. For comparative purposes, the desulfurization of residual oil in 1983 will require about 1.6×10^6 Btu per kilowatt (excluding materials energy penalties).

The summary figures presented in Table 1-1 include all the energy associated with desulfurizing residual oil for use in United States power plants. This conforms to the assumption that all energy attributable to air pollution control should be estimated. Foreign oil desulfurization accounts for nearly 20 percent of the energy estimate of Table 3-15 for 1977 and for approximately 13 percent of the estimate of Table 3-16 for 1983. The effects on the totals of Table 1-1 are approximately four percent and two percent for 1977 and 1983, respectively.

TABLE 3-15. SUMMARY OF RESULTS FOR ENERGY COST OF MEETING AIR POLLUTION REGULATIONS: 1977

Control Strategy		Energy Penalty (10^{12} Btu)
Low Sulfur Coal (8.6×10^6 kw)		15.48
Capacity Loss	.07	
Transportation	15.41	
Flue Gas Desulfurization (61.1×10^6 kw)		117.06
Capacity Loss	.83	
Operating Energy Penalty	103.43	
Limestone Extraction	.43	
Limestone Transport	.67	
Transport Sludge to Landfill	2.29	
Lime	-	
Materials/Energy (Scrubber)	9.41	
Precipitators (84.5×10^6 kw)		32.13
Capacity Loss	.14	
Operating Energy Penalty	16.06	
Materials Energy (Precipitator)	15.93	
Residual Desulfurization (Domestic Only)		76.29
Residual Desulfurization (All Residual)		140.19
TOTAL (Domestic Only)		240.96
TOTAL (All Residual)		304.86

TABLE 3-16. SUMMARY OF RESULTS FOR ENERGY COST OF MEETING AIR POLLUTION REGULATIONS: 1983

Control Strategy		Energy Penalty (10^{12} Btu)
Low Sulfur Coal (58.2×10^6 kw)		104.03
Capacity Penalty	.07	
Transportation	103.96	
Flue Gas Desulfurization (106.8×10^6 kw)		204.15
Capacity Penalty	1.46	
Operating Energy Penalty	180.79	
Limestone Extraction	.75	
Limestone Transportation	1.16	
Transport Sludge to Landfill	3.95	
Lime	-	
Materials Energy (Scrubber)	16.04	
Precipitators (227.3×10^6 kw)		43.73
Capacity Loss	.18	
Operating Energy Penalty	21.38	
Materials Energy (Precipitators)	22.17	
Residual Desulfurization (Domestic Only)		80.52
Residual Desulfurization (All Residual)		147.98
TOTAL (Domestic Only)		432.43
TOTAL (All Residual)		499.89

APPENDIX A: COMPARISON OF POLLUTION CONTROL-RELATED ENERGY CONSUMPTION ESTIMATES

Before developing the estimates presented in the main body of this report, the work of others on the same problem was reviewed in depth. The review proved frustrating, for few of the written reports provided information on assumptions, rationale, or methodology which was sufficient for purposes of judging the validity of the estimates.

Table A-1 lists some of the studies which have attempted to develop national-level estimates of the energy requirements for pollution control. Table A-2 presents a comparison of the estimates produced by these studies with those developed during this project. To a large degree, the various results cannot be compared--basic data from EPA and CEQ has changed since all of the studies were completed, and differing assumptions (many of which are unknown) among the studies would naturally lead to diverse results. However, the comparison shows that although analysts disagree on the distribution of energy penalties for pollution control among sectors, most would peg the overall penalty for control of pollutants from stationary sources at about 2 percent of national energy consumption.

The following pages contain brief comments on each of the other studies. To appreciate the contribution of each effort, however, the final reports themselves should be reviewed and evaluated.

TABLE A-1

PREVIOUS STUDIES OF THE ENERGY REQUIREMENTS FOR POLLUTION CONTROL

Short Title	Full Document Title	Brief Description
DSI (old) Study	First-Order Estimates of Potential Energy Consumption Implication of Federal Air and Water Pollution Control Standards for Stationary Sources, July 1975	This is an earlier report by DSI using data from 1974. The methodology and assumptions are basically the same as for the new study, with the exception of those for municipal wastewater treatment. National energy estimates are derived for control of industrial air and water pollution control, for abatement of air and thermal water pollution from electric power plants, and for improving municipal wastewater treatment plants to meet federal water quality standards.
Michigan Study	Energy Costs of Limiting the Degradation of the Environment; Report to the Energy Policy Project by A. Crampton, et al, Physics Department, University of Michigan, Ann Arbon, Michigan January, 1974.	A careful review of the energy implications of controls in five sectors: transportation, stationary source air pollution, waste heat from steam power plants, industrial waste-water, and both liquid and solid aspects of agricultural and municipal wastes. Conceptually the approach covers direct fuels and electricity plus energy behind raw materials and capital construction. Energy penalties are given in Btu for each control, but are not always given at the national level due to further assumptions needed about implementation and timing. Use is made of energy conversion factors for materials and construction from Herendeen's input/output analysis based upon the 1963 economy.

58

TABLE A-1 (continued)

PREVIOUS STUDIES OF THE ENERGY REQUIREMENTS FOR POLLUTION CONTROL

Short Title	Full Document Title	Brief Description
RPA Study	A Brief Analysis of the Impact of Environmental Laws on Energy Demand and Supply; prepared for Federal Energy Office, Environmental Policy Analysis Division, by Resource Planning Associates, Inc., June, 1974.	Discusses five sectors which add to energy demand (stationary sources air pollution control, mobile sources, lead restrictions, water quality in both thermal and waste content, and municipal solid wastes) and also five sectors which tend to restrict new energy supply (delays in refinery expansion, nuclear power plants and Alaska pipeline; restrictions on offshore oil leases and surface mining). Presents data for 1973 and 1980. Nature of impacts of regulations and the penalties or savings resulting are expressed in brief summary fashion, and the basis of numbers used is not always clear.
Heller Data	Economic Impact, Energy Requirements and Effluent Reductions in Phase I Industries Due to Best Practical Control Technology Commercially Available; prepared by James Heller, Office of Water Programs, Environmental Protection Agency, Washington, D. C.; early 1973.	An assembly of data on 30 industries listing numbers of plants and possible investment and operating costs needed for implementation of best practicable control technology commercially available; an estimate of the added energy involved both in kwh and as a percentage increase; and percentage of plants currently meeting standards. The timing of the application of the abatement procedures is in effect 1977 - 1983. The methods by which energy and costs of clean-up were estimated are not described, but are based on EPA Effluent Guidelines Limitations documents.

TABLE A-1 (continued)

PREVIOUS STUDIES OF THE ENERGY REQUIREMENTS FOR POLLUTION CONTROL

Short Title	Full Document Title	Brief Description
Hirst Study	Energy Implications of Several Environmental Quality Strategies; Eric Hirst, ORNL-NSF-EP-53, ORNL-NSF Environmental Program, Oak Ridge National Laboratory, Oak Ridge Tennessee; July, 1973	Subjects covered are mass transit, automotive controls, wastewater treatment, solid waste management, air pollution, and waste heat, as well as recycling and energy recovery. The intent is to find operating energy for the control systems. The data cover only direct energy, not that of raw materials and disposal. The procedure is to evaluate energy implications of stringent standards upon 1970 emissions levels. The report contains limited explanatory or interpretive remarks on how energy costs were derived or multiplied to the national level.
Economics of Clean Water	The Economics of Clean Water - 1973, U. S. Environmental Protection Agency, Washington, D. C., December 1973, a report to the Congress from the Russell E. Train	Municipal, industrial, and electric utility wastewater and thermal discharges are discussed. Estimates are given for capital and operating costs to meet 1977 effluent standards, including needs for new municipal sewage treatment plants. Direct energy costs are presented for power plant cooling towers.
National Commission Study	Staff Report: National Commission on Water Quality, 1976.	A full investigation of all aspects of achieving the goals set forth for 1983 in the Federal Water Pollution Control Amendments of 1972. Energy estimates are not emphasized in this study.

TABLE A-2

COMPARISON OF ESTIMATES OF ENERGY CONSUMPTION FOR POLLUTION ABATEMENT

Study	Year	Water Pollution Control (10^{12} Btu)			Air Pollution Control (10^{12} Btu)	
		Power Plant Thermal Pollution Control	Municipal Waste-water Treatment	Industrial Water Pollution Control	Power Plant Air Pollution Control	Industrial Air Pollution Control
DSI (new)	1977	93	-	479	305	676
	1983	156	181	1079	500	1179
DSI (old)	1977	86	36	228	103 - 342	503
	1983	205	253	285	282 - 406	510
Michigan	1977	-	-	400	-	124
	1981	-	236	-	-	-
	1985	250	-	-	800	-
RPA	1980	274	80	85	213	-
Heller	1977	-	-	82	-	-
Economics of Clean Water (EPA)	1977	432	-	-	-	-
	1983	792	-	-	-	-
National Commission	1977	-	137	376	-	-
	1983	294*	269**	822	-	-

* The higher of two estimates published by the National Commission on Water Quality. The lower estimate is 45 x 10^{12} Btu.

** Estimate for 1990.

COMMENTS ON OTHER ESTIMATES OF ENERGY CONSUMPTION FOR CONTROL OF AIR AND WATER POLLUTION BY POWER PLANTS

DSI (old)

The methodology and assumptions used in the earlier DSI study are very similar to those of the current study. The old study did not fully consider the energy equivalent of new capacity required to replace the electrical generation needed for pollution control devices. Also, the old study used different estimates of the amount of generating capacity affected by environmental regulation.

RPA Study

The estimates developed by RPA include only direct energy requirements for pollution abatement and do not include energy cost for the disposal of residues or the supply of chemicals, or required capital energy expenditures for construction of equipment. The estimates were based on reported energy penalties for abatement procedures and estimates of the national energy requirements from projections of the Department of Interior and the National Petroleum Council.

Abatement for meeting air standards includes a 6 percent of plant output penalty for stack gas scrubbing in 1973 and 5 percent in 1980 (reflecting improvements in technology). 1980 installed scrubbing capacity is assumed to be 90,000 MW with a 65 percent power plant load factor, 98 percent particulate removal and 95 percent SO_x removal. The 1980 energy penalty is estimated as 213 x 10^{12} Btu for air pollution control.

Water abatement procedures assume a 3 percent energy penalty of total plant power output. This amounts to 274 x 10^{12} Btu in 1980.

Economics of Clean Air

The report estimates the total direct energy required to operate mechanical forced draft cooling towers to abate thermal emissions in 1977 and 1983. The report in general gives costs in dollars, except to predict coal requirements for abatement for power plants. No back-up information on the source of the numbers is given. The estimated energy penalty for thermal pollution is given as 432 x 10^{12} Btu in 1977, and 792 x 10^{12} Btu in 1983.

Michigan Study

This report recognizes and includes most of the factors required for total energy accounting. It neglects energy for transporting raw materials or waste because these are dependent upon the location of the abatement procedure, and the raw material source or the residue disposal source.

This total accounting procedure leads to some errors in the estimates because many of the numbers required are unavailable. In these cases, the study used the results of the Herendeen input-output analysis, which provides coefficients to determine the dollar cost associated with segments of the national economy. Unfortunately, these coefficients were determined based upon the 1963 national economic activity. Thus, the estimates to not include changes in national economic activity between 1963 and the projected year 1985, nor do they include effects of technological change. The report thus uses the factors 200,000 Btu/1963 $ operating and maintenance costs and 75,000 Btu/1963 $ of capital expenditure amortized over the life of the equipment to estimate process energy requirements when data is unavailable. These coefficients may not be appropriate for specific activities.

Fortunately, these coefficients were not used extensively to estimate power plant abatement energy requirements. Instead, a detailed survey was made of power plant generating capacity and abatement needs. Thus, the estimates are probably more realistic than estimates presented by other investigators. For meeting air standards, the report assumed:

- A 6.5 percent energy penalty of total plant output for SO_x and particulate removal
- Thirty percent of national energy is used for electric power generation
- Forty-two percent of power plant fuels are coal and 13 percent oil
- For coal, 30 percent low sulfur coal, 50 percent high sulfur coal, and 20 percent synthetic fuels derived from coal
- For oil, 50 percent low sulfur oil and 50 percent high sulfur oil
- 0.01 percent of national energy requirements required for control of particulate emissions

- Energy requirements for SO_x scrubbing pump power based upon installed rather than operating horsepower

- 40-60 percent of abatement energy required for stack gas reheat in wet scrubbing operations

- For water pollution control, a 3 percent penalty of total plant output was assumed for cooling towers.

Michigan's estimate of the 1985 energy penalties for pollution abatement by power plants is 800 $\times 10^{12}$ Btu for water pollution control.

National Commission Study

The National Commission on Water Quality was created by the Congressional Act of Public Law 92 500, the Federal Water Pollution Control Act Amendments of 1972, to thoroughly investigate "...all aspects of the total economic, social, and environmental effects..." of the law. The study was not intended to emphasize energy requirements, and it did not do so. However, the Commission's findings include estimates of the energy necessary to meet the standards of PL92 500.

Energy for thermal pollution control is taken from Table II-38 of the National Commission study. It is not clear from the report how energy estimates were developed. The estimates appear to have been made from contractors' technology assessments.

COMMENTS ON OTHER ESTIMATES OF ENERGY CONSUMPTION FOR MUNICIPAL WASTEWATER TREATMENT

DSI (old)

The earlier DSI study employed methodology and assumptions different than those used in the revision. The old study developed energy requirements from estimates of:

1. "Incremental" costs of new municipal wastewater treatment plants
2. Distribution between 10 million gallon per day (MGD) and 100 MGD plants
3. Costs and energy consumption of 10 MGD and 100 MGD plants

There were several data anomalies that affected results. First, the incremental costs did not increase monotonically between 1977 and 1983 as expected. Consequently, the numbers of tertiary treatment plants estimated for 1983 were incompatible with the projected funds needed for their construction.

A second problem was the assumed distribution between 10 MGD and 100 MGD plants. Most (more than 80 percent) of the existing plants in the U. S. are smaller than one MGD, and the distribution of new plants is not projected to deviate dramatically from the existing one.

A third and probably most important aberration resulted from the combination of costs, plant distribution, and per-plant costs and energy consumption. In the old study the total capacity of new plants was approximately equal to all the existing capacity of the United States. Since close to 75 percent of the population is now served by municipal sewage plants, it is not expected that new capacity will equal old.

Energy estimates in the earlier study exceeded those presented in the current report, due mainly to larger estimates of new capacity.

Hirst Study

This paper surveys a broad field of abatement and presents some quick conclusions without explaining the assumptions or methods of calculation. The only national energy total given is 290 x 10^{12} Btu for electricity for a hypothetical situation of secondary treatment of all wastewater (both industrial and municipal) in 1970. The estimate is the product of:

41 kwh/person (secondary level)
x3 (factor to include industrial wastes on BOD basis)
x 205 million total population
x 11,600 Btu/kwh

RPA Study

This survey quotes several other sources as to electricity use in treatment; it does not attempt to quantify other energy consumed in the treatment - disposal process. RPA assumes that all expenses of treatment after 1968 (quoted as 13.5 MB/D oil equivalent) are due to EPA regulations. Their estimates of wastewater treatment energy for 1977 and 1980 are 50 x 10^{12} Btu/year, respectively.

Michigan Study

This is an ambitious effort that recognizes and attempts to quantify the entire range of operating energies. Some of the findings are supported by original research. Unlike the other studies, which report only the electricity used by treatment plants, the Michigan work included analysis of other fuels, as well as the energy associated with producing chemicals for treatment plants plus the energy consumed in fabricating and constructing the plants themselves. These data were used for "building-up" an estimate of direct and indirect energy consumptions for wastewater treatment in 1971. For forecasting purposes, Michigan used coefficients from input/output analysis to calculate operating energy demands. As a result, their energy estimates are higher than the others--for 1981 they forecast 236 x 10^{12} including "capital" energy. The paragraphs below comment on some aspects of the Michigan approach.

Chemical Energy. Michigan utilizes a coefficient relating value of industrial chemicals to the energy implicit in the whole process of producing them, including manufacture and shipment to a representative pattern of locations. These coefficients were derived by Robert A. Herendeen based on 1963 input/output data for the United States economy. The coefficient chosen was 0.24 x 10^6 Btu/$ 1963, representing a rough average of several specific chemicals. The uncertainty in the applicability of the coefficient to the wastewater treatment chemical pattern actually used is considerable, but the crossover to energy equivalents is at least indicative of magnitude.

Other Direct Fuels. A limited amount of natural gas, and of gasoline and other oils, are used in treatment plants. These were extrapolated up to national levels on the basis of volumes of water used per capita, but the applicability of the sample data to the national census of plants is weak.

Total Operating Energy. As an approach to forecasting operating energy estimates, Michigan utilized a factor of 117,000 Btu/$ 1963 developed by Herendeen for the category of "Water and Sanitary Services" operations. This was devalued to $ 1972 and applied to certain wastewater treatment plant costs estimated by CEQ.

No attempt was made to forecast 1977 and 1983 using built-up costs. Using the Herendeen factor, energy costs in the future (based on constant 1972 dollars) are directly proportional to dollar costs of operations and, for example, are expected to double by 1981. The problem with the coefficient is that it is based on the structure of the economy in the 1960's, whereas in the 1970's the trend toward tertiary treatment brings much more intensive use of electricity and chemicals (and probably much more automation) than has yet been experienced. Hence, the use of the coefficient introduces basic uncertainties as to its real application.

Total Capital Energy. The acts of construction involve considerable energy expenditure, and a Herendeen factor of 75,000 Btu/$ 1963 to represent construction of public utilities is suggested. One problem with this coefficient is that a significant portion of municipal wastewater system costs are for sewer pipe and excavations for gathering lines and storm drains, which are lower in energy consumption than treatment plant construction. The Michigan Study, however, applied the factor to the entire expected capital investment. Furthermore, the investment base used (from CEQ sources) included interest and depreciation on total installed sewage plant at the given dates rather than cost of actual construction over a meaningful period.

National Commission

Table II-19 of the National Commission report lists energy for the operation and maintenance of publicly owned treatment works. Energy given in thousand of barrels of oil equivalent per day has been converted to trillions of Btu in Table A-1 of this Appendices.

There is no discussion of the energy estimates for municipal wastewater treatment in the National Commission study.

COMMENTS ON OTHER ESTIMATES OF ENERGY CONSUMPTION FOR INDUSTRIAL WATER POLLUTION CONTROL

DSI (old)

The methodology employed in the earlier DSI study was nearly the same as that used for the new one. The major causes of different results are revised estimates of the investments needed for industrial water pollution control.

Heller Data

One of the Heller Data summaries is a tabulation listing the "annual energy increase expected" for 1977 BPCTCA. Neither the source of these data nor the method of estimation is provided with these summaries. The major consumers, excluding steam-electric power plants, are listed below, converting from kwh/year to Btu/year using an overall electric thermal efficiency of 32.5 percent, or 10,500 Btu/kwh:

	Annual Energy Increase 10^{12} Btu/year
Pulp and Paper	22.0
Fertilizer	16.0
Non-ferrous (aluminum)	15.0
Petroleum	8.4
Organic Chemicals	6.3
Iron and Steel	3.3
Inorganic Chemicals	3.2
	74.2
Total all Industries (excluding steam-electric power plants)	82.0

It is assumed that the above represent the direct energy consumption (fuel and electricity) only and do not include the energy associated with chemical consumption, residuals disposal, and capital construction.

RPA Study

RPA's study gives a 1977 national total for 26 proposed effluent guidelines of 40,000 BPD (85 x 10^{12} Btu/year). Details on the data and estimation methods are not included. It is noted that it compares almost exactly with Heller's figure.

Michigan Study

The Michigan Study presents an estimate of total energy--defined as fuel, electricity, and the energy associated with chemical consumption, material flow, and capital construct. This is done by examining a few examples of end-of-pipe pollution control technology to determine the relationship between total energy and the operating and maintenance (O&M) cost and then projecting this to the national level. The method is described briefly below.

Electricity is converted to thermal units using an efficiency of 30 percent (11,400 Btu/kwh). Fuel energy values are used directly without adding the energy required by the energy-producing industries. Lime was determined as representing two-thirds of the total chemical usage and, thus, its energy value of 0.17×10^6 Btu/$ (1968) was used for all chemicals. Capital construction was charged with an energy consumption of 60,000 Btu/$ capital (1968), subject to 15-year depreciation. Two examples were then developed from activated sludge treatment plant data. One for sewage treatment gave 0.14×10^6 Btu/$ O&M (1968), plus fuel, and a mixed sewage-paper mill treatment plant gave a value of 0.19×10^6. For an organic chemical industry example, they report a value obtained from the Dow Chemical Company of 0.2×10^6 Btu/$ O&M (1968), excluding capital construction energy, but no supporting data are included. They conclude from these few examples that a large, well-operated treatment plant will expend in total energy 0.2×10^6 Btu/$ O&M (1968) and recommend that this be applied to all Phase I industries. While this approach has considerable appeal because of its simplicity, an inadequate number of different industries were examined to permit its application on a national scale with any degree of reality.

A second point of criticism is their estimation of the operating and maintenance cost as being 1/6 of the capital cost of a pollution control facility. This was determined from the figures given in the 1972 Economics of Clean Water, which reports $12 billion (1971) total industry expenditure to meet the effluent guidelines and $2.4 billion annual costs. The Michigan Study treats the latter as almost all O&M costs ($2 billion), stating that part, but not the major part, of this is interest and depreciation (a review of the 1972 Economics of Clean Water shows that this assumption is incorrect).

The Michigan Study has thus estimated the national energy usage from this $2 billion O&M costs, and an energy coefficient of 0.2×10^6 Btu/$ O&M (1968), to give 400×10^{12} Btu/year in 1977 for all industries except steam-electric power plants.

National Commission Study

The National Commission study lists energy requirements by industrial sector, as was done in this report. However, assumptions and methodology used to obtain the data are not reported. The information is apparently taken from contractors' technology assessments of each sector, and analytical procedures (and quality) may vary widely. There is no way to assess the accuracy of the findings. Estimates of energy for industrial water pollution control are found in the National Commission report Table II-35.

COMMENTS OF OTHER ESTIMATES OF ENERGY CONSUMPTION FOR INDUSTRIAL AIR POLLUTION CONTROL

DSI (old)

The methodology for the earlier DSI study was nearly the same as for the new one. The differences between results of the old and new study are almost entirely due to different projections of industrial investments for air pollution control.

Michigan Study

The Michigan Study, in which particulate removal was taken as the major control process other than industrial fuel combustion, gives a figure of 6×10^8 kwh/year (6.9×10^{12} Btu/year) for the national energy requirement for industrial air pollution control.

This is based on electrostatic precipitators, cyclones, and baghouse filters, a total industry particulate emission for 1970 of 13.3×10^6 tons/year, an average loading of 5 gr/SCF, and 1.3 BHP/1000 CFM.

The estimate is very much on the low side, for it considered only low energy control equipment; whereas, in fact, many industries require high pressure drop scrubbers to meet the air standards. It also ignores scrubber pumps and the requirements of absorbers and adsorbers, which are characteristically large energy users.

For the energy required for industrial fuel combustion, the Michigan Study gives 0.17 percent of 1970 national total of 69×10^{15} Btu/year or 117×10^{12} Btu/year. Adding their estimate for particulate removal then gives a total of 124×10^{12} Btu/year.

For comparison, Hirst gives a total national energy usage for power plants, furnaces, cement plants, incinerators, and fossil fuel cleaning facilities of 39×10^9 kwh/year, or 410×10^{12} Btu/year.

APPENDIX B: BIBLIOGRAPHY

Alonso, J. R. F., "Estimating the Costs of Gas-Cleaning Plants," Chemical Engineering, Vol. 78, No. 28 (December 13, 1971), 86-96.

Alpert, S. R., et al., in Oil and Gas Journal, February 7, 1966.

American Petroleum Institute, Annual Statistical Review - Petroleum Industry Statistics 1964-1973, September 1974.

Barile, R. G.; Meyer, P. W.; "Turbulent Bed Cooling Tower," Chemical Engineering Symposium Series, No. 119, Vol. 16 (1971), 134-141.

Blume, H. H., et al., "Remove Sulfur From Fuel Oil at Lowest Cost," Hydrocarbon Processing, September 1969, 131.

Chemical Process Engineering, McGraw-Hill, May 1972.

Chemical Process Industries; 2nd edition - 1956, 134; 3rd edition - 1967, 102.

Colorado School of Mines Research Institute, Mineral Industries Bulletin, Vol. 18, No. 4 (July 1975), 12 (Table 5).

Crampton, A., et al. (M. Ross, spokesman), Energy Costs of Limiting the Degradation of the Environment, Report to the Energy Policy Project, Physics Department, University of Michigan, Ann Arbor, January 7, 1974.

Gifford, D. C., "Operation of a Limestone Wet Scrubber," Chemical Engineering Progress, Vol. 69, No. 6 (June 1974), 86.

Gleason, R. J.; McKenna, J. D.; "Scrubbing of Sulfur Dioxide from a Power Plant Flue Gas," American Institute of Chemical Engineers Symposium Series, No. 126, Vol. 68 (1972), 119-131.

Gortelyou, C. G., "Commercial Processes for Sulfur Dioxide Removal," Chemical Engineering Progress, Vol. 65, No. 9 (September 1969), 69.

Herendeen, Robert A., An Energy Input-Output Matrix for the United States, 1963: User's Guide, Center for Advanced Computation Document No. 69, University of Illinois, Urbana, March 1973.

Hollinden, G. D.; Kaplan, N.; "Status of Application of Lime-Limestone Wet Scrubbing Processes to Power Plants," American Institute of Chemical Engineers Symposium Series, No. 137, Vol. 70 (1974), 212-216.

Hydrocarbon Processing, September 1970.

Jimeson, R. M.; Adkins, G. G.; "Waste Heat Disposal in Power Plants," Chemical Engineering Progress, Vol. 67, No. 7 (July 1971), 64.

Kals, W., "Wet Surface Air Coolers," Chemical Engineering, July 26, 1971, 90.

Kellogg, H. H., "Energy Efficiency in the Age of Scarcity," Journal of Metals, Vol. 26, No. 6 (June 1974), 25-29.

Oleson, K. A.; Boyle, R. R.; "How to Cool Steam-Electric Power Plants," Chemical Engineering Progress, Vol. 67, No. 7 (July 1971), 70.

Sebald, J. F., "Survey of Evaporative and Non-Evaporative Cooling Systems," American Institute of Chemical Engineers Symposium Series - Water, Vol. 70, No. 136 (1974), 437.

Soo, S. L., "A Critical Review on Electrostatic Precipitators," American Institute of Chemical Engineers Symposium Series, No. 126, Vol. 68, (1972), 185-193.

Stormont, D. H., "Hydrogen Recovery Takes on New Luster," Oil and Gas Journal, March 8, 1965.

Tennessee Valley Authority, Sulfur Oxide Removal from Power Plant Stack Gas: Use of Limestone in Wet-Scrubbing Process, PB-183 908.

Tennessee Valley Authority, Conceptual Design and Cost Study: Sulfur Oxide Removal from Power Plant Stack Gas. Magnesia Scrubbing, Regeneration: Production of Concentrated Sulfuric Acid, May 1973, PB-222 509.

Tennessee Valley Authority, James Crowe, personal communication, November 3, 1976.

U. S. Atomic Energy Commission, Energy Implications of Several Environmental Quality Strategies, July 1973, prepared by Eric Hirst, Oak Ridge National Laboratories (ORNL-NSF-EP-53).

U. S. Department of Commerce, Energy Consumption of Environmental Controls: Fossil Fuel, Steam Electric Generating Industry, January 1976, prepared by James Mahoney, et al., Environmental Research and Technology, Inc., Concord, Massachusetts.

U. S. Council on Environmental Quality - Environmental Protection Agency, The Economic Impact of Pollution Control: Macroeconomic and Industry Reports, March 1975, prepared by Chase Econometric Associates, Inc., Bala Cynwyd, Pennsylvania.

U. S. Council on Environmental Quality - Environmental Protection Agency, Final Report, Evaluation of Municipal Sewage Treatment Alternatives, February 1974, prepared by Pacific Northwest Laboratories division of Battelle Memorial Institute, Richland, Washington.

U. S. Council on Environmental Quality, The Fifth Annual Report, December 1974. Washington: Government Printing Office.

U. S. Council on Environmental Quality, The Relationship Between Energy Consumption, Pollution Control, and Environmental Impact, March 31, 1975, prepared by Development Sciences Inc., East Sandwich, Massachusetts.

U. S. Energy Administration, Project Independence Report, November 1974. Washington: Government Printing Office.

U. S. Energy Administration, Project Independence Blueprint, Final Task Force Report, prepared by the Interagency Task Force on Coal under direction of Department of the Interior, November 1974. Washington: Government Printing Office.

U. S. Energy Office, A Brief Analysis of the Impact of Environmental Laws on Energy Demand and Supply, June 1974, prepared by Resource Planning Associates, Inc., Cambridge, Massachusetts.

U. S. Energy Research and Development Administration, Application of Net Energy Analysis to Consumer Technologies, December 1976, prepared by Development Sciences Inc., East Sandwich, Massachusetts (Contract No. E[49-1]-3847).

U. S. Environmental Protection Agency, Air Pollution from Fuel Combustion in Stationary Sources, October 1972. Washington: National Technical Information Service (PB-222 341).

U. S. Environmental Protection Agency, Alvin L. Alm, Assistant Administrator for Planning and Management, memoranda to the Administrator (EPA) re "Energy Impact of EPA's Programs," January 11, 1974, and March 28, 1974.

U. S. Environmental Protection Agency, Capital and Operating Costs of Pollution Control Equipment Modules, Vol. II, July 1973, prepared by H. G. Blecker and T. M. Nichols (EPA-R5-73-0233).

U. S. Environmental Protection Agency, Cost Estimates for Construction of Publicly-Owned Wastewater Treatment Facilities, 1974 "Needs" Survey, Final Report to the Congress, February 10, 1975.

U. S. Environmental Protection Agency, Final Report on The Cost of Clean Air, 1974, January 15, 1974, prepared by Battelle Columbus Laboratories, Columbus, Ohio.

U. S. Environmental Protection Agency, Development Document for Effluent Limitations Guidelines and New Source Performance Standards for the Petroleum Refining Point Source Category, April 1974. Washington: Government Printing Office.

U. S. Environmental Protection Agency, Development Document for Effluent Limitations Guidelines and Standards of Performance - Pulp, Paper, and Paperboard Industry, July 1974, prepared by Wapora, Inc., Bethesda, Maryland.

U. S. Environmental Protection Agency, Development Document for Proposed Effluent Limitations Guidelines and New Source Performance Standards for the Steam-Electric Power Generating Point Source Category, March 1974.

U. S. Environmental Protection Agency, Economic Analysis of Effluent Guidelines - Steam Electric Power Plants, December 1974.

U. S. Environmental Protection Agency, Economic and Financial Impacts of Federal Air and Water Pollution Controls on the Electric Utility Industry, Technical Report, May 1976, prepared by Temple, Barker & Sloane, Inc., Wellesley Hills, Massachusetts.

U. S. Environmental Protection Agency, Economic Impact, Energy Requirements, and Effluent Reductions in Phase I Industries Due to Best Practical Control Technology Commercially Available, early 1973, prepared by James Heller, Office of Water Programs.

U. S. Environmental Protection Agency, The Economics of Clean Water - 1973, December 1973, a report to the Congress from the Administrator, Russell E. Train.

U. S. Environmental Protection Agency, Electrical Power Consumption for Municipal Wastewater Treatment, July 1973, prepared by Robert Smith, Advanced Waste Treatment Research Laboratory, National Environmental Research Center, Cincinnati, Ohio.

U. S. Environmental Protection Agency, James Ferry, personal communication, October 4, 1976.

U. S. Environmental Protection Agency, Draft Final Report, First Order Estimates of Potential Energy Consumption Implications of Federal Air and Water Pollution Control Standards for Stationary Sources, July 1975, prepared by Development Sciences Inc., East Sandwich, Massachusetts (Contract No. 68-01-2498).

U. S. Environmental Protection Agency, Impact of Environmental Control Technologies on the Energy Crisis, January 11, 1974, prepared by T. W. Bendixen and G. L. Huffman, National Environmental Research Center, Cincinnati, Ohio.

U. S. Environmental Protection Agency, Implications of Alternative Policies for the Use of Permanent Controls and Supplemental Control Systems (SCS).

U. S. Environmental Protection Agency, Preliminary Draft, Particulate and Sulfur Dioxide Emission Control Cost Study of the Electric Utility Industry, prepared by Pedco - Environmental Specialists, Inc., Cincinnati, Ohio (Contract No. 68-01-1900).

U. S. Environmental Protection Agency, Preliminary Draft Final Report on the Economic Impact of the Clean Air Act, 1975, prepared by Battelle Memorial Institute, Columbus, Ohio.

U. S. Environmental Protection Agency, Preliminary Draft Final Report on the Economic Impact of the Water Pollution Control Act, 1975, prepared by Vanderbilt University, Nashville, Tennessee.

U. S. Department of Health, Education, and Welfare, Control Techniques for Particulate Air Pollutants, January 1969. Washington: National Air Pollution Control Administration.

U. S. Interagency Committee for Evaluation of State Air Implementation Plans, Projected Utilization of Stack Gas Cleaning Systems by Steam-Electric Plants, April 1973, prepared by Sulfur Oxide Control Technology Assessment Panel. Washington: National Technical Information Service.

U. S. Department of the Interior, An Analysis of Constraints on Increased Coal Production, January 1975, prepared by J. Bhutani, et al., Mitre Corporation, Bedford, Massachusetts (Contract No. 14-01-0001-1937).

U. S. Department of the Interior, Bureau of Mines, 1973 Final Summary - Crude Petroleum and Natural Gas.

U. S. Department of the Interior, Bureau of Mines, Availability of Heavy Fuel Oils by Sulfur Level, Mineral Industries Survey, April 25, 1975.

U. S. Department of the Interior, Bureau of Mines, Crude Petroleum, Petroleum Products, and Natural Gas Liquids: 1973 Final Summary, Mineral Industries Survey, February 14, 1975.

U. S. Department of the Interior, Bureau of Mines, Crude Petroleum, Petroleum Products, and Natural Gas Liquids: December 1974, Mineral Industries Survey, April 18, 1975.

U. S. Department of the Interior, Bureau of Mines, Mineral Industry Surveys, June 1976.

U. S. National Science Foundation - Environmental Protection Agency - Council on Environmental Quality, Environmental Impacts, Efficiency and Cost of Energy Supply and End Use, Vol. 1 (November 1974), prepared by Hittman Associates, Incorporated, Columbia, Maryland (PB-238 784).

U. S. Power Commission, Steam-Electric Plant Air and Water Quality Control Data - Summary Report for the Year Ending December 31, 1971, June 1974.

Van Driessen, R. P.; Rapp, L. M.; "Residual Oil Desulfurization in the Ebullated Bed," Seventh World Petroleum Congress Proceedings, Vol. 4, 261-274.

U.S. GOVERNMENT PRINTING OFFICE: 1978 720-335/6656 1-3