ENERGY LABORATORY

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

GLOBAL ENERGY FUTURES AND CO_2-INDUCED CLIMATE CHANGE

EXECUTIVE SUMMARY

MIT Energy Laboratory Report No. MIT-EL 83-015
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REPORT PREPARED FOR

DIVISION OF POLICY RESEARCH AND
ANALYSIS, NATIONAL SCIENCE FOUNDATION

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15 November 1983

EXECUTIVE SUMMARY

INTRODUCTION, FINDINGS AND CONCLUSIONS

1.1 Introduction

This report deals with energy options relevant to ameliorating the buildup of carbon dioxide in the atmosphere in future years, hence also to ameliorating the predicted consequent climatological and other effects.

The problem arises primarily because of burning of fossil fuels, aggravated by the injection of other antropogenic gases into the atmosphere; these are transparent to visible light but absorb infrared radiation. Thus Earth's surface warms up via incoming sunlight, but its cooling mechanism--re-radiation of infrared heat--is impaired. The natural concentration of CO_2 and water vapor now does this to a considerable extent, raising what would have been a global average temperature of about 255°K to an average 285°K. The consensus grows that enhancement of this phenomenon will cause substantial global changes, some of them deleterious.

Our report accepts a number of phenomena as given (including relevant uncertainties). Principal among them are:

1. CO_2 put into the atmosphere, mainly by burning fossil fuel, will be partly absorbed in the upper ocean and perhaps by increased biomass, but some 40 - 60% of it will remain in the atmosphere for centuries, in quasi-equilibrium with the slowly-changing ocean.

2. Increased CO_2 will raise the mean global temperature. Typical numbers are 1.5 - 4.5°C for a doubling of preindustrial atmospheric CO_2 level with larger increases at high latitudes.

3. CO_2 temperature rises of this order (coupled with contributions from other greenhouse gases such as NO_x, chloro-fluoromethanes, etc.) are much larger than anything in recorded history. Global agriculture and other basic activities will be substantially affected in ways hard to predict at present.

4. No good ways have yet been proposed for extracting the CO_2 from any significant fraction of the world's fossil fuel combustion and sequestering it, in the ocean deeps for instance (But Section 4.1.4 has a further comment on this).

We do not suppose all climate changes, even large ones, are necessarily harmful. However, civilizations tend to organize and optimize their activities with respect to their current environment; thus, changes are on that account more likely to be harmful than beneficial at least in the short term. Also, it is only prudent to explore in advance the energy option space available, in case later action is decided on. By the term "option space," we mean the range of energy futures that appear possible (with trade-offs) taking into account technological, economic and environmental opportunities and constraints. That is what we have done.

At the end of this short chapter we list our Findings and Conclusions. After that, our study contains several major parts. First, in Chapter 2, we take up the question of energy modeling for an uncertain future, and discuss methods and long-term energy scenarios developed by others, in particular the recent work of Nordhaus and Yohe, and Hamm on highly aggregated global energy-economic models. We have developed a set of our own scenarios, incorporating a range of future energy costs, resource availabilities (including cutoffs and moratoria), end-use efficiencies, etc. using a disaggregated energy model due to Edmonds and Reilly of the Institute for Energy Analysis (IEA). A discussion of this model, our reasons for choosing it instead of some other, and descriptions of the scenarios are in Chapter 3.

It is well appreciated that the energy use and carbon emissions predicted by models depends sensitively on the values of exogenous parameters such as efficiencies of energy use and the relative costs of various fossil and non-fossil energy alternatives. For this reason, we have devoted considerable attention to an assessment of the current status and long-term trends in these areas, and summarize our findings in Chapter 4. These "mini-assessments" of both fossil and non-fossil options and of opportunities to improve energy productivity have been made in a way that they can stand alone, irrespective of CO_2-climate.

Both those major parts build on our prior work on energy options which are responsive to the CO_2 challenge: (Perry et. al. 1982), and (Araj 1982). The basic conclusion of these studies was that high fossil fuel use into the early 21st century and low asymptotic CO_2 levels were incompatible because of the long time required to change patterns of energy use significantly--in particular, to make a transition from predominant use of fossil energy to either renewable and/or nuclear technologies. Half a century was typical, suggesting that results expected by the year 2040 should guide our activities in the near future.

Over such long developmental and transition times, many opportunities will appear for increasing energy productivity both in its supply and in its use, as well as reducing costs. We have taken special notice of this, both in the mini-assessments and in their incorporation into several of the scenarios.

Many of the new energy options are non-fossil, therefore naturally in the direction of ameliorating the CO_2-climate problem. The new options are also substantially electric (e.g., nuclear power, solar photovoltaic, wind). This coupled with the convenience of electricity as an energy carrier implies that the current trend toward a more-electric world will continue. Thus we consider it important to inspect the status of electric system integration (Chapter 5), in particular, the incorporation of energy storage and non-dispatchable sources. The state-of-the-art here is rapidly changing, both on account of new technologies of dispatch and control, and on account of new developments in computer simulation of electric power systems.

In Chapter 6 we review a thorny issue that arises in all attempts to account for costs and benefits over time: how to discount the future. The problem is particularly acute for CO_2, because of the long times between commitment and payback, extending over generations. It is also acute because the climate impacts are predicted to occur at times much longer than the usual time perspectives inherent in the U.S. political process and those characteristic of free-market economic decision making, whereas the potential benefits of increased coal exploitation (for example) seem both certain and immediate. We find discounting to be useful for comparing options that are (for example) similarly spaced in time, but not for judging present cost/benefit of far future events.

New energy options require materials, and Chapter 7 gives our estimates for what would be required early in the 21st century in our MIT/IEA scenarios. The ones involving high solar penetration are very materials-intensive.

The global character of energy-CO_2-consequences implies that any substantial responses must be international, and one can ask whether the debate about it is going on at the right level, internationally. Is it time to consider international protocols, as protocols about acid rain and other transboundary pollutants are being discussed, and sometimes implemented? We conclude, after studying acid rain and other examples, that the time is propitious for enlarging the global discussion.

1.2 Findings and Conclusions

Well-recognized uncertainties exist in both the timing and consequences of CO_2-induced climate changes as well as the possibility of similar impacts due to other so-called greenhouse gases. On this basis, stringent measures to restrict the use of fossil fuels now are both unjustified and infeasible. However, given the potential for severe impacts, the possibility that such impacts will have a negative synergism with other environmental stresses occuring at the same time, and the inertia in the energy supply and demand system, it makes sense to develop now strategies for reducing future fossil fuel carbon emissions, rather than relying solely on research to narrow uncertainties and/or ameliorative measures, such as building dikes and developing new strains of "greenhouse-resistant" crops.

We now present below our general findings and conclusions, and follow these with more detailed topical ones.

GENERAL

1. On the basis of current understanding of the effect of CO_2 on climate and trends in global energy use, a significant CO_2 warming in the next century probably cannot be avoided. However, the rate of increase of atmosphere CO_2 due to fossil fuel consumption can be significantly reduced via the adoption of realistic energy strategies that are relatively "CO_2-benign." That is, while technical and other limits bound the range and composition of future global energy use, the bounds appear to be fairly wide, with a spread of a factor of several in annual carbon emissions by the middle of the next century. By "CO_2-benign," we mean an atmospheric CO_2 increase from its present 340 ppmv to about 420 ppmv by the year 2050, corresponding to a "CO_2 doubling time" of several centuries.

2. Early action will help to minimize later difficulties, because the time from conception of a new energy supply technology to its widespread adoption is half a century or longer.

3. The most important and effective options relate to increasing energy productivity on a world-wide scale, an activity that is beneficial quite apart from its impact on CO_2-climate, and that can lead to a halving of the global energy requirements per unit of production or service in less than 50 years.

4. It will be impossible to develop global consensus for any one simple set of energy options, because of different stages of industrialization, different available resources, different perceptions of climatological or economic winning or losing, etc. However, the time seems propitious for extending the global debate on CO_2-climate, based on recent attention to other international environmental problems, to the benefit of all.

5. The trend toward a more-electric future world, coupled with the fact that most non-fossil energy options are electric, indicates the need for and benefit of studying future electric systems closely.

6. Electric power systems that incorporate storage, interactive load control and other operations involving joint generator-user decisions and technologies will make electric power systems much more versatile and responsive to demand, and result in cheaper average costs of electric power.

MODELS AND MODELING

1. The large spread in projections of future global energy demand are in the main due to the normative content of the modeling process, particularly in the modeler's view of the feasibility and desirability of significant reductions in energy demand due to corresponding increases in the efficiency of its use.

2. Several long-term energy CO_2 models that represent a significant improvement on the prior state-of-the-art, have been developed recently. However, more work is needed in this area, particularly on how to account for the possibility of CO_2-climate changes on the energy-economic system.

3. It is customary to take population growth as a given in energy demand modeling. Such growth is an important constraint on limiting future increases in energy use since some minimum level of per capita energy consumption is required for a decent living standard and considerations of justice, and equity require that this be provided. A concomitant effort to limit population growth would ameliorate the demand for energy, as well as be beneficial in many other ways, such as reducing stress on land use, food, and social order.

COAL

1. A CO_2-greenhouse effect of the magnitude presently discussed would require a major global shift to coal. There isn't enough oil and gas, and shale looks like a less likely prospect.

2. Coal's adoption for major global energy will not be prevented by:

- Resource limitations.
- Lack of wide distribution.
- Cost of extraction and use by present technology or improvements of it.
- Lack of knowledge of how to burn it without SO_2, particulates or other emission problems (except CO_2).
- Less surely (but probably) concern for the CO_2 issue alone (because of wide divergence of views and goals) before substantial CO_2 buildup.

3. Coal's adoption would be limited by:

- High cost of less-polluting technology of combustion (but we think the cost will not be prohibitive).
- Environmental and other problems of mining or alternatively the cost of ameliorating them (but we think they could be overcome, except for CO_2 itself).
- Wide acceptance of nuclear power, mainly for electric power production, but also for industrial processes and district heat.
- Lowering of the cost of photovoltaic power by a factor about 5 below the best present technology(economically attractive windpower--a likely prospect--would also help, but the resource base is more limited).
- A continuing shift toward a more technologically sophisticated world, for which electricity is better matched than heat by flames, a shift that reduces demand for all combustible fuel, not just coal.

NUCLEAR FISSION

- In Western Europe, Japan, parts of the U.S., the U.S.S.R. and China, and elsewhere, nuclear power appears to cost significantly less than coal power, especially given environmental restrictions against coal typical of present U.S. practice. Nuclear power will be cheaper almost everywhere that environmental restrictions on coal are significantly increased.
- Polarization of views about nuclear power in the U.S. and some other countries and even the present virtual stagnation of the U.S. nuclear sector will not prevent vigorous development in other regions.
- Leadership in nuclear technology and commerce is likely to pass to Japan and/or Europe in the next decade, in particular, when Japan enters the international market on some opportune occasion.
- Public concern about nuclear wastes will abate (but not disappear), to the extent that progress is visible on implementing the Nuclear Waste Policy Act of 1982.

NUCLEAR FUSION

It will not be ready for significant commercial power production during the critical period before (say) 2050, because of:

- Extreme technological demands on materials to withstand neutron irradiation, to breed tritium, to withstand ion bombardment, and other tasks.
- Difficulties with hot maintenance (if the fuel cycle involves production of neutrons, as presently envisaged).
- Susceptibility to many criticisms that are also applicable to fission.

Beyond 2050, we cannot be sure.

BIOMASS

- The sustainable yeild is moderate at best, 4.7 TW maximum, more likely 2 - 2.5TW.
- Environmental costs are liable to be high, leading to biomass being used for premium needs only (e.g., some ethanol and methanol) or by people living near exploitable forests who are not part of a money economy, or for conversion of wastes associated with other primary uses.

SOLAR PHOTOVOLTAIC (PV)

- Eventual costs for complete systems will almost surely lie in the range 60¢ - $3.00 per peak watt, but it is too soon to be much more definite. With 0.2 effective capacity factor, this is $3000 - $15,000/kw average output. The lower number is attractive for wide adoption, the upper is prohibitive.
- Substantial deployment of solar PV (10% of electric power generation, for example) could not take place until after year 2000, because of the need for cost reduction, establishment of new manufacturing facilities, and re-structuring of the electric utility sector to accommodate dispersed non-dispatchable generators.
- PV is an order of magnitude more material and land intensive than nuclear or coal power.
- The competition between flat plates vs. concentrators will probably not be resolved for another decade.
- PV and wind have the advantage of implementation in small arrays at moderate unit expense, a decided advantage.
- Solar PV plus storage is generally cost-inferior to nuclear or coal plus storage, if the latter are allowed on the system.

WIND

- Attractive in selected regions, perhaps with a limit ≈ 1 TW globally.
- Large machines are more effective than small ones, to capture steadier and stronger winds aloft.
- Marginally economic now without subsidy in favorable locations, if compared with oil-powered generation.
- Combinations of wind/hydro and perhaps solar PV/hydro can be regionally very attractive, especially if the water flow tends to be counter-correlated over the course of seasons of the year.

ENERGY STORAGE

- It benefits electric power principally.
- It aids both baseload (coal or nuclear) power and also solar and wind, but the latter systems plus storage look much more expensive than baseload plus storage.
- Both batteries and hydro will be good candidates. Batteries are presently within a factor 2 of fulfilling the requirement, and are likely to permit many new electric system arrangements.
- If cheap baseload is allowed on the system, energy storage generally decreases the attractiveness of non-dispatchable sources, unless the latter are as cheap per unit of energy output as baseload power--an unlikely prospect.
- Large hydrogen storage systems will probably be subsequent to a much more electric world, which presumes other technological options at earlier times.

REDUCING ENERGY CONSUMPTION

- Energy per unit of GNP in constant money units or per unit of physical output can decrease at the rate of about 1%/year without adversely affecting GNP, because of long-term technological improvement and system replacement. This improvement seems achievable in all regions and sectors.
- Opportunity exists to continue this long-term trend in decreased energy use.
- Under exceptional circumstances such as rapidly rising energy costs, the 1%/year rate rose to about 2%/year in the U.S.
- This is the most important single opportunity to ameliorate CO_2 buildup, and appears attractive in its own right, both economically and environmentally.

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CHAPTERS 1-8

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Ms. Barbara Bell-Teneketzis toiled good-naturedly and effectively with typing and many other tasks associated with preparing a report of this size and complexity.

Chapter 1

INTRODUCTION, FINDINGS AND CONCLUSIONS

1.1 Introduction

This report deals with energy options relevant to ameliorating the buildup of carbon dioxide in the atmosphere in future years, hence also to ameliorating the predicted consequent climatological and other effects.

The problem arises primarily because of burning of fossil fuels, aggravated by the injection of other antropogenic gases into the atmosphere; these are transparent to visible light but absorb infrared radiation. Thus Earth's surface warms up via incoming sunlight, but its cooling mechanism--re-radiation of infrared heat--is impaired. The natural concentration of CO_2 and water vapor now does this to a considerable extent, raising what would have been a global average temperature of about 255°K to an average 285°K. The consensus grows that enhancement of this phenomenon will cause substantial global changes, some of them deleterious.

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- Wide acceptance of nuclear power, mainly for electric power production, but also for industrial processes and district heat.
- Lowering of the cost of photovoltaic power by a factor about 5 below the best present technology(economically attractive windpower--a likely prospect--would also help, but the resource base is more limited).
- A continuing shift toward a more technologically sophisticated world, for which electricity is better matched than heat by flames, a shift that reduces demand for all combustible fuel, not just coal.

NUCLEAR FISSION

- In Western Europe, Japan, parts of the U.S., the U.S.S.R. and China, and elsewhere, nuclear power appears to cost significantly less than coal power, especially given environmental restrictions against coal typical of present U.S. practice. Nuclear power will be cheaper almost everywhere that environmental restrictions on coal are significantly increased.
- Polarization of views about nuclear power in the U.S. and some other countries and even the present virtual stagnation of the U.S. nuclear sector will not prevent vigorous development in other regions.
- Leadership in nuclear technology and commerce is likely to pass to Japan and/or Europe in the next decade, in particular, when Japan enters the international market on some opportune occasion.
- Public concern about nuclear wastes will abate (but not disappear), to the extent that progress is visible on implementing the Nuclear Waste Policy Act of 1982.

NUCLEAR FUSION

It will not be ready for significant commercial power production during the critical period before (say) 2050, because of:

- Extreme technological demands on materials to withstand neutron irradiation, to breed tritium, to withstand ion bombardment, and other tasks.
- Difficulties with hot maintenance (if the fuel cycle involves production of neutrons, as presently envisaged).
- Susceptibility to many criticisms that are also applicable to fission.

Beyond 2050, we cannot be sure.

BIOMASS

- The sustainable yeild is moderate at best, 4.7 TW maximum, more likely 2 - 2.5TW.
- Environmental costs are liable to be high, leading to biomass being used for premium needs only (e.g., some ethanol and methanol) <u>or</u> by people living near exploitable forests who are not part of a money economy, <u>or</u> for conversion of wastes associated with other primary uses.

SOLAR PHOTOVOLTAIC (PV)

- Eventual costs for complete systems will almost surely lie in the range 60¢ - $3.00 per peak watt, but it is too soon to be much more definite. With 0.2 effective capacity factor, this is $3000 - $15,000/k average output. The lower number is attractive for wide adoption, the upper is prohibitive.
- Substantial deployment of solar PV (10% of electric power generation, fo example) could not take place until after year 2000, because of the nee for cost reduction, establishment of new manufacturing facilities, and re-structuring of the electric utility sector to accommodate dispersed non-dispatchable generators.
- PV is an order of magnitude more material and land intensive than nuclear or coal power.
- The competition between flat plates vs. concentrators will probably not be resolved for another decade.
- PV and wind have the advantage of implementation in small arrays at moderate unit expense, a decided advantage.
- Solar PV plus storage is generally cost-inferior to nuclear or coal plus storage, if the latter are allowed on the system.

WIND

- Attractive in selected regions, perhaps with a limit ≈ 1 TW globally.
- Large machines are more effective than small ones, to capture steadier and stronger winds aloft.
- Marginally economic now without subsidy in favorable locations, if compared with oil-powered generation.
- Combinations of wind/hydro and perhaps solar PV/hydro can be regionally very attractive, especially if the water flow tends to be counter-correlated over the course of seasons of the year.

ENERGY STORAGE

- It benefits electric power principally.
- It aids both baseload (coal or nuclear) power and also solar and wind, but the latter systems plus storage look much more expensive than baseload plus storage.
- Both batteries and hydro will be good candidates. Batteries are presently within a factor 2 of fulfilling the requirement, and are likely to permit many new electric system arrangements.
- If cheap baseload is allowed on the system, energy storage generally decreases the attractiveness of non-dispatchable sources, unless the latter are as cheap per unit of energy output as baseload power--an unlikely prospect.
- Large hydrogen storage systems will probably be subsequent to a much more electric world, which presumes other technological options at earlier times.

REDUCING ENERGY CONSUMPTION

- Energy per unit of GNP in constant money units or per unit of physical output can decrease at the rate of about 1%/year without adversely affecting GNP, because of long-term technological improvement and system replacement. This improvement seems achievable in all regions and sectors.
- Opportunity exists to continue this long-term trend in decreased energy use.
- Under exceptional circumstances such as rapidly rising energy costs, the 1%/year rate rose to about 2%/year in the U.S.
- This is the most important single opportunity to ameliorate CO_2 buildup, and appears attractive in its own right, both economically and environmentally.

Chapter 2

ENERGY MODELS AND MODELING

2.1 Introduction

The problems involved in using analytic models to forecast the supply of, demand for, and price of either individual energy sources (e.g. oil, coal, nuclear power, solar photovoltaics), or total energy in a given country, region or globally have become the subject of an increasing literature. See, e.g., (Landsberg 1982), (Koreisha and Stobaugh 1983), (Robinson 1982 a,b). In this chapter, we briefly consider this issue, with particular reference to those energy models which have been devised with the CO_2 problem in mind.

Critiques of energy models and modeling can be broadly grouped under the following categories.

(1) Analytic Structure: The ideal model would, on the one hand, be detailed enough to capture basic features of the real world, (e.g., some level of disaggregation by geographic region and fuel type, and the impact of resource depletion and technological change on the price of fuels and energy technologies) and, on the other, be sufficiently transparent and tractable to enable both the model developer and others to derive results under a variety of input conditions with a clear understanding of how the model translates these inputs into outputs. The recent trend has been towards formal models which are relatively simple in structure--we discuss several in the following--and to a greater emphasis on their use for determining the sensitivity of alternative futures to differences in the value of various exogenous parameters, (e.g., energy price and income elasticities, and the pace of technological change) rather than on prediction, per se. This is mostly to the good, but it would be nice to "have one's cake

and eat it too." That is, to have both simplicity and the ability to gain insight into such issues as: the feedback of CO_2-induced climate change on the global economy, the effect of a moratorium on nuclear power and of a sudden cutoff in the supply of oil from the Middle East, and the possible capital, land use, or material constraints in the introduction of new energy technologies. In these terms, the state of the modeling art still leaves much to be desired.

(2) Validity of Input Data: Having all the right "knobs to turn" in terms of analytic structure is an illusory benefit if the appropriate settings are poorly known or unknown. Unfortunately, this is the general situation with regard to data on past and present energy use and resources in many developing countries and the centrally planned economics. (See, for example (Smil 1981) for a discussion of how little is known about non-commercial energy use in developing countries). The data base for the OECD countries is much better, but this is a mixed blessing as far as energy forecasting is concerned since there is a natural tendency to extrapolate past trends into the future. Since 1973 this has lead to systematic overestimates of energy use in the OECD countries, particularly the U.S. However, some energy forecasts have also had the opposite bias; e.g., projections of OECD energy use in the decade 1960-1970 were consistently underestimated (Freidman 1981).

Energy models for projecting future CO_2 emissions are inherently global and long-term; this has the advantage of being relatively insensitive to short-term phenomena such as constraints in the supply of certain fuels due to the present lack of the required infrastructure (e.g., gas pipelines, coal ships), yearly fluctuations in energy demand due to variable weather conditions, and perturbations in birth rates. On the other hand, uncertainties compound over time, and it is quite likely that the world 50 years hence will be quite different in terms of geopolitical and economic structure, with marked implications for energy use and the CO_2 problem (Ausubel 1983).

(3) Mind-Sets, Biases, Hidden Agendas, Etc.

In the introduction to their essay on limits to models Koreisha and Stobaugh tactfully note that model results are: "often modified by personal judgments to make the results correspond more closely to the specialists' understanding of the real world." This process is well illustrated by a comparison of two well-known energy demand forecasts for the year 2030 (Lovins et al 1982), (IIASA 1981). The former adopts the same economic and populations growth assumptions of the latter to make the point that these assumptions can be satisfied using only about one-fourth the energy, provided that the energy/GNP ratio is reduced by the same factor. Moreover, according to Lovins, such a reduction is not only technically feasible, but also makes good sense from an economic, environmental, and sociopolitical perspective. In particular, since such a modest energy demand can be met almost entirely by decentralized renewables, there would be no need for centralized fossil or nuclear energy sources, so that both the CO_2 problem and all the ills Lovins attributes to nuclear power fade away. The IIASA agenda is not as explicit, but the view of both centralized nuclear and fossil plants (including those that produce synthetic fuels) is much more benign; indeed they are preferable to the radical changes in energy productivity and lifestyle that IIASA feels are implied by the low energy futures of Lovins et al.

Here then are two energy forecasts which are, in reality, largely "backcasts" (Robinson 1982b). That is,the driving force is either an explicit or implicit view of what constitutes a desirable energy future, and the model input assumptions with regard to elasticities, prices, resources, technological change, etc. are used to show how one can get from here to there.

In practice, most modeling attempts are combinations of forecasting and backcasting, or, to say the same thing in different words, of "positive" and "normative" approaches (Ausubel and Nordhaus 1983). For example, in previous work, (Perry et al 1981) we have developed scenarios of non-fossil energy use over time based on the assumption that certain atmospheric CO_2 concentrations should not be exceeded, and that total energy use follows the IIASA and World Coal Study (WOCOL 1981) projections.

4) To What End?

Because of past embarrassments with forecasts of energy supply and demand which have proved to be quite wide of the mark, the emphasis in recent work has been on using models in an "if... then" manner to explore alternative futures rather than on making predictions. For example, Edmonds and Reilly provide the following rationale for their work (Edmonds and Reilly 1983):

> In short the future, and particularly the distant future, is impossible to predict. What is hoped for is that conditional scenarios can be constructed to explore alternatives in a logical, consistent, and reproducible manner. The model is not a crystal ball in which future events are unfolded with certainty, but rather an energy - CO_2 assessment tool, of specific applicability, which can shed insight into the long-term interactions of the economy, energy use, energy policy, and CO_2 emissions.

On the other hand, the model results and corresponding implications for policy which are most often quoted in the published literature usually refer to one or at most a few base or reference cases. Thus, at the end of the above-cited paper, Edmonds and Reilly summarize their base case results, and conclude that:

> The pattern emerging from the modeling effort, continued slowing of CO_2 growth in this century followed by a jump in the rate of increase, should caution policy makers and researchers from being lulled in believing the CO_2 problems will "go away" on the basis of present trends and short-term forecasts.

Similar remarks apply; e.g. to the previously cited work of Perry et al those prescription for deriving the amount of non-fossil energy required to avoid exceeding various CO_2 limits is general, but whose illustrative examples are based on the IIASA and WOCOL study demand scenarios principally in order to demonstrate that those high-fossil-energy scenarios and low CO_2 limits are virtually impossible to reconcile.

The danger is that the projections, scenarios, constraints, etc. derived on the basis of specific assumptions will be taken out of context and used to justify government policy decisions to, e.g., subsidize the development of various renewable resources, modify the licensing procedures for nuclear reactors, place a "CO_2 tax" on coal, etc. In the real world, a wide variety of long-term futures are possible, and it is important to make explicit the underlying basis for key assumptions which largely determine the results. As previously indicated, these are often normative, and involve such factors as: the possibilities for innovation in both fossil and non-fossil energy supply to technologies and for more rational energy use, structural changes in the world economy, (the inevitability of) population growth, and the feasibility of alternative paths of economic development.

In summary, criticisms of energy modeling focus on their use for forecasting supply and demand in the long-term. Given especially the sensitivity of outcomes to the values of a small set of uncertain exogenous parameters, and the impossibility of taking into account unexpected events such as wars, formation of oil cartels, breakthroughs in the development of new technologies, the timing of economic cycles, and the discovery and utilization of significant new energy resources (e.g. deep-pressurized gas), it would be folly to attempt to draw implications for present policy on the basis of specific predictions of energy supply and demand in say, 2050. What is useful is to expose this sensitivity of the model results to a wide range of possible values of the exogenous parameters in a consistant and objective manner. We say possible rather than plausible because it is very difficult for the modeler to avoid his own normative judgements about what assumptions are "beyond the pale". Moreover, the model should be sufficiently disaggregated to enable the user to ask questions about, e.g., the ease of substitution between specific fossil and non-fossil fuels as a function of place and time, while retaining a transparent analytic structure unencumbered by knobs to turn for which the data are non-existent or unreliable, or whose meanings are inscrutable.

The model we have chosen for our own work is the one developed by Edmonds and Reilly which we have previously mentioned. To place this model in context, we first briefly discuss two other recent energy-economic models which were devised specifically to address the CO_2 issue, and which complement the Edmonds and Reilly model in various ways. These are due to Nordhaus and Yohe (Nordhaus and Yohe 1983) and Hamm (Hamm 1983). A discussion of the Edmonds and Reilly model along with our own results, and a summary comparison of all three models is given in Chapter 3. We also note that Ausubel and Nordhaus (Ausubel and Nordhaus 1983) have prepared a more extensive critique of models which have been used to predict CO_2 emissions from fossil fuel use, and that Hamm has assessed the application of input-output analysis to modeling the CO_2 problem. (Hamm 1982)

2.2 The Nordhaus and Yohe (N/Y) Model

The goal of Nordhaus and Yohe is to construct a simple and transparent model of the global economy and CO_2 emissions over a 125 year time horizon (1975-2100), and to use this model to investigate the sensitivity of the results relating to CO_2 emissions to current uncertainties in the value of ten exogenous parameters. The model is based on an aggregate global production function of the Cobb-Douglas form:

$$X(t) = A(t)\ L(t)^{\ d(t)}E^{[1-d(t)]}, \tag{1}$$

where X(t) is the global GNP, A(t) is the neutral productivity growth factor, L(t) is the world population, [1-d(t)] is the share of GNP devoted to paying for energy, and E(t) is a weighted sum of the aggregate non-fossil and fossil energy consumption, $E^n(t)$ and $E^c(t)$:

$$E = [bE^c(t)^r + (1-b)\ E^n\ (t)^r]^{\ 1/r} \tag{2}$$

Here b is a fixed parameter which reflects the relative consumption of $E^c(t)$ and $E^n(t)$ at t=o, and $(r-1)^{-1}$ is the elasticity of substitution between $E^c(t)$ and $E^n(t)$, i.e.,

$$(r-1)^{-1} = \frac{d\ \ln\ (E^c\ (t)/E^n(t))}{d\ \ln\ (P^c\ (t)/P^n(t))}, \tag{3}$$

where $P^c(t)$ and $P^n(t)$ are the respective prices.

These prices in turn are determined by the relative rate of technological change in the fossil and non-fossil industries and also, in the former case, by the effects of resource depletion.

A noteworthy feature of the model is that by allowing the parameter d to be a function of time, the production function is not constrained by unitary income and price elasticities of demand as would be the case if d were a constant in Equation (1). In the N/Y model d(t) is a function of the weighted aggregate price of energy, P(t), and $(q-1)^{-1}$, the elasticity of substitution between total energy and labor. The latter represents the aggregate of all nonenergy inputs into production; i.e.,

$$d = [K\ P(t)^{q/q-1} + 1]^{-1}, \tag{4}$$

$$(q - 1)^{-1} = \frac{d\ (\ln E(t)/L(t))}{d\ (\ln P(t)/W(t))}, \tag{5}$$

where K is a constant and W(t) represents the wages paid to labor.

To run the model, values are chosen for r and q as well as for the parameters which specify population and neutral productivity growth, technological change, and the size, composition, and depletion of the fossil fuel resource base. The resulting outcome for fossil fuel consumption along with a parameter representing the marginal airborne fraction of CO_2 gives the CO_2 atmospheric concentration. To account for the current uncertainties in the values of the ten parameters, high, medium and low estimates are used for each, giving a total of 3^{10} different possible outcomes.

The reported results, based on sampling 100 of 1000 outcomes, can be summarized as follows:

(1) The annual growth rates of key output variables calculated as the probability weighted means of 100 random runs are as shown in Table 2.1.

Noteworthy is the large increase in non-fossil fuel consumption and the large decoupling between energy and GNP to the year 2000. After 2000, both economic and energy growth slow, and the decoupling between the two is much smaller. These trends, plus the tendency to substitute non-fossil for fossil fuels as a consequence of the increasing relative prices of the latter, result in modest increases in the CO_2 atmospheric concentration; e.g., the nominal doubling level (600 ppm) is reached around the year 2070.

(2) A random sample of 100 outcomes for CO_2 emissions and concentrations shows that the odds are equal whether the 600 ppm level will be reached in the period 2050-2100 or outside that period. There is one-in-four chance that this concentration will occur before 2050 and one-in-twenty that it will occur before 2035. (In the next chapter, we compare the outcomes corresponding to the 5, 25, 50, 75 and 95th percentile of carbon emissions with our own results using the Edmonds and Reilly model and other selected scenarios.)

(3) Two different techniques were used to compute the relative contribution of uncertainties in the ten exogenous parameters to the overall uncertainty in the CO_2 atmospheric concentration in 2100. In one method, the contribution is calculated as the uncertainty induced when a particular parameter takes its full range of uncertainty and all other parameters are set equal to their most likely values. In the other method, the contribution is the difference between the case in which all parameters vary according to their full range of uncertainty and the case in which all the parameters again vary according to their full range except the one of interest which is set at its most likely value. In both methods, the three most sensitive parameters in order of decreasing importance are: the ease of substitution between fossil and

non-fossil fuels, general productivity growth, and the ease of substitution between energy and labor. The authors consider this result to be an important surprise, suggestive about research priorities in the CO_2 area.

(4) The impact of taxes on fossil fuels as a means of reducing their consumption and hence the growth of CO_2 concentrations was considered. (The efficacy of this policy has been investigated previously by Nordhaus and by Edmonds and Reilly; (Nordhaus 1980) (Edmonds and Reilly 1982); in the latter work, the impact of both global and US only taxes were considered.) The major finding is that a significant reduction in CO_2 requires a significant tax; e.g., global taxes of about $60 per ton coal equivalent reduce the year 2100 CO_2 concentrations by only 15% from the base case. (We note that achieving global consensus on such a tax would be very difficult.)

2.1.1 Critique of the Model

The N/Y model has both the advantages and the drawbacks inherent in a high degree of aggregation. Regarding the former, the model includes many parameters of obvious importance in the determination of CO_2 atmospheric concentrations; e.g., the impact of resource depletion and technological change on the prices of fossil and non-fossil fuels, the ease of substitution between energy and labor and between fossil and non-fossil fuels, and neutral productivity growth. Moreover, the fact that only ten parameters need to be specified implies that the effort of uncertainty in these parameters on the model results can be assessed using a relatively small sample of all possible outcomes. On the other hand, models without either disaggregation either geographically or within the fossil and non-fossil fuel categories have obvious limitations. For example, the substitution of either nuclear reactors or photovoltaic cells for coal in the electric sector would reduce

CO_2 emissions, but these two non-fossil technologies are quite different in such matters as economic scale, environmental impact, grid integration, prospects for technological change, etc. This implies that both the ease of substitution between fossil and non-fossil fuels and the non-CO_2 implications thereof may vary in ways which cannot be captured by highly aggregated models. However, the question of what degree of aggregation is most useful is a difficult one.

Three final points: (1) Although the model does incorporate technological change on the supply side, there is no handle to account for the possibility of improvements in energy end-use efficiency which are not driven by price; (2) As previously noted, the model incorporates exogenous elasticities of substitution between labor and total energy, and between fossil and non-fossil energy. These can be estimated from the price elasticities of demand for both total energy and fossil fuels, and the value share of energy in GNP using relations between these quantities which follow from the definition of the production function; See e.g. (Hogan 1979). However, the income elasticity of demand, $d(\ln X)/d(\ln E)$, at constant price cannot be specified exogenously. Rather the fact that $d(\ln X)/d\ln E)$ is not fixed but varies over time in this model is a consequence of the changing price of energy. Thus the effect of changes in income elasticity as a function of economic development cannot be captured. (3) Finally, the model does not account for the possibility of feedback from CO_2-produced environmental change to energy policy.

2.3 The Hamm Model

Like Nordhaus and Yohe, Hamm uses a highly aggregated production function to model the global economy, and emphasizes the importance of sensitivity analysis to identify those parameters whose range of uncertainties cause the greatest variation in the model outcomes. However, there are significant differences between the two models which can be summarized as follows:

(1) While Nordhaus and Yohe use an equilibrium model, Hamm's approach is to choose an optimum path for economic development based on maximizing the value of objective function J which is given by:

$$J = \sum_{t=0}^{T} (1+\delta)^{-t} \log C_t + \Phi K_T - \Theta \sum_{t=0}^{T} F_t \qquad (6)$$

where: t is the index of time in the model; t = 0 is the year 1975 and t = T, the terminal time, is 2050.

δ is the social discount rate. (There is a voluminous literature on the appropriate value for δ; see, e.g. (Lind 1983) and the discussion in Chapter 7.)

C_t is the dollar value of consumption in year t, and Log C_t is commonly taken to represent the flow of value or utility from consumption at time t. Thus the first term in Equation (6) is the utility flow discounted at the rate δ and summed over the time horizon T.

K_t is the terminal capital stock and Φ is a measure of the tradeoff between present consumption and future capital; e.g., a value of $\Phi = 6.67 \times 10^{-15}$ implies that society is indifferent between a $1 increase in present (1975) consumption and a $30 gain in capital stock in 2050.

F_t is the fossil energy use in year t and Θ is a measure of the tradeoff between present consumption and fossil energy use; e.g., a value of $\Theta = 2 \times 10^{-4}$ implies that society is indifferent between a $1 increase in present consumption and an increase of one ton coal equivalent in fossil energy resource left to future generations. Note that the Θ term means that the effective price of fossil energy (in utility terms) is raised by Θ above its market price.

In sum, the conventional feature of this objective function is the term which represents discounted utility; the unconventional features are the inclusion of terms which represent concern for future generations through the value placed on stocks of capital and fossil fuel resources left at the end of the time horizon. (Both fossil and non-fossil energy are taken into account in deriving the consumption, C_t; the last term in the objective function represents an extra fossil diseconomy.)

(2) The production function is a generalization of that used by Nordhaus and Yohe in two respects: (a) capital and labor are independent inputs to the production process instead of being lumped together in a single nonenergy factor. There is a unit elasticity of substitution between both capital and labor and also between fossil and nonfossil fuels. (Recall that in N/Y the latter can be specified exogenously.) Also, there is a constant elasticity of substitution between the pairs of inputs: (capital, labor) and (fossil, nonfossil energy) which can be specified exogenously. (b) CO_2 feedback effects on production are included both as a decrease in the productivity of all resources and as an increase in depreciation of capital stocks with increasing atmospheric CO_2 concentrations.

(3) Fossil energy enters the model as a "choice" variable. That is, three possible future paths of fossil energy use over time (high, nominal, low) are specified exogenously and the objective function chooses the optimum path. Nonfossil energy use is determined as a percentage of total fuel use; this percentage, the market share, is assumed to increase linearly with time along one of three exogenous paths. The other choice variable is the investment rate given as a percentage of the GDP. Choices are limited to three discrete values: high, 22%; nominal, 16%; and low, 10%.

(4) The cost of fossil/nonfossil energy is assumed to increase/decrease with time, driven primarily by resource depletion and technological progress, respectively.

The model runs by specifying values for the choice variables and exogenous parameters, and calculating values of GDP and the objective function J. With regard to the choice variables, Hamm's basic finding is that with all exogenous parameters at their nominal values, the combination which maximizes both GDP and the objective in 2025 and 2050 is nominal fossil fuel use and high investment. This is true both with and without the inclusion of the effects of CO_2 on productivity and depreciation. Sensitivity of the results to variations in the value of the exogenous parameters is tested by letting a specific parameter take on its extreme values with all other parameters set at their nominal values. By this criterion the most sensitive parameters are found to be: (1) Θ, the incremental shadow price of fossil fuels consum before 2050. For example, if Θ is increased from its nominal value of a \$1 decrease in 1975 consumption per savings of one ton coal equivalent in 2050 to \$4 per ton, the optimal fossil fuel path is shifted from nominal to low; (2) the rate of nonfossil energy introduction. For example, a change in the nonfossil market share from nominal to high (e.g., 30% to 65% in 2050) causes the optimal fossil fuel path to again shift from nominal to low; (3) the overall rate of technological improvement as given by the neutral productivity growth factor. An increase in this parameter from 0.4%/yr to 1.2%/yr shifts the optimal fossil fuel path from nominal to high. This somewhat paradoxical result can be explained as follows. In most energy models, the GNP is specified first; then technological improvement gives the same economic output with, e.g., a smaller energy input. By contrast, in Hamm's model, fossil fuel use is specified along one of three possible paths; then technological progress gives a higher level of output with a given fossil fuel input; in particular, the highest GDP occurs at the highest energy. This is true notwithstanding the inclusion of CO_2 feedbacks because the range of fossil fuel paths chosen does not lead to significant differences in atmospheric CO_2; e.g., the CO_2 level in 2050 is 1.7 and 2 times the pre-industrial level for the low and high fossil fuel paths, respectively.

2.3.1 Critique of the Model

In a useful self-assessment of his work, Hamm, like Nordhaus and Yohe, stresses the importance of narrowing the uncertainty in key energy/economic variables such as the investment rate, the rate and distribution of technological progress, and the ability to substitute among different inputs to production. His major criticisms of the model itself are that the treatment of technological change, particularly relative change between fossil and nonfossil inputs, needs improvement, and that the range of the choice variables, investment rates, and fossil fuel use was too limited.

We are in basic agreement with these comments, especially regarding relative technological change. In the N/Y model this aspect is handled in a more transparent manner. Beyond this, the Hamm model, like N/Y, is highly aggregated geographically and with regard to fuels. However, it can accommodate CO_2 feedbacks, and it also makes explicit the centrality of societal choice in energy/economic decision-making via the choice of objective function and associated parameters such as the social discount rate and the incremental shadow price of fossil fuels.

Table 2.1 Annual Growth Rates of Key Output Variables In The Nordhaus and Yohe Model

[percent per annum]

	1975-2000	2000-2025	2025-2050	2050-2075	2075-210
GNP	3.7	2.9	1.5	1.5	1.5
Energy Consumption	1.4	2.7	1.2	1.1	1.2
Fossil Fuel Consumption	0.6	2.5	0.9	0.5	0.4
Nonfossil Fuel Consumption	5.6	3.1	1.8	2.0	2.0
Price of Fossil Fuel	2.8	0.3	1.2	2.9	1.1
Price of Nonfossil Fuel	0.5	0.1	0.1	0.1	0.1
CO_2 Emissions	0.6	2.6	1.2	0.9	0.4
Concentrations	0.3	0.6	0.8	0.8	0.8

Note: These are calculated as the probability weighted means of the 100 random runs.

Chapter 3

THE EDMONDS AND REILLY MODEL AND DERIVED SCENARIOS

3.1 Introduction

In addition to the N/Y and Hamm models discussed above, we considered using a number of other more elaborate energy models. Eventually, we chose a model devised by Edmonds and Reilly at the Institute of Energy Analysis. The basic reason for this choice is that we wanted to test the sensitivity of CO_2 outcomes to uncertainties in the price and availability over time of a variety of fossil and nonfossil supply technologies. The Edmonds and Reilly (E/R) model includes most of the technologies of interest, and therefore we have used it to develop eleven energy-CO_2 scenarios to the year 2050. These scenarios are discussed in Section 3.4 of this chapter; further details are in Appendix B. To place these results in context, we first briefly describe and critique the model itself.

The two most interesting approaches, aside from E/R, that we considered are exemplified by the Leontief world model (Leontief 1966) and the PILOT model (Dantzig 1981). The former is an input/output model, based on input/output tables from a number of different countries, plus a world-trade sector. Input/output modeling has the virtue of richness: one can include a large array of technologies by adjusting the appropriate coefficient. The problem with the input/output approach based on the world model is that it would be necessary to add our own pollution sector.

PILOT is a linear programming model, and also can accommodate a virtually inexhaustible array of energy technologies. However, it is a U.S.-only model, whereas we needed one with global coverage. Also a pollution sector would have been needed here as well.

After considering these possible models, as well as others such as ETA-MACRO (Manne 1981) we concluded that each of these alternatives would require a substantial additional development effort before it could be useful for our purposes. The E/R model, on the other hand, was basically available and ready to run.

3.2 E/R Model Overview

The E/R model has been extensively documented by the developers and their coworkers; for a fuller discussion, see in particular (Edmonds and Reilly 1983), (Edmonds and Reilly 1983a).

The model forecasts energy paths and determines atmospheric carbon release by fossil fuel type and world region to the year 2050. Its key features can be summarized as follows:

(1) The world is divided into nine regions (Figure 3.1). More detail is provided for in the OECD regions than in the nonmarket economies or less industrialized countries because of the better quality of the OECD data base. The time horizon is from 1975 to 2050. Projections can be developed for any year, but three benchmark years have been chosen for scenario development--2000, 2025, and 2050.

(2) Nine primary energy sources are considered separately: coal, conventional oil, unconventional oil (e.g., heavy oil, tar sands, shale), conventional gas, unconventional gas (e.g., deep-pressurized gas), biomass, and three nonfossil electric sources: hydro, solar (e.g., photovoltaic and wind), and nuclear. Nonelectric solar (e.g., for low temperature heat) and

noncommercial fuels are not considered.* For the determination of energy demand, the nine supply sources are aggregated into four secondary energy types: solids, liquids, gas, and electricity. Trade across the model's world regions is allowed for in solids, liquids, and gas, but not in electricity.

(3) Energy prices are adjusted in successive iterations until global supply and demand for each traded fuel balance within a prespecified bound.

(4) CO_2 emissions from fossil fuels are accounted for at each stage of the fuel cycle. For example, synthetic gas from coal will release CO_2 at the gas conversion stage and again when it is burnt.

3.2.1 Calculating Energy Demand

The major determinants of the level and composition of energy demand in a given region are: population, GNP, and the relative prices of the various energy types. The actual calculation of demand is rather complicated; to give an indication of the level of detail in the model, we outline it below and in Figure 3.2.

(1) The regional price for a given primary fuel type (e.g., coal in the U.S.) is the sum of an assumed base world market price corresponding

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* In our work, we have attempted to account in part for the consumption of non-commercial fuels by having part of the biomass resource available at very low cost (corresponding to gathering sticks, rice, straw, dung, etc.).

to domestic production in coal-rich areas, transport costs, and any taxes or subsidies. The price of a secondary fuel type (e.g., electricity or synthetic gasoline from coal) can then be calculated by taking into account conversion efficiencies and nonenergy costs.

(2) The cost of providing energy services to energy end-use sector k using secondary fuel type j, P_{jk} (e.g., automobile transportation using synthetic gasoline from coal, with price per passenger-mile as the measure) then follows from assumed end-use conversion efficiencies and nonenergy costs.

(3) The aggregate cost P_k of energy services in sector k is a weighted sum of the P_{jk}, where the weights are exogenous shares for fuel j in sector k, S_{jk}.

(4) P_k, together with assumed values for the following exogenous parameters: base GNP*, population, and price and income energy service elasticities, determine the total demand E_k for energy services in sector k.

(5) The E_k from (4) is combined with: values of endogenous fuel service shares $S_{jk}{}^*$ (calculated from the P_{jk} and values of fuel-specific exogenous price and income energy service elasticities), the fuel requirements per unit service g_{jk}, and value of an exogenous parameter, $TECH_{jk}$, which accounts for the possibility of future improvements in end-use energy productivity which are not driven by price. This gives F_{jk}, the total

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* The actual GNP is endogenous, depending on both base GNP and energy prices through an energy-GNP feedback mechanism.

demand for fuel j in sector k.

(6) Summed over all sectors, the result is the region's total demand F_j for secondary fuel type j. The total regional demand for primary fuels then follows from secondary demand and the relevant conversion efficiencies.

3.2.2 Calculating Energy Supply

For price-supply modeling, the nine primary energy types are divided into three categories:

(1) Resource-constrained nonrenewable resources; e.g., conventional oil and gas. Their production over time is assumed to follow a Hubbert bell-shaped curve. This implies that maximum production occurs when half the resource is exploited and that cumulative production follows a logistic curve. Prices do not affect the exploitation of these resources.

(2) Resource-constrained renewable resources. This category is further divided into resources whose production over time is or is not price-responsive. The most important example of price-insensitive resources is hydroelectricity; these are modeled as being phased in over time as determined by a logistic curve with total resource and prices as exogenous inputs. The only example of price-sensitive resources treated in the model is biomass. Both biomass from waste as well as biomass from farms are included. The waste resource base is considered to be proportional to the level of economic activity, while that available from farms is independent of it. Since biomass and coal have many common characteristics, e.g., they can be consumed as solids or converted to liquids or gases, the price of coal is assumed to govern the price of biomass feedstocks except that, as previously noted, part of the resource is made available at very low cost to represent consumption of non-commercial fuels.

(3) Unconstrained or backstop technologies. These include unconventional oil and gas, coal, solar electric, and nuclear. Their supply is specified in terms of: production cost, P, the ratio of output at time t, Q_t, to a base output Q^*, $g = Q_t/Q^*$, and three exogenous parameters a, b, c, by the equation:

$$P = a \exp \left(\frac{g}{b}\right)^c \tag{1}$$

This equation is depicted in Figure 3.3. It is seen that P increases as Q_t increases, and that there is no production if P falls below a, the breakthrough price. If more output is demanded from the backstop sector than its base rate, prices rise in the short-term above the long-term backstop price P^*, and vice versa. The price elasticity of supply ε follows from Equation (1)

$$\varepsilon = \frac{\partial \ln Q}{\partial \ln P} = \frac{(g/b)^{-c}}{c} \tag{2}$$

Technological change in the supply side is accommodated by decreasing the breakthrough price as a function of time.

3.3 Critique of the Model

In comparison with the models of Nordhaus and Yohe and Hamm - see Chapter 2 - the Edmonds and Reilly model is highly disaggregated; hence, useful in principle for determining how future energy paths and CO_2 emissions depend on the relations between the economy, energy supply and demand, and technological change. The price the user pays for this flexibility is not an excessive amount of computation--a run takes only seconds of CPU time--but the need to specify over 60 categories of inputs (See Appendix A), many of which can be further disaggregated by region, fuel type, and year. Testing sensitivity in the manner of Nordhaus and Yohe then becomes a heroic task; the overriding issue, however, is whether the level of detail in the E/R model is optimum for deciding about CO_2 and energy policy.

Beyond this general point, there are several specific areas in which the model could be improved. Some of these have also been noted by Edmonds and Reilly, and by others; e.g., (Reister, 1983).

(1) Additional energy end-use categories. We have previously mentioned two additional energy end-use categories we believe to be important: low-temperature heat and non-commercial fuels, particularly firewood. The importance of both is well recognized; for example, the former accounts for about 40% of end-use energy consumption in OECD countries, while the latter is the primary energy source in the rural sector of many developing countries.

(2) Modification of the supply function for backstop technologies. Two aspects of the specification of supply functions for backstop technologies are problematical. First, the impact of technical change is currently modeled as an exogenous decrease in the breakthrough price over time. It would be more realistic to have the breakthrough price at a given time depend on the cumulative production of the resource to that time.

A second problem is that the supply function in Equation (1) slopes steeply upward if the exponent c is high. After experimenting with the model, Reister reports that the supply function for coal is almost completely inelastic in the region where the model calculates its equilibrium prices. This implies that the coal output in each year is constrained to be very close to the base output (i.e., very close to Q*). Consequently, the exogenously chosen base outputs appear to play too large a role in determining the equilibrium. Reister does not present alternative estimates of the supply elasticities for backstop technologies. However, we believe such estimates are readily available, and it would be advantageous to have the supply functions for backstop technologies recalibrated in the model.

(3) Making the supply of conventional oil and gas price-responsive. We have noted that the resource-constrained non-renewable resources (conventional oil and gas) used Hubbert curves. As noted later in this report, we feel that the extraction cost estimates for these resources are higher than specified in the E/R base case. The lack of an explicit supply function made it necessary to resort to awkward adjustments to E/R model parameters in order to adjust the extraction costs.

(4) Inclusion of CO_2 feedback in the economy. As noted in Chapter 2, only Hamm's model includes this link. It is modeled there as a non-linear decrease in overall productivity and an increase in the depreciation rate of capital with rise in CO_2 concentration. This is rather rudimentary but, given the current state of knowledge about the impact of climate change, it is difficult to see how it can be improved upon.

(5) Capital formation and depreciation. Capital formation and depreciation are not considered in the model. That is, every 25 years the slate is wiped clean in terms of energy facilities, and the mix of technologies is determined anew on the basis of current prices. However, the buildup and depreciation of a capital stock are important factors in the penetration of new technology. For instance, a world where a significant investment had been made in the infrastructure required for a

major increase in coal use would be less likely to reduce coal use significantly, even in the face of clear indications of adverse CO_2-induced climate change.

The reason capital has to be omitted is probably related to the equilibrium modeling methodology used in the E/R model. If capital were present the computational burden would rise because equilibria in all time periods would have to be calculated simultaneously. More importantly, it would be necessary to specify rules for saving and investment in different energy sectors and regions. This would necessitate an additional elaboration of the macroeconomic side of the model.

Table 3.1 gives a summary comparison of the Edmonds and Reilly, Nordhaus and Yohe, and Hamm models. In noting the differences, it is important to keep in mind that the intent of the modelers is different. Thus, Nordhaus and Yohe are mainly interested in determining the effect of current uncertainties in various energy-economic-carbon cycle parameters on the range of possible future paths for energy use and CO_2 emissions. Hamm's analytic framework is more ambitious: rather than deriving future energy paths, the model seeks optimum futures in terms of an objective function which includes both discounted consumption and the effects of resource depletion, as well as a production function which accounts for CO_2 feedbacks to the economic sector. The basic similarity is that both Nordhaus and Yohe and Hamm use a highly aggregated approach in an attempt to gain insight into the relative importance of uncertainties in the parameters which drive the energy-economic system. By contrast, the Edmonds and Reilly model is intended as an analytic tool for those who want to explore how alternative energy-CO_2 futures depend on a much more detailed specification of the energy-economic system. As previously noted, this makes the model more difficult for the user to deal with--both in terms of understanding the analytic structure and specifying inputs--but also gives the user more degrees of freedom to explore.

3.4 Scenarios Developed Using the Edmonds and Reilly Model

In this section we briefly describe the eleven scenarios which were developed for this study using the Edmonds and Reilly model; they are referred to in the following as the MIT cases. All are variations on an Institute of Energy Analysis (IEA) scenario which we call the IEA base case. Noteworthy features of the latter are the availability of large quantities of inexpensive fossil fuels, particularly coal, and an increase of energy end-use efficiency of 1%/yr. in the industrial sector of OECD countries. However, no increases in end-use efficiency are assumed in the OECD transportation and residential/commercial sectors nor in the non-OECD countries. (End-use is not disaggregated in the latter.)

A detailed characterization of the IEA base case and the MIT variations thereof is given in Appendix B; Figure 3.4 is a summary map of the relations between the cases. The resultant projections of global primary energy demand and carbon emissions to the year 2050 are shown in Figures 3.5 and 3.6, respectively. For comparison purposes, the latter Figures also show the energy and carbon emission projections of IIASA, Colombo and Bernardini, and Lovins, (IIASA 1981), (Lovins et al 1982), while Figure 3.7 has superimposed the outcomes of the Nordhaus and Yohe model corresponding to the 5, 25, 50, 75, and 95th percentiles of carbon emissions. Finally, Tables 3.2 compares the GNP and energy use projections in the year 2025 for the IEA base case and the MIT cases.

3.4.1 MIT Case Summaries: Some "CO_2-Benign" Results

The MIT cases are summarized below. All assume increased end-use efficiencies as compared with the IEA base case, and, except for case K, have higher synfuel costs. In addition, as indicated in Figure 3.4 and the summaries, we have explored the impact of both evolutionary and abrupt changes in energy supply conditions. The former include higher/lower costs for fossil fuels/solar electricity; the latter are a cutoff in the supply of oil from the Middle East and a moratorium on nuclear-generated electricity. The results are as expected; in particular, the high fossil fuel and low solar electric prices and the increased end-use efficiencies which characterize cases L, J, and M lead to substantial reductions in both total energy use and carbon emissions and a significant penetration of solar in the electric sector as compared with the IEA base case and the IIASA and Colombo and Bernardini scenarios.

The relatively CO_2-benign scenarios, J, L and M in particular, are not low-energy in a Draconian sense; Figure 3.5 shows them comparable to that of Colombo and Bernardini. They would require global awareness and collaboration, starting very soon. While perhaps at the lower limit of possible realities, these scenarios do not appear to us impossible; recall that energy projections for the early 2000's now being made are much below what people believed possible only a decade ago.

What future atmosphere CO_2-levels do these scenarios imply? Their carbon emissions are on the average not much different from today's values, about 4.8 GT/year. If we assume a constant atmospheric retained fraction of 0.53 and no other complications, we would find an increase of 80 ppmv, to about 420 ppmv at the year 2050. The "CO_2 doubling time," often used to gauge the degree of difficulty, becomes about 250 years, beyond all predictable sight. These scenarios are not quite benign, but show that an option space exists in which the CO_2-climate problem is much ameliorated.

Case A

In this case, oil and gas prices were increased, and biomass resources were substantially reduced. Since the conventional oil and gas are not price responsive in the model, the effect of increased prices were simulated by moving a portion of the conventional oil and gas resources to the unconventional oil and gas resource category and raising the breakthrough prices of the latter.

Biomass is viewed as being competitive in price, but difficult to sustain. The global biomass resource specified is 1115 EJ/yr.

In addition, nuclear costs were raised to account for current trends. Transmission and distribution costs are included in these estimates.

Case B

For this case, coal reserves were reduced and prices increased. These changes were made to simulate the effect of non-CO_2 environmental constraints on coal use. The changes result in a large decrease in coal use and in carbon emissions. For example, the projected average price of coal in Japan in the year 2000 is \$3.60/GJ (1975\$), an increase of about a factor of 4 compared with the base case. The current coal price in Japan is about \$3.00/GJ ≡ \$80/tonne. This is equivalent to \$1.75/GJ in \$1975 assuming a $(1.08)^{-1}$ deflation factor.

Case C

This case is a combination of Cases A and B: higher fossil fuel prices, smaller coal reserves, higher nuclear costs, and less biomass resource. The resulting energy consumption is 60% of the energy consumed in the IEA Base Case.

Case D

The new feature of this case is an optimistic view of the development of photovoltaic technology. That is, it is assumed to be available in the year 2010 at \$0.30 per peak watt (1980\$) for finished modules. At $(1.08)^{-1}$ deflation, this is \$.205 per peak watt in 1975\$. Assuming equivalent balance-of-system costs and a capacity factor 0.2 (corresponding to mid-latitude average insolation day/night-summer/winter, etc.), the total system cost is \$2.05 per watt, or \$9.50/GJ electric, assuming a capital charge rate of 15%/yr.

Thus, the differences from the base case include: increased efficiencies, higher synfuel costs, and the new solar price. Note that this case has the same coal values as the base case: large reserves at inexpensive prices.

Case E

Case E is a combination of all changes from the previous cases except for the higher nuclear costs. In other words, this is Case C with the optimistic solar minus higher nuclear costs. Main characteristics are: higher fossil fuel prices, less biomass resource, lower solar prices, and less coal available. Total energy consumption decreases 65% with a large shift from fossil fuels to solar. However, nuclear demand remains very high as in the base case.

Case F

The output of this case is very similar to Case C since the solar photovoltaic price of \$0.63 per peak watt $\equiv$ \$20/GJ electric is approximately the same solar price as the base case.

Case G

There is no case G.

Case H

This case includes a nuclear power moratorium: existing reactors are shut down and no new plants are built after the year 2000. This is modeled by making the breakthrough price of nuclear energy very high. Hence, by the year 2025 there is a negligible amount of nuclear capacity worldwide. This is combined with the assumptions of Case E, producing a further decrease in energy consumption from the IEA base case. The energy supplied by nuclear in Case E partially shifts to oil and coal, and to an even greater degree to solar.

Case J

The changes from Case E are a higher unconventional oil price, a cut-off in oil from the Middle East in 2000, and increased end-energy efficiencies everywhere, in all sectors. That is, these efficiencies increase geometrically from 1%/yr. in 1975 in all end-use sectors of all countries. The result is a 20% decrease in global energy consumption as compared to Case E.

Case K

The inputs changed in this case are nuclear costs, end-use efficiencies, and the Mideast oil supply. The nuclear breakthrough price is considerably higher in this case than in the other cases except H. The efficiencies for the OECD industrial sector and in all of the non-OECD regions are higher than those specified in cases A through H. Compared to Case J, the efficiency for OECD industrial sector is equal, but the efficiency increase in the non-OECD regions is much lower than in J. Furthermore, the OECD residential/commercial and transportation sector efficiencies are higher in all the other cases. The Middle East oil supply is cut off by the year 2000, as in J. However, since this case has large reserves of coal at cheap prices, as in the base case, the liquid fuel demand is met by synfuels whose use grows by about 50% compared to the base case.

Case L

As compared with Case E, this case is characterized by a large decrease in unconventional resources, a slight decrease in coal prices, and increased end-use efficiencies. This case highlights the impact of increased end-use efficiencies on primary energy consumption.

Case M

Case M is similar to Case L, however it also has higher coal prices and lower coal reserves. Moreover, unconventional resources are essentially eliminated. Thus, the main characteristics of this case include: high end-use efficiencies, small coal reserves, high coal prices, small biomass resource, no unconventional oil, and low solar prices.

	General Features	Geographical Disaggregation	Energy Supply Types	Technological Change	Elasticities
monds and Reilly	Equilibrium; Disaggregated by Fuel Type and Region; Projects Energy Use and CO_2 Emissions; No CO_2 Feedback to Economy or Energy Sector.	Nine global regions; end use in OECD regions divided into industrial, transport, and commercial/residential sectors.	Nine primary; four secondary; solids, liquids, gases, electricity.	On energy supply via changing prices over time for backstop technologies; on energy demand via energy productivity parameter.	Exogenous regional income and price elasticities by secondary fuel type; elasticities of substitution between fuels in logit share formalism.
ordhaus and Yohe	Equilibrium; Highly aggregated; projects energy use and CO_2 Emissions; No CO_2 feedback to economy or energy sector.	None.	One Fossil; one non-fossil.	On energy supply via price adjustments over time for fossil and non-fossil fuels; overall change via neutral productivity factor.	Exogenous elasticities of substitution between fossil and non-fossil fuels and between energy and non-energy sectors of productio
amm	Optimizing; highly aggregated; energy use a choice variable; CO_2 feedback to economy; explicit consideration of capital sector.	None.	One fossil; One non-fossil.	On energy supply via price adjustments over time for fossil and non-fossil fuels; Overall change via neutral productivity factor.	Unitary elasticities of substitution between capital and labor and between fossil and non-fossil fuels; exogenous elasticity of substitution between capital labor and fossil/non-fossil input pairs.

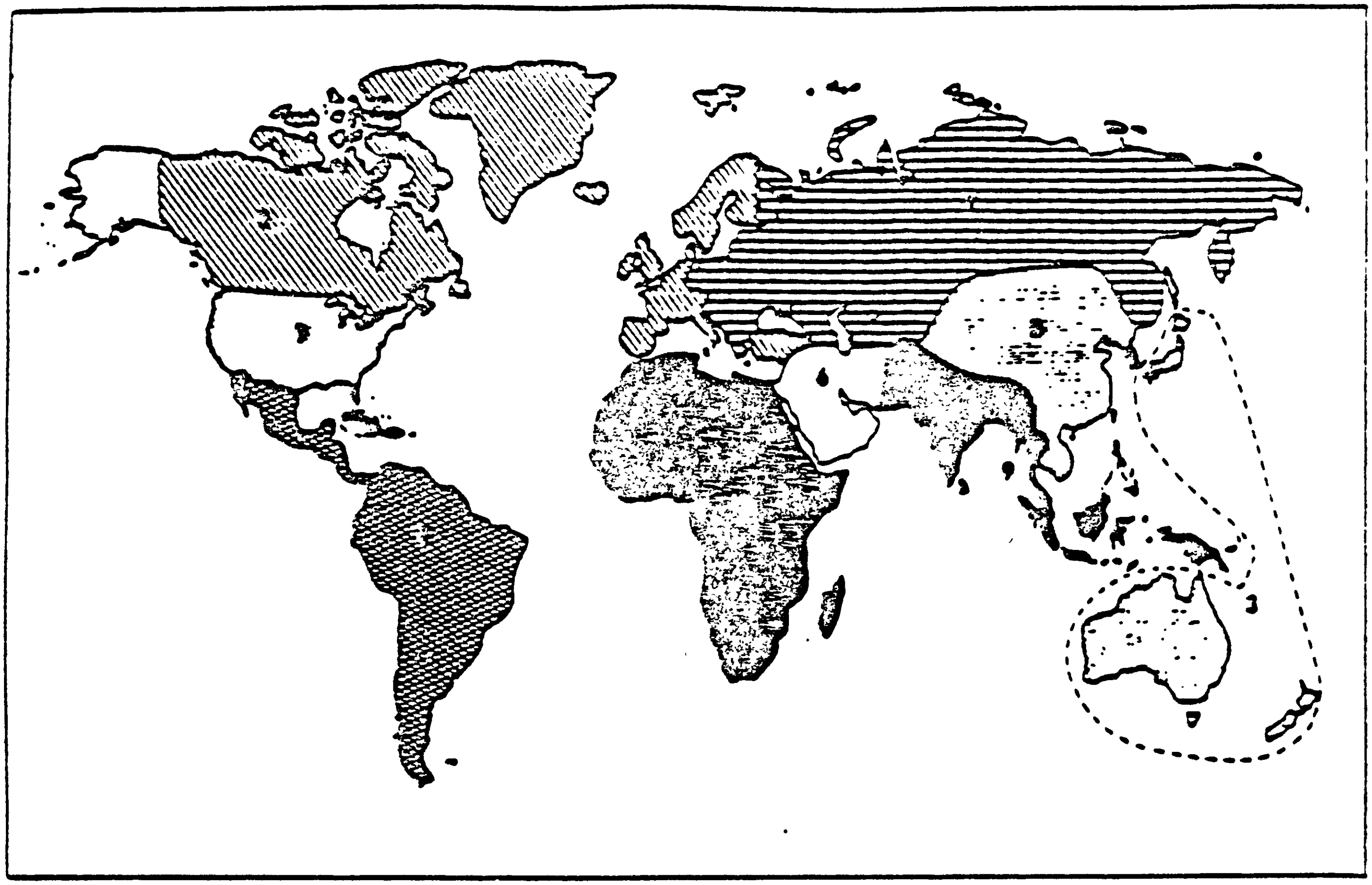
Table 3.1

Summary Comparison of Edmonds and Reilly, Nordhaus and Yohe and Hamm Energy-CO_2 Models

Table 3.2 Comparison of IEA Base Case and MIT Cases

Values in 2025 (Base Case = 1.00, (1975))

Scenario	GDP	ENERGY	ENERGY/GDP
Base Case	1.00 ($\$25.4 \times 10^{12}$)	1.00 (921 EJ) (28.6 TWyr)	1.00 (36 MJ/$) (9.9 kwh/$)
Case A	0.99	0.77	0.71
Case B	0.99	0.71	0.72
Case C	0.97	0.59	0.61
Case D	1.00	0.78	0.78
Case E	0.98	0.65	0.66
Case F	0.98	0.59	0.60
Case H	0.97	0.59	0.61
Case J	0.98	0.52	0.53
Case K	0.98	0.71	0.72
Case L	0.98	0.55	0.56
Case M	0.98	0.52	0.53



Key: 1. USA; 2. OECD West; 3. OECD Asia; 4. Centrally planned Europe; 5. Centrally planned Asia; 6. Middle East; 7. Africa; 8. Latin America; 9. South and East Asia.

Figure 3.1

Geopolitical Divisions in the Edmonds and Reilly Model

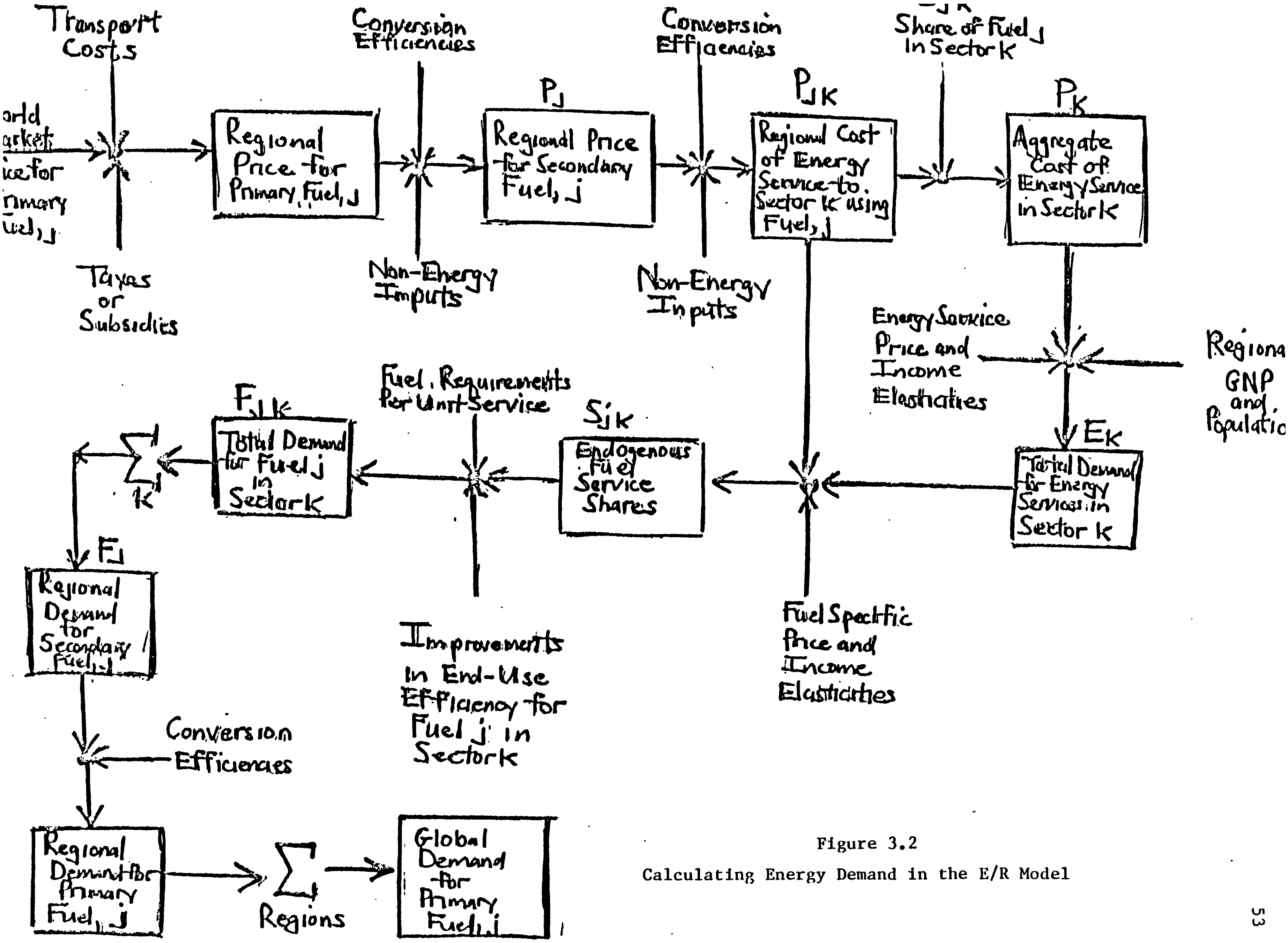


Figure 3.2

Calculating Energy Demand in the E/R Model

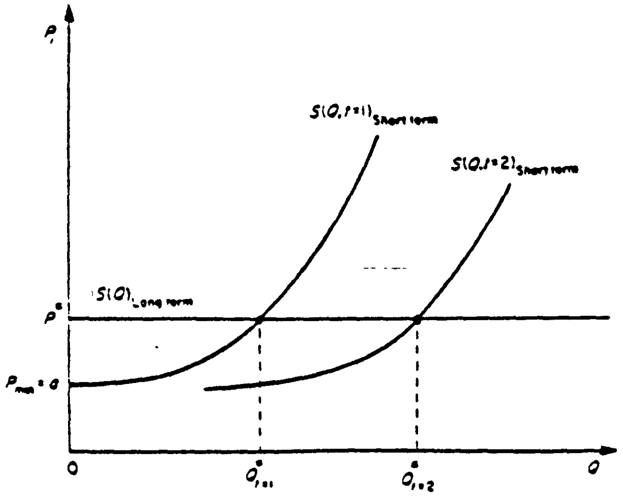


Figure 3.3

Supply Schedule for Backstop Technologies

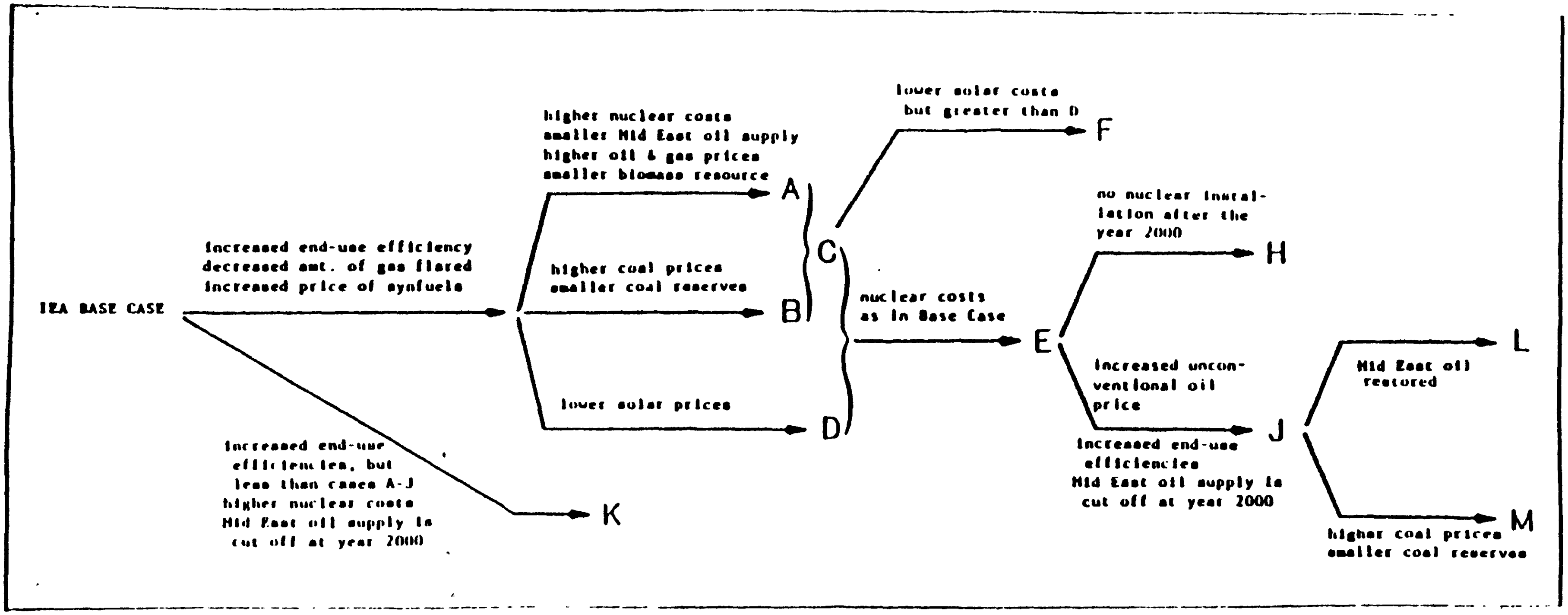


Figure 3.4

Summary Map of IEA Base Case and MIT Cases

Figure 3.5

Global Primary Energy Projections: MIT Cases and other Scenarios

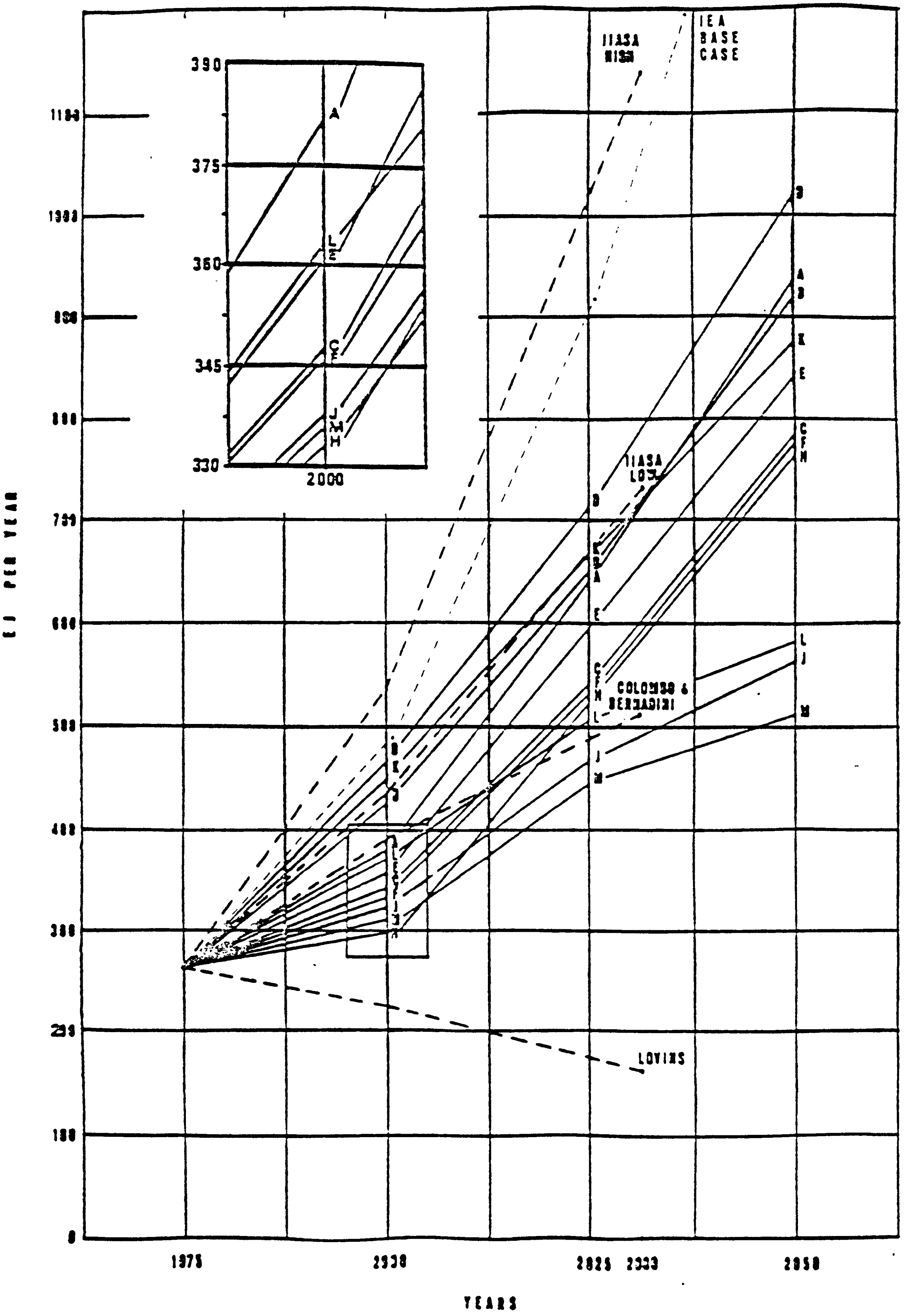


Figure 3.6

Global Carbon Emissions: MIT Cases and Other Scenarios

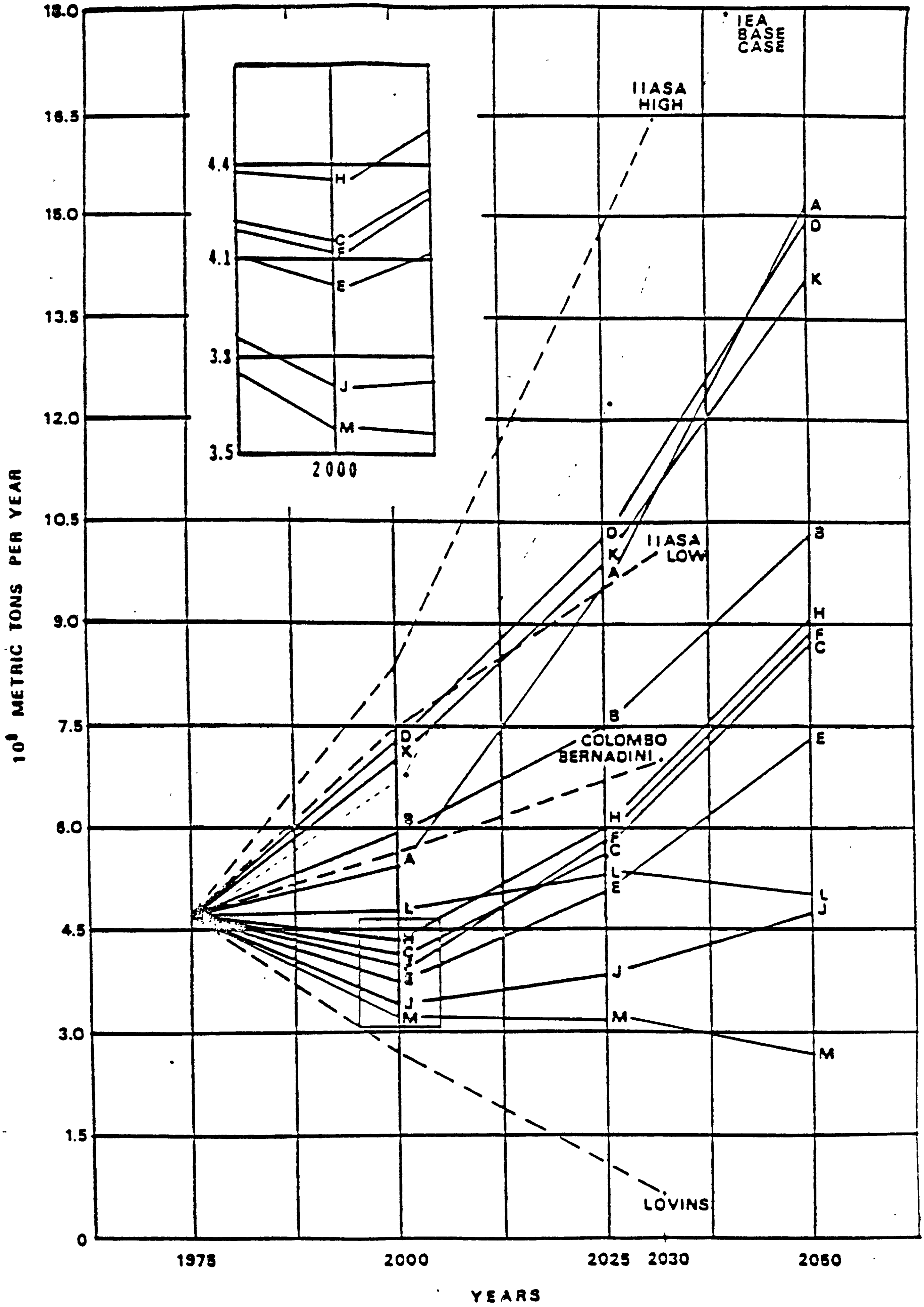
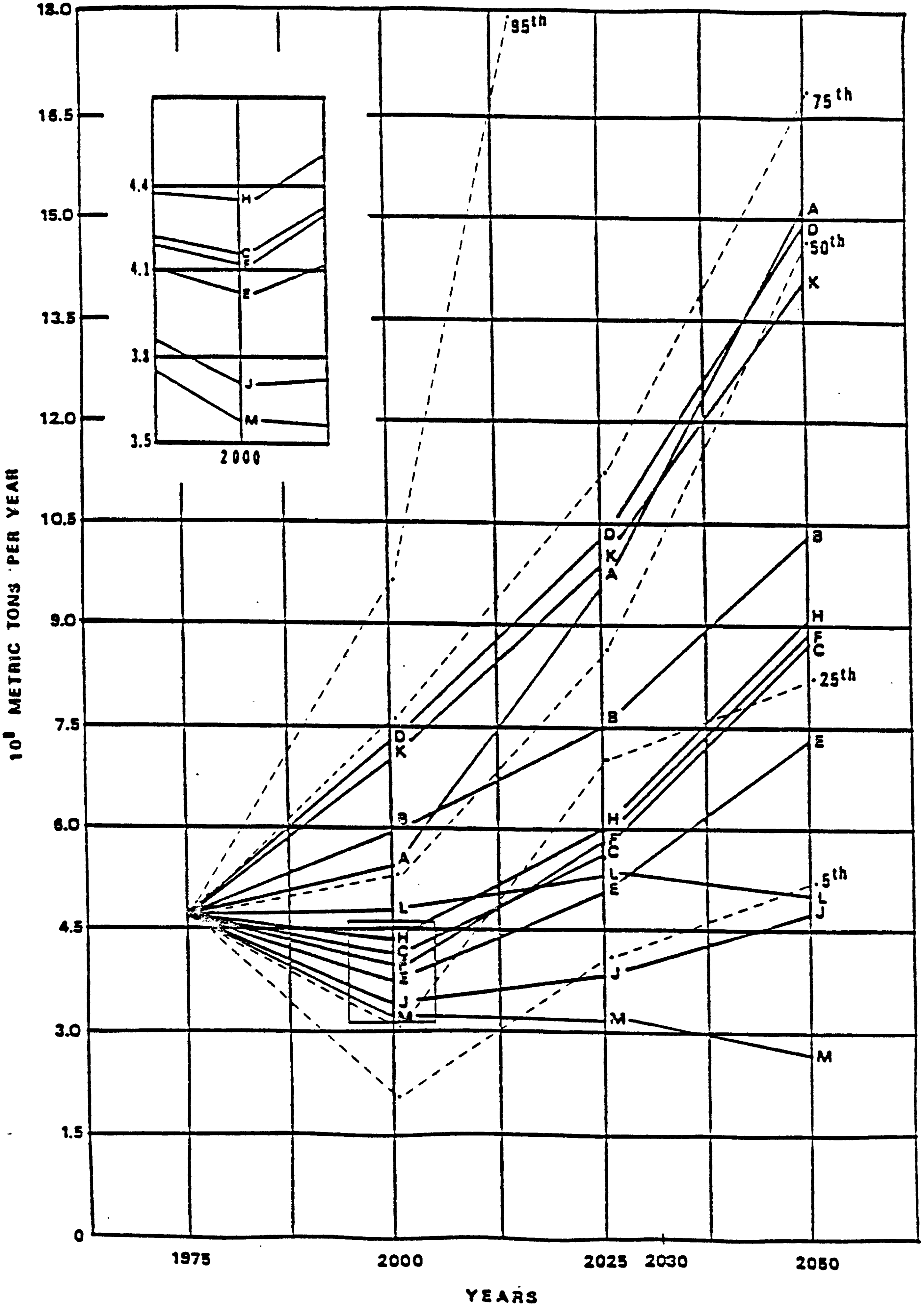


Figure 3.7

Global Carbon Emissions: MIT Cases and Selected N/Y Scenarios



Chapter 4

MINI-ASSESSMENT OF SELECTED ENERGY SUPPLY AND DEMAND TECHNOLOGIES: FUTURE OPPORTUNITIES AND CONSTRAINTS

In Chapter 3, we delineated a range of possible energy futures using the Edmonds and Reilly model as an analytic framework together with values of the required input data. In the latter, the primary focus of our work has been on the supply side; that is, on the price and availability of various energy resources and the technologies to exploit these resources. (The need to consider both is easily seen, e.g., the resource endowment of uranium was irrelevant to the evaluation of energy supplies until the development of a technology to convert uranium to usable energy through nuclear reactors, and the amount of usable energy that can be derived from this resource depends on whether the reactors are burners or breeders of fissile material.) (Vogely1983). In this and succeeding chapters, we attempt to provide justification for these inputs and support for the results in the form of mini-assessments of selected energy supply and demand options, and issues related to their implementation. In particular, we consider: coal, solar photovoltaic (PV), wind, biomass, nuclear fission and fusion, materials use, energy storage, efficiencies in energy end-use, and the problems involved in integrating intermittent energy sources (e.g. PV and wind) in an electric grid. No attempt has been made to provide comprehensive overviews of these areas. Rather we have tried to identify those current developments and long-term trends which are particularly relevant to the CO_2 problem; e.g., what are the long-term prospects for such generating technologies as fluidized bed combustion of coal, thin-film photovoltaics, battery storage, and advanced fission? That is, our emphasis is on assessing the state of future knowledge: what we may be able to do in say, 25-50 years, and the consequences thereof for CO_2, rather than short-term problems and opportunities.

4.1 Coal

The relevance of coal to the CO_2 problem can be seen from Figure 4.1.1 In brief, combustion of all estimated recoverable oil and gas resources will not raise the atmospheric CO_2 concentration above about 450 ppm. However, combustion of any significant fraction of the large coal resource base--here estimated to be 5000 Gtce of recoverable resource--will increase atmospheric CO_2 well above 600 ppm, which represents a doubling of the preindustrial CO_2 concentration, and is often used as a benchmark for the onset of serious adverse climatic impacts. There are some obvious caveats to this identification of the CO_2 problem exclusively with coal. Thus, on the one hand, there may be serious climatic impacts at much lower CO_2 concentrations, and, on the other, large additional amounts of carbon are contained in sources which are not now in commercial production (e.g. oil shale, heavy oils, tar sands, and perhaps unconventional sources of natural gas), but which may be exploited in the future. Taking these factors into account, it would probably be more accurate to say that a risk-averse position with regard to CO_2-induced climatic impact would involve limiting the use of all fossil fuels. Still, given: (1) the large size and wide geographical distribution of coal resources, (2) the array of technologies now under development to extract and burn it in a more cost-effective and environmentally benign fashion, and (3) the fact that significant exploitation of sources such as oil shale and tar sands poses environmental problems just as daunting as that involved in coal use, if not more so, a focus on coal seems justified.

An interesting perspective on the linkage between CO_2-induced climate changes and the use of coal has been explored by Ausubel. (1983). He points out that such climate changes, if they occur, will not occur in a vacuum. That is, the world in say, 2030, may, for example, be populated by twice as many people as today, many of whom will live in countries characterized by both social inequity and technological sophistication, including the capability to make atomic weapons. The geopolitical impact of such changes, and their possible synergism with CO_2-induced climate change, is difficult to predict. However, as Ausubel points out, the assumptions which lead to increased levels of CO_2 also directly imply changes in human settlement, international trade, industrial structure, as well as other aspects of the environment; he surveys, in particular, the health and environmental consequences of greatly increased coal extraction and use.* Exploring these non-CO_2 implications of the assumptions which produce CO_2 is important because it may indicate whether the world will be "saved" from potential CO_2-induced problems by technical, economic, and environmental constraints which preclude reaching dangerous CO_2 concentrations in the first place. Before commenting on this, we summarize some information on coal resources and reserves, extraction, combustion, and conversion to gases and liquids.

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* It is worth noting that the assumptions that lead to significantly reduced levels of future CO_2 emissions also imply marked technical, economic, and sociopolitical changes.

4.1.1 Coal Reserves and Resources

Table 4.1.1 taken from (IEA 1982), compares two recent estimates of coal resources and reserves. While the bulk of reserves and--to an even greater extent--resources are located in a small number of countries, we note that the estimated resource base outside of the three largest, the U.S., U.S.S.R., and People's Republic of China, is roughly a factor of two larger than estimated total global oil resources. Moreover, estimates of both resources and reserves have been continuously revised upwards in recent years (see Table 4.1.2) and given the fact that known deposits are not always reported, and that there has been little exploration activity in many regions (e.g., much of Africa, Central America, Western Siberia, Northern China) (Wood 1983), the technically and economically recoverable resource estimate of 5000 Gtce used in Figure 4.1.1 may well prove to be conservative. At first glance this appears academic from the perspective of potential CO_2-induced climate change since this is already enough coal to increase atmospheric CO_2 concentrations many-fold over pre-industrial levels. However, to the extent that coal is found more widely in otherwise energy-resource-poor developing countries, the future of CO_2 emissions will not lie in the hands of very few countries, and hence, the possibility of international cooperative actions to limit coal use because of climate change seem both necessary and (unfortunately) increasingly unlikely.

4.1.2 Coal Mining and Transportation

The labor intensity characteristic of coal extraction, particularly underground mining, is larger than that of other nonrenewable resources, and this is sometimes seen as a possible constraint on a significant expansion of coal use. That is, given the fact that coal mining involves higher probabilitie of occupational health and disabling injury than almost any other trade, and also that the mines themselves may be located in inhospitable regions (e.g., Western Siberia), it may not be possible to attract the required labor force to sustain production at significantly higher rates. On the other hand, increased demand for coal usually leads to more favorable work incentives (e.g. increased pay, health benefits, and job training) in regions where alternative employment is often scarce; moreover, more strip mining, innovations in underground mining, and the opening of new and larger mines should increase labor productivity. For example, in the U.S. labor productivity has been increasing since 1979, after a steady decline in the 1970's. In the People's Republic of China, where one-third of coal output comes from more than 20,000 small rural mines and pits, and only one-third of all coal mining operations are mechanized, a modernization and mechanization program is underway with foreign participation. In sum, labor availability may well be a problem in the short term, but should not constrain ultimate production to levels which would have a negligible impact on the CO_2 problem.

The same general comment applies to transport of coal from mine to user. There are well-recognized inadequacies in the entire transport chain, including inland transport and the ports and ships required for a greatly increased international coal trade. The bill for remedying this will not be cheap, e.g., the World Coal Study (WOCOL 1980) estimates that for the OECD countries alone, infrastructure costs (including new mines) required to support an increase in coal use to a level of 2000 mtce/yr by the year 2000 will be on the order of $200 billion (U.S. 1978 $). However, WOCOL also notes that this sum is less than 1 percent of the estimated aggregate capital formation of these countries during the period to the year 2000. Moreover, just as in the case of mine labor productivity, new technological developments such as coal slurry pipelines and economies of scale in ocean transport using large carriers should facilitate increased coal use.

4.1.3 Coal Combustion

Although coal causes environmental impacts throughout its fuel cycle from extraction to end-use, combustion is the part of the fuel cycle which elicits the greatest public concern, particularly on what comes out of the stack. This includes carbon dioxide, sulfur and nitrogen oxides, particulates, trace metals and metalloids such as arsenic, chromium, beryllium and cadmium, organic compounds, and radionuclides. Recently, the focus of concern, especially in industrial countries, has shifted from environmental impacts in the neighborhood of the stack to the long-range transport, conversion, and deposition of the sulfur and nitrogen oxides—the acid rain problem (see Chapter 8). In the U.S., emission controls require desulfication of flue gases, usually by scrubbing with lime or limestone. This is expensive, both in capital and operating cost, and creates a sludge which is difficult to dispose of. Although coal washing to remove most of the inorganic sulfur and the development of dry scrubbing techniques can ameliorate the problem somewhat, a better solution, particularly for high sulfur and high ash coals, is fluidized bed combustion.

A fluidized bed is formed when a bed of finely divided particles is subjected to an upward air stream of such velocity that the particles become turbulently suspended and resemble a bubbling liquid. The bed is heated up by burners directed into the surface, and, when a temperature of about 600°C is reached, crushed coal is introduced at the base of the bed and is burnt, continuously maintaining a temperature of 800-900°C, which is below the fusion temperature of most coal ash. Because coal is only a minor constitute of the bed, consisting mainly of ash, limestone or dolomite can be added and is effective in suppressing 80% to 90% of the SO_2 emission; the sulfur emerges with the solid residues as calcium sulfate. Moreover, at temperatures of 800-900°C, which are much lower than those in conventionally-fired boilers (∿1400°C), nitrogen in the air is no longer "fixed," and the quantity of NO_x formed is determined solely by the nitrogen content of the coal. This lower combustion temperature also results in a reduction of the quantity of trace metals emitted.

For power generation, which is currently the largest market for coal, pressurized fluidized bed combustion may be even more advantageous. This is because the high heat transfer rate in fluidized beds allow the larger heat release rate of pressurized combustion to be matched by an appropriate heat transfer surface in a unit of modest dimensions. As in an atmospheric fluidized bed, steam is raised in tubes immersed in the bed, but after a hot gas cleaning stage, the high pressure off-gases can be used to drive a gas turbine, thus combining the efficiency advantage of combined cycle operation with the environmental benefits of reduced SO_x and NO_x emissions.

Fluidized bed combustion is an active area of research, development, and demonstration in the U.S. and Western Europe. These range from basic studies on the fluid mechanics of beds to the operation of various pilot-scale atmospheric and pressurized facilities. The atmospheric version is more highly developed at the present time, but in the longer term, pressurized combustion seems very attractive for utility power generation, in comparison with both conventional coal combustion with flue gas scrubbing as well as nuclear power and such renewable options as wind, photovoltaic, and hydro.

4.1.4 Gasification for Power Generation

An alternative method for generating electricity which can achieve both high thermodynamic efficiency and minimal environmental impact is to first gasify the coal and then use the gas, after scrubbing to remove sulfur and particulates, to fire a gas turbine from which the exhaust gases are used either to raise process steam or to drive a steam turbine in a combined cycle. (The potential advantage of the latter as compared with combined cycle operation using pressurized fluidized beds is a limitation on the efficiency of bed combustion, due to the fact that at temperatures above about $1000^{\circ}C$ there is an increasing risk of softening, agglomeration, and subsequent defluidization of the ash particles.)

Note that the fuel gas need not have a high energy content since it is burnt on site rather than transported long distances. Two major areas of current technology development in coal gasification systems are high temperature gas turbines and gasifiers which are insensitive to coal type. Like fluidized beds, such systems would be attractive for utility power generation as well as topping cycles for industrial cogeneration.

Some proposed versions of these coal conversion plants have the CO_2 effluent appearing fairly clean and concentrated; the main original purpose was to produce CO_2 for oil recovery and other industrial uses. Our conclusions that: (a) only coal could cause a large CO_2-climate problem, (b) much of that coal would be used to generate electricity, (c) effluent controls would probably become much more severe (apart from CO_2 considerations) offers a glimmer of hope for sequestering a substantial amount of CO_2. Much of the CO_2 extraction and concentration, tasks that seemed hopeless in conventional combustors, will be done as a natural part of the cycle. But exploring the practicality of this would require a whole separate study.

4.1.5 Coal and the Liquid Fuel Problem

Supplying liquid fuels for transport after conventional oil effectively runs out is often called "the energy problem within the energy problem." Many alternatives have been suggested including electric vehicles, hydrogen, oil shale, and the alcohol fuels, methanol and ethanol. The prospects for the non-alcohol alternatives can be briefly summarized: (1) Although there has been a significant effort to develop batteries with the specific energy, cycle life, and cost required for electric vehicle applications, none are as yet available (Cairns 1981). Moreover, even if a breakthrough occurs, it will take man years to put the necessary infrastructure into place. Given this, an optimistic view is that electric vehicles are a serious option in the next century, particularly for urban transport. (2) Like the substitution of electricity for petroleum, the use of hydrogen requires a new distribution system and a new fuel tank. The latter is a significant design problem. More fundamental still is the question of where the hydrogen will come from. Currently, most hydrogen is manufactured by steam reforming of methane; some is also made by coal gasification. The only significant non-fossil option is electrolysis of water using cheap hydroelectric power, which, unfortunately, is not generally available. Many alternatives to electrolysis for hydrogen production have been suggested, e.g., solar photolysis of water and irradiation of semiconductor/liquid junctions, but this work is still at the laboratory stage. Overall, we judge "the hydrogen economy" to be, at best, a distant prospect. (3) Although the resources of oil shale are estimated to be larger than those of conventional oil (∿400 vs. ∿250 Gtoe respectively), only a small fraction is exploitable with present technology, and commercial production is currently limited to the Soviet Union, the People's Republic of China, and a little i Brazil. On the one hand, above-ground retorting at present requires substantial amou of fresh water and creates a substantial waste disposal problem, while underground combustion is hard to control. Nevertheless, improvements in recovery technology and corresponding increases in production are probable, although it is difficult to predict how large a fraction of the ultimate resource will be recoverable. If the fraction is high, it would have a significant, negative impact on the CO_2 problem since the CO_2 release per unit of energy produced from carbonate shale is about a factor of two greater than that characteristic of liquids derived from coal, because of the partial calcining of the carbonate rock during the retorting process, which both releases CO_2 and leaves the alkaline spent shale residue.

In sum, shale is a large resource, although still small compared with coal. If environmental problems in its exploitation can be overcome, particularly in the U.S., it could significantly extend the life of petroleum as a transport fuel, with a disproportionately large impact on CO_2.

Turning now--and again briefly--to the alcohol fuels, recent attention has focused on the ambitious effort by Brazil to largely replace imported petroleum as a motor fuel with ethanol derived from sugar cane. This program has been extensively described and critiqued in the literature, and useful overviews have been given by Goldemberg (1981), (1982) covering technical and economic considerations, socioeconomic impacts, and the applicability of the Brazilian experiences to other countries. We note that there has been considerable skepticism about the unsubsidized cost of both the Brazilian program and the corn to ethanol (gasahol) program in the U.S.; from this perspective, non-economic factors such as security of energy supply and opportunities for increased employment in rural areas are used to justify programs which cannot pay their own way. On the other hand, these factors, as well as others which have more negative implications such as the morality of producing fuels rather than food from agricultural sources and the long-term environmental impacts are clearly important. Indeed, biomass-to-alcohol programs, particularly in developing countries, raise the issue of the distribution of costs and benefits of energy policies to different societal groups in particularly acute forms. Unfortunately, further exploration of this would carry us too far afield; see; e.g., Smil (1983), which is both well-documented and pessimistic.

The relevance of the above to coal is that methanol from biomass appears to be within limits of its availability, the cheapest and most appropriate of biomass fuels. This is because it can be made from a wide range of carbonacious materials, e.g., short rotation forestry, which does not compete directly with food production, and also because the production technology is potentially cheap. However, methanol can also be derived from coal, and especially in countries where coal is relatively plentiful and cheap; e.g., U.S., U.S.S.R., P.R.C., Austrailia and South Africa, it seems clear that this will be the feedstock of choice. Indeed, studies by the Volkswagen Company in Germany (Bernhart et al 1981), predict that by the end of the century only half of the cars in the world will run on gasoline; of the remainder 15% will use diesel, 3.5% biomass ethanol, 23% coal methanol, some off LPG, and a little off electrical drive systems.

The above should not be taken to denigrate the potential importance of biomass-derived fuels in selected countries. As Goldemberg (1982) points out, the lack of abundant fossil fuels, the abundance of land and forests, a highly developed urban sector, and external debt are common characteristics of many Latin American and some African and Southeast Asian countries which are favorable to a sustained economic development based on locally produced liquid fuels from biomass. Moreover, many of these schemes have a large biological and engineering development potential and can be implemented efficiently in a relatively decentralized manner. Nevertheless, on a global basis, it appears that coal will be the preferred future feedstock for liquid fuel.

4.1.6 Conclusion

Within the coal community it is conventional wisdom that while there are problems in increasing coal use in the short run, its long-term future is assured. The concern about the possible impacts of CO_2-induced climate change aside, we would agree that there are good grounds for optimism about the future prospects for coal. The resource base is considerable, and the use of new technologies, particularly improved methods of combustion and efficient means of conversion, could significantly mitigate the adverse non-CO_2 health and environmental impacts that coal use on an expanded scale would otherwise have. Thus, it is unlikely that the coal resource will be largely unexploited because it will price itself out of the market or it is perceived to be a dirty fuel. Rather the saving grace from the CO_2 perspective probably lies in: (1) further opportunities for energy end-use efficiency, especially in developed countries, (2) the increasing penetration of various renewable resources, and (3) the possibility that technology innovation and institutional reform will lead to a revival in the future of nuclear power in the U.S. and elsewhere. Taken together, these developments imply that fossil energy use need increase slowly, if at all. The CO_2 problem does not disappear, but the possibilities for preventive or remedial action are greatly enhanced.

Table 4.1.1

World Coal Resources and Reserves, Comparison of Estimates

	Geological Resources				Technically and Economically Recoverable Reserves			
	WEC[1]		WOCOL[2]		WEC[1]		WOCOL[2]	
	Btce	%	Btce	%	Btce	%	Btce	%
United States	2570	25.4	2570	23.9	177	27.8	167	25.2
USSR	4860	48.0	4860	45.2	110	17.3	110	16.6
People's Republic of China	1438	14.2	1438	13.4	99	15.5	99	14.9
United Kingdom	164	1.6	190	1.8	45	7.1	45	6.8
Germany	247	2.4	247	2.3	35	5.5	34	5.1
India	57	0.6	81	0.7	33	5.2	12	1.8
Republic of South Africa	58	0.6	72	0.7	27	4.2	43	6.5
Australia	262	2.6	600	5.6	27	4.2	33	5.0
Poland	126	1.2	140	1.3	21	3.3	60	9.0
Canada	115	1.1	323	3.0	10	1.6	4	0.6
Others	230	2.3	229	2.1	53	8.3	56	8.5
TOTAL	**10127**	**100.0**	**10750**	**100.0**	**637**	**100.0**	**663**	**100.0**
Largest Five Countries	9377	92.6	9791	91.1	466	73.2	481	72.5
Largest Ten Countries	9897	97.7	10521	97.9	584	91.7	607	91.5

[1] Estimates by World Energy Conference, 1978

[2] Estimates by World Coal Study in 1980

Table 4.1.2

Changes in World Coal Resource Estimates
(billion tce)

	Geological Resources	Reserves[1]	Ratio of:	
			Reserves/ Resources (%)	Reserves/ Production (years)
1974 (WEC)	8603	473	5.5	189
1976 (WEC)	9045	560	6.2	207
1977 (WEC)	10124	637	6.3	230
1980 WOCOL Estimate	10750	663	6.2	239

[1] Technically and economically recoverable reserves

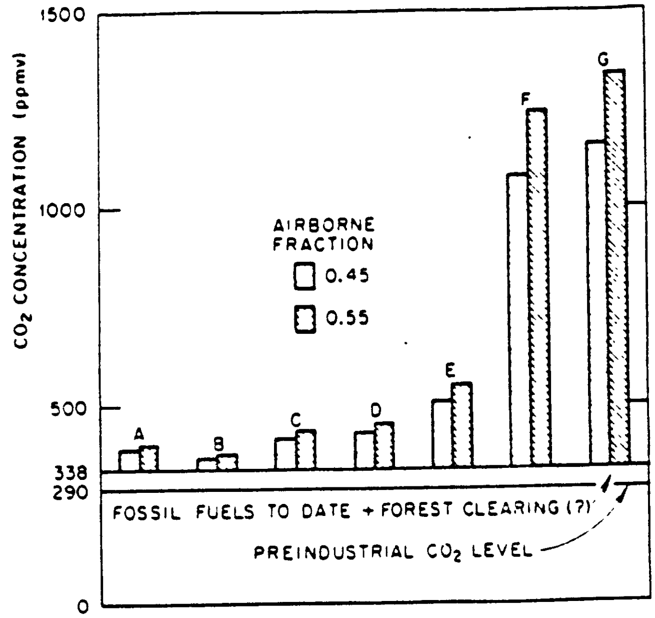


Figure 4.1.1

Atmospheric CO_2 concentrations produced by combustion of estimated recoverable resources of fossil fuels for airborne fraction of 0.55 or 0.45. A. Oil resources; B. Gas resources; C A + B, all oil and gas; D. Coal reserves (636 Gtce); E. C + D; F. Coal resources (including reserves); G. C + F.

4.2 Solar Photovoltaic Energy

Much has been written about this; rather than attempt a detailed assessment, we note the existence of several reviews (see the annotated bibliography) and briefly summarize the facts and trends that are relevant to the global energy-CO_2 problem.

We believe that if solar PV power is to be a major global energy option (i.e., at the terawatt level), it will consist in the main of multi-megawatt solar PV farms tied to local or regional power utilities. Several reasons exist for this. First is the increased electrification of the world (as described endemically in this report), which is happening, solar PV or not. Second is the increased ability of electric utility grids to accept energy from decentralized sources (see Chapter 5). Third, the operation and maintenance (O&M) costs associated with small stand-alone systems are estimated to be very large. In this last context, the SCI report (see bibilography) estimates O&M costs of 3.5 mills/kwh (1979 dollars) for 10 MWe systems, rising sharply for smaller installations. (These estimates are based on experience with diesels, batteries, fuel cells, etc.: the specific technology seemed less dominant in determining costs than were issues such as the need for travel time between sites because of lack of permanent personnel (SCI 1980). Note that 10 MWe systems are still capable of capturing many of the benefits of reduced transmission and even some distribution (T&D) costs and losses. Such systems are still "small" by most electric utility standards. Current plans for multi-megawatt systems described below support this view. Various tax incentives can favor either the end-user or the utility; this is a redistributional problem, of secondary importance.here.

Focussing on these "large" systems simplifies the arguments to follow. The driving force for development and cost reduction of both modules and balance of system (BOS) will come via such systems; in any event, whatever smaller systems that eventually develop will benefit from the spinoff. We think that kw-size applications will be limited to remote locations and some special needs, and not to the roofs of the world's houses. Regarding this latter application: (1) the need for keeping the temperature low and the efficiency high conflicts with the usual schemes for saving energy in the home by insulated roofs; (2) a PV-covered roof gets dirty, and cannot be safely walked on; (3) despite claims by some PV enthusiasts that people will delight in caring for their own energy systems, most do not now service their own applicances or (usually) cars; this is related to the observation by many that efficient and reliable PV modules will be made in large (centralized) factories, from which will naturally flow the capability of service; (4) the capital cost is higher, in addition to O&M; this is particularly so for the cost of power-conditioning equipment.

4.2.1 Recent Relevant History

Sales and contracts for solar PV systems have grown by a factor of 2 or more in each of the past several years; from 1.5 to 2 million dollar installations in Colombia and North Africa in 1980-81 (Haq 1981) to $10 million and larger projects in service today. The largest and most advanced of these are in California, stimulated by a combination of Federal and State support, tax incentives, more public receptivity, relatively cloud-free sites, etc. Table 4.1 summarizes most recent information about these California installations.

According to Solar Age, April 1982, the market share of the three major US photovoltaic suppliers was:

Solarex (AMOCO, etc.)	38%
ARCO-SOLAR	26%
Solar Power (Exxon)	15%

ARCO-SOLAR has now overtaken Solarex, at least temporarily.

4.2.2 Some Future Cost Projections

The Department of Energy 1978 forecasts of \$.50/W_p (in 1978 dollars) in 1986 will not be met. In the 1978-83 period, improvements seem to have come at about half the 1978-expected rate.

Discussions with senior Jet Propulsion Laboratory personnel (Daniel et al. 1982-83) confirmed the view that modules, probably polycrystalline silicon, would be available for 1985 delivery at \$4-5/Wp. If all the technology available in the US were put under one factory roof, we would be able to supply finished modules at a price of \$2.70/W_p in 1980 dollars. Advances now foreseen and very probable would bring this down to an asymptotic \$1.50/W_p. For multi-megawatt systems, the power conditioning is expected to be only 10-15% of the module cost at most.

What might be a rock-bottom ultimate cost? A reasonable backing for any panels is expected to cost about 60¢/ft^2, or 6¢/W_p at 10% efficiency. This and other costs leads to an estimate of about 30¢/W_p (1980 dollars) for modules alone. We see here a factor of 5 between the extremes for asymptotic module cost. If past experience is any guide, the balance of the system (not including storage) will approximately double these costs (see SMUD phases I-III), although some of the engineering design and other costs will be non-recurrent. Taking a factor 2 as a guide, we have \$.60 and \$3.00/W_p for entire systems.

What does this amount to in electric energy cost? At 20% capacity factor, a good day-night-summer-winter average, we have \$3000-\$15,000/kwe, on a continuous basis. At 15%/year rate of return on investment, this comes to 5.1¢-25.5¢/kwh, or \$14.3-\$73.3/GJ. The higher number would make solar PV prohibitively expensive except for special purposes, hence unfeasible for large-scale penetration. The lower one would allow solar PV to compete very well for daytime intermediate and peaking power. But intermittent electricity at a generation cost of 5.1¢/kwh is still much too expensive to be stored (in batteries, for example) for off-peak use, provided either coal or nuclear power are available. Any solar PV system which costs much in excess of this lower asymptote will face severe problems in adoption, without either large incentives and/or subsidies, or prohibitions of both coal and nuclear power, and perhaps even on oil. Furthermore, this lower asymptote seems far enough away that significant penetration of PV is unlikely this century; however, utilization of these technologies on a small scale is well-suited to current paths of low growth in electricity demand.

These asymptotic costs are used in our global energy scenarios worked out in conjunction with IEA. Deflated back to 1975 prices (the calculational basis), they are \$9.50 and \$47.50/GJ; we also try an intermediate value of \$20/GJ.

The path to improved and cheaper PV (and wind) systems could be in some ways smoother than the path to developing new nuclear reactors or (especially) controlled nuclear fusion. Very importantly, both solar PV and wind can be developed technically with relatively small units, hence without the necessity of constructing billion-dollar or even more costly proof-of-principle experiments.

4.2.3 Future Technical Trends

The low costs of PV modules needed to permit their entry into the bulk electric market must come via substantial technological and perhaps scientific advances. Principal considerations are these:

(a) Sawn single or polycrystalline silicon will probably not do. Semiconductor grade silicon sold for \$80/kg in 1982. There is much optimism that this cost can be reduced to \$14/kg (Deb 1982) and new techniques may reduce it to \$7/kg. It is expected that advanced sawing technology will not produce more than one slice per mm of ingot (0.5 mm blade width, 0.5 mm sawn slice). At \$7/kg, this comes to \$16/m^2 of wafers, or 16¢/W_p for the refined silicon ingots alone, which is half the 30¢/W_p for modules in the low-cost estimates. The various technologies to grow silicon ribbon from melt look more promising (Deb 1982). A ribbon thickness of 0.2 mm with small material waste would be adequately frugal of silicon use, even at $16/kg (6.4¢/$W_p$).

Much research has gone into development of amorphous silicon made by a silane process (a-Si:H) or by sputtering. The band-gap can be modified somewhat by inclusion of appropriate impurities. Efficiencies up to 8% have been reported, but the work is not nearly so far advanced as single- or poly-crystalline silicon.

(b) Thin films look promising. These can be a-Si, as mentioned above, or possibly other materials. The attractiveness of thin films lies principally in the hope that very cheap automated techniques can be developed to make them. Here, a high photon absorption coefficient is a great advantage, because the film can therefore be relatively thin; for example, a Ga-As cell need be only a few microns thick. R&D work is intense, much of it proprietary.

Ga-As films are particularly attractive because the band gap 1.4 ev is almost optimal for absorbing solar photons, and offers a theoretical maximum conversion efficiency of 26% (leading to 15%-20% in practice, one hopes). Ingenious methods are being developed to grow it even in very thin single crystals. For example, the CLEFT technique developed by Fan and co-workers (Fan 1981, 1982a) of growing micron-thick crystals of 5-10 cm^2 area epitaxially on a reusable substrate, then cleaving them off without damage, is a remarkable accomplishment, and gives hope for even more future advances. Extensive use of arsenic raises significant environment/health problems. Supplies of gallium are not well known, but are certainly relatively small.

Elaborations of these film techniques are being tried to develop stacked multilayer, multigap cells that convert a larger fraction of the solar energy to electricity. (Largest-gap junction nearest the front surface captures high energy photons photons, but is virtually transparent to lower energy ones, which penetrate to the next lower-gap junction, etc.). Work is still in an early stage, and the possibility of 30% conversion efficiency exists (Fan 1982b).

(c) Concentrators versus flat plates. It is still a horse race, with possibly a decade to go before we see if there is even a clear winner. New technology for concentrators (e.g., new plastic Fresnel lenses) will bring the cost down, but the solar cells live in a very severe and changing envivonment. The choice between flat plates and concentrators depends on:

- cost of concentrators vs. cost of flat cells.
- cost of flat one-sun cells vs. cost of highly sophisticated cooled cells with maximum efficiency.
- costs of reliable trackers.
- cost and availability of PV material -- silicon is (or can be made) plentiful, but GaAs, CuInSe, etc., cannot be so plentiful.
- the environment -- for example, flat plates still give about 40% reception on hazy or overcast days, but the efficiency of concentrators drops drastically under such conditions. For example, at Barstow, California, 100 miles ENE of California (just beyond Hesperia), LA smog decreases total reception by 15% (Mackin 1982).

(d) Aggressive and competent development. There is some worry that the U.S. solar PV industry is less than optimally structured. One worry is whether companies with the ability to produce the cells have the ability to sell them. Vice versa, do small companies with aggressive sales policies have the competence to produce them? Some other countries, expecially Japan and now Taiwan, are working very hard; according to some observers Japan is in the lead in much solar cell R&D, for example a-Si (Maycock 1982). Any large solar PV future is bound to take a long time to develop. It would be too massive for rapid movement. However, the entire solar and energy program in the U.S. has too-short time perspectives and there are few incentives to do any different. For example, there are few incentives at the moment to spend something like $30 to $50 million of capital expense to turn out about 50 MW/year of PV output (this is a present estimate of the cost of factories). Nevertheless, PV is much easier than nuclear reactors in many ways, because there is only about a two-year lag in the factory investment before obtaining a return on capital, instead of a decade or more. The initial markets will not be major U.S. grid-connected systems and the question arises whether the U.S. companies will be smart enough to beat out the Europeans, or (more important) the Japanese.

4.2.4 Brief Annotated Bibliography

Electricity from Sunlight: The Future of Photovoltaics, by Christopher Flavin. Worldwatch Paper No. 52, December 1982. A very readable 63-page summary of large and small projects, cost reduction trends, national programs. Also 82 references. Points out that this renewable technology did not develop so much with the "environmentalists" (as did wind, OTEC, biomass, etc.) but as part of science, technology and industry. This can be some advantage, and Flavin favors the technology.

Basic Photovoltaic Principles and Methods, Report SERI/SP-290-1448, February 1982, published by Technical Information Office, Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO 80401. A nice semi-technical overview.

Solar Photovoltaic Energy Conversion (Principal Conclusions of the American Physical Society Study Group, H. Ehrenreich, Chairman), published by American Physical Society, 335 East 45th Street, New York, NY 10017. An excellent review of the basic science and progress up to late 1978.

Photovoltaics as a Terrestrial Energy Source: Vol. I, Introduction; Vol. II, System Value; Vol. III, An Overview; by Jeffrey L. Smith, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, October 1980. An excellent review, especially with respect to the problems of systems integration, incentives, cost projections, etc. A summary of this is "Photovoltaics," by the same author, *Science* *212* 1472-1478 (1981).

Preliminary Analyses of Industrial Growth, and the Factors that Affect Growth Rate, Edward Edelson and Tom K. Lee, Jet Propulsion Laboratory, California Institute of Technology, Paper 5101-4, January 1977. Old, but important concepts. Study of growth rate of several rapidly growing industries, showing how the projected PV growth rates tend to surpass practical experience. Has statistics and some simple modeling.

Decentralized Energy Technology Integration Assessment Study, Systems Control, Inc. Report, SCI Project 5278, December 1980 (1801 Page Mill Rd., Palo Alto, CA 94304). This report is more extensively used in our section on integration of PV, etc., systems, but some calculations are very applicable here.

"Solar Cells: Plugging into the Sun," J.C.C. Fan, *Technology Review*, vol. 80, No. 8, August/September 1978. Good description of principles and techniques as of that date; still good reading. 18 pages.

Photovoltaic Systems Program Summary, Department of Energy Report DOE/CE 0033, January 1982. A description of all their funded projects, with funding level, but not much useful overall assessment.

Table 4.1

MAJOR CALIFORNIA PHOTOVOLTAIC INSTALLATIONS

Site	Owner	PV Supplier	Size MW	Power Sold To	Year of Operation	Cost $million	Note
Hesperia, 60 mi. NE of Los Angeles	ARCO-Solar	ARCO-Solar	1	Southern California Edison	1982	Propri-etary	a
Carissa Plains I, between Bakersfield and San Luis Obispo	ARCO-Solar	ARCO-Solar	6	Pacific Gas & Electric	1984	Propri-etary	b
Carissa Plains II	ARCO-Solar	ARCO-Solar	16 total	Pacific Gas & Electric	?	Propri-etary	c
SMUD I	SMUD	ARCO-Solar	1 ac (1.2 dc)	SMUD	April 1984	11.4	d
SMUD II	SMUD	Several (?)	1 ac (1.2 dc)	SMUD	1986?	10.4	e
SMUD III	SMUD	?	5 ac	SMUD	?	40	f

NOTES

(a) 1' x 4' panels assembled to 30' x 30' single-axis tracking units.

(b) Robert E. Robertson, Manager of Engineering, ARCO-Solar Industries, Inc., private communication. Has side-mirrors in panels for non-focused concentration.

(c) Entire plant (640 acres) to operate unmanned, by remote control.

(d) Sacramento Municipal Utility District. \$7 for modules ($\$5.80/W_p$ dc); 50¢/W_p for support; power conditioning, \$400,000; site construction \$1.46 million; field engineering, \$1 million. Mostly Federal money. These data from E.S. "Ab" Davis, "Assessment of the Single-Axis Tracking Flat Plate Concept for SMUD PV PHase I," Jet Propulsion Laboratory Report 5250-15, August 9, 1982, also private communications. Mark Anderson, Project Manager, SMUD, private communications.

(e) Specifies only 8' x 16' arrays to match mechanical and electric interfaces. Bids asked mid-October 1983 for 900 kw dc from one supplier, 3 x 100 kw dc from others. SMUD offers to pay \$3.6 million. Deflated to 1980 dollars (basis for original plan), this comes to \$7.67 million total, with \$2980/kw contributed by SMUD.

(f) Up from original 2 MW ac. Expect complete solar panels at $\$4.00/W_p$ dc, SMUD pays 50% of costs.

4.3 Wind

Despite some 1200 TW of solar power that goes into driving global winds, the scarcity of good wind-power sites limits the development possibility to very much less. Even 0.1% of this, or 1.2 TW, is probably optimistic, implying the presence of large high-performance windmills on windfarms that would occupy more than one percent of the world's land surface. Nevertheless, it is regionally important, and discussion of it brings out clearly some problems and critical issues related to non- or semi-dispatchable power.

Because good wind-sites are scarce, hence unlikely to be where their power output is needed, their output will be almost entirely electric, bringing them into competition with PV and nuclear power, amongst the various nonfossil options. The wind blows somewhat unpredictably even at the best of sites; therefore wind power has a limited capability of displacing more conventional (and dispatchable) installations that must respond reliably to demand. That is, the capacity credit is likely to be modest, less than the fuel credit.

A simple calculation establishes some of these points, particularly the fuel credit. Suppose the electric power demand is P_1 (kilowatts) for 0.7 of every day, and P_2 ($>P_1$) during the remaining 0.3; this corresponds roughly to daily periods of normal and peak loads. Suppose also that the wind blows at optimally usable speed a fraction f of the time, and not at all during the remainder (1-f); the times are unpredictable. This two-level windspeed is not a bad approximation for our purpose, because the v^3 dependence of wind-power on speed makes slow winds almost valueless; at speeds greater than the optimal one, most machines limit the output, in order to avoid failure. Suppose also that oil-burning power stations are available at \$500/kwe capital cost, oil costs \$5/GJ (\$30.50/bbl), the oil plant has 40% thermal efficiency, the annual cost of capital is 10%, and all systems have 90% technical availability.

What can we afford to pay for the wind-farm assuming that transmission costs of the two systems are the same?

First, consider no energy storage (e.g. pumped hydro), and (for the moment) no capacity credit. Then we require that the entire demand be met by oil if necessary. The fuel cost of electricity is \$5/0.4 = \$12.50/GJ, and the wind cost must be less than this. To replace continuous power P_1, we have a wind capacity factor of 0.9f, and it can be easily checked that the annual output of the wind-farm is 28.4f GJ/year per kwe of name-plate capacity. The saving is therefore \$355f/year-kwe, and with money at 10%, we can afford to spend \$3350f/kwe for the complete windfarm.

If f = 0.5, corresponding to the best sites, the break-even comes at \$1775/kwe; if wind farms are available for less than this, we should buy them up to the capacity P_1, unless other circumstances intervene, based on a fuel calculation alone.

What about building beyond P_1, to replace some peaking power as well? Now the additional windmills operate only 0.3 as often as the others, so their cost must not exceed \$1183f/kwe or only \$591 if f = 0.5.

Several important considerations have been omitted in this simple example.

1. Capacity Credit. The combined system is less likely to be inadequate to supply any given load than was the oil-only one. Therefore on a reliability (i.e. loss-of-load-probability) basis, some fraction of the installed wind capacity can be applied to reducing the base-load plants. Just how much depends on detailed calculations of the joint probability of the demand exceeding any given amount, and the wind not blowing optimally. This topic will be examined in Chapter 5, on system integration.

2. Spinning Reserve. Here, especially if the system penetration of the windmills is greater than a few percent, a negative credit may apply. The

reason is that the wind may not blow, in an unpredictable way, and the load may have to be picked up rapidly. Again, the detailed nature of wind fluctuations and calm periods will determine the outcome, to be discussed in Chapter 5.

3. Operation and Maintenance. It is liable to be high for small isolated windmills, giving the advantage to substantial windfarms.

Now suppose that the wind-energy system of this example had retrievable-on-demand storage for more than one day, but for a shorter time than the maximum windless periods. In that case, we replace fuel at all times and can afford \$3350f/kwe up to maximum power P_2. If storage time exceeds the maximum windless time, then the whole oil system could profitably be replaced, if it cost less than \$3350f + 500 per kwe, or \$2275/kwe in our example with f = 0.5. But note the continuing caveats about spinning reserve (if the storage will not deliver in time), and O&M.

The wind parameters and postulated system in this example were close to the best available. First, the wind profile was good. Figure 4.3.1 shows the wind duration and derived available power for Kahuku, Hawaii, one of the world's best wind sites, where indeed $f \simeq 0.5$ (full power equivalent for 4300 hours/year). Second, the competition was high-cost fuel. If the alternatives had been nuclear or solar PV with either low (or zero) fuel cost, the wind sytem could not have fared well, both because of its unreliability and the competition with cheap (or free) fuel. Energy storage overcomes that drawback, one might claim. That is so, but the same energy storage systems would turn daytime solar PV into night-time lights, and cheap off-peak (night-time) nuclear power into peaking power, as discussed at greater length in section 4.8 on energy storage.

From this simple example, one can see why windpower is attractive in:

- Scandinavia, where:
  - the winds are good, especially in Denmark and Southern Sweden;
  - hydropower is available, especially in Norway; the two systems are complementary as detailed calculations have shown. See the section on energy storage for more details.
  - the skies are often cloudy;
  - traditional dependence on oil is high;
  - there is no cheap coal.

- California (and some other U.S. sites), where:
  - tax incentives and other subsidies, plus PURPA, make it attractive;
  - there is high dependence on oil;
  - there are good winds in selected locations;
  - there are impediments to use of nuclear or coal.

- Hawaii, where:
  - almost all the California advantages apply;
  - trade winds are exceptionally reliable 9 to 10 months of the year.

Table 4.3.1 shows the results of a July 1983 poll we conducted of major U.S. manufacturers. It is not complete, but we think that most major installations have been included. According to these entries alone, about 107 MWe are presently installed, chiefly in California. This total has more than doubled each recent year. Prices range from $1200/kwe at the factory to about $2000/kwe for a complete installation. The Pacific Gas and Electric Company and Southern California Edison Company programs are largest. Compare these costs with those derived in the initial example. With present tax incentives, an effective capacity factor as low as f = 0.25 would still represent an attractive investment. Material requirements are principally 20 to 30 kg metal per kilowatt for 50 kw size machines, and less for larger ones. Thus both material and land demands of wind-power seem not to be severe.

As stated earlier, good wind sites are scarce, and they have not been catalogued in detail in enough potentially useful sites. High but intermittent wind speed is actually a disadvantage. A steady wind of 8-15 m/sec (18-35 mph) can be ideally designed for, which suggests the tropical trade winds, some temperate westerlies, island or mountain pass locations, etc. Furthermore, wind speed and steadiness both tend to improve markedly some tens of meters above ground level. This favors large windmills (>100 kwe, say).

As with other systems, a tradeoff exists between economies of scale arising from larger size (e.g. transmission lines, central systems) and economies arising from mass production of many small units. In our opinion, if wind-power is to play any substantial role in our electric future, it will be with windmills in the megawatt range: at 0.5 capacity factor, 2000 one-megawatt machines are required per GWe, surely enough to capture the principal economies of mass production.

The present price of about $2000/kwe installed will drop with time, advances coming in engineering and manufacturing, not in applied science. Therefore, prospects for cost reduction by a factor 2-3 seem bright, but beyond that not good (unlike hopes for solar PV). At about $1800/kwe it will and does replace oil marginally in good locations. At about $700/kwe it would replace coal similarly, and we are optimistic enough to think this could happen in selected sites.

Table 4.3.1 Major wind installations, July 1983.

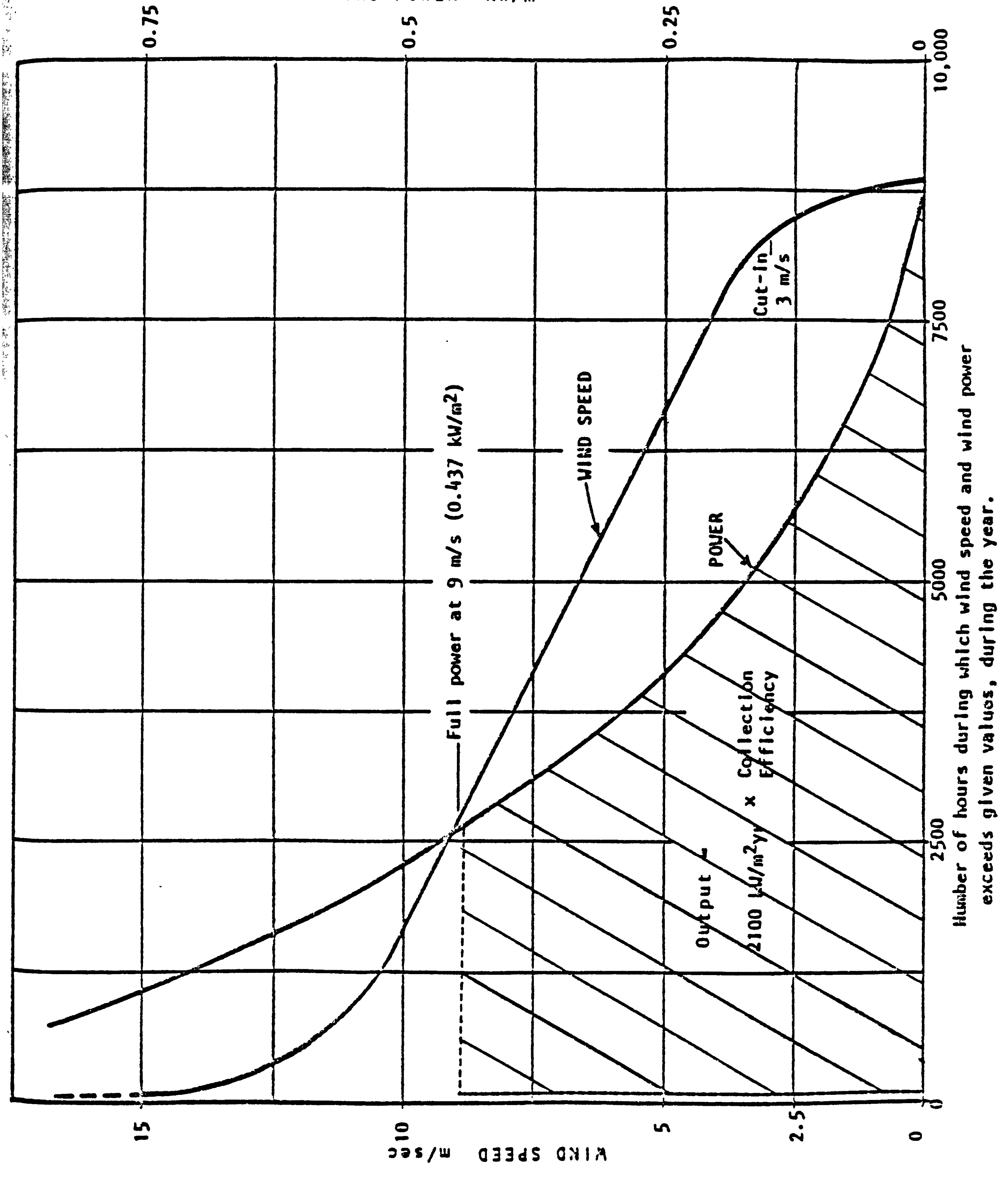
Manufacturer	Rated Unit Size KW	Installed/Location	Number Ordered	$/Unit Prices Factory delivered/installed (1983 $/kw)	Comments
Fayette Mfg. PO Box 1149 Tracy,CA 95376 (415)443-2936	85kw	>240/Altamont Pass,CA	0	$118,000 installed ($1388/kw)	Has produced over 10^6kwh
PM Wind Power	25kw	3/Ohio 1/Texas	0	$35,000 delivered ($1400/kw)	
Boeing	2500kw	3/Goodnoe Hills,WA 1/Solano,CA 1/Wyoming	1	The unit in CA - PG&E $6.3 million installed(1980$) $7.5 million (1983$) ($3000/kw)	The one ordered is R&D for NASA 3 Mw
Hamilton Std.	4MW 3MW	1/Wyoming 1/Sweden	0		Prototypes
Wind Power Systems	40kw	222 { Tahachapi, CA Altamont, CA	0	$60,000-$80,000 installed ($1500-2000/kw)	Prices differ due to 2 tower sizes that are offered
American Wind Energy Systems (designers)*	50kw 75kw 100kw	150/Tehachapi, CA 20/Pacheco Path,CA	*	~$65,000/unit factory ($1300/kw)	*HallMath,Inc. manufactures the WEC. They have "thousands" of orders.
Carter Wind Systems	25 kw	10/Texas 4/Montana 100/California	-	$30,000 - everything except foudation & deliver ($1200/kw) delivery & installation=$5/mile	

Manufacturer	Rated Unit Size KW	#Installed/Location	Number Ordered	$/Unit Prices	Factory delivered/ installed (1983 $/kw)	Comments
Energy Science	50kw*	have installed 50kw 20/Calif. 8/Hawaii		$70,000	factory	*They no longer manufacture 50kw
	60kw					
U.S. Wind Power	50kw	600 Altamont, CA	500-600 for PG&E	entire windfarm $2000/kw	installed	Included station foundation ... everything
		100kw Prototype	0			
Westinghouse	7.3 Mw	-	1/Hawaii	$14.2 million	installed ($1945/kw)	Prototype
Windtech, Intl.	25kw	3/Calif.		~$28,000	delivered ($1120/kw)	
	50kw	1/Tehachapi		~$45,000	delivered ($900/kw)	
	75kw	1/Tehachapi	25/Tehachapi	~$55,000	delivered ($733/kw)	
DAF Indal	50kw	1/TX, US 7/Canada 1/Ireland 1/Australia 2/California,US	—	~$130,000	factory ($2600/kw)	
	230kw	1/California 1/Prince Edward Island				Discontinued
	500kw	1/Gulf of St.Lawrence,CANADA				$500,000 factory ($1000/kw)

Manufacturer	Rate Unit Size KW	Installed/Location	Number Ordered	$/Unit Prices Factory Delivered ($/kw) Installed	Comments
Turbowind	300kw	30/Altamont Pass	60	$700,000 factory ($2333/kw)	
Windmaster	200kw	5/USA 4/Europe	50	$160,000 factory ($800/kw)	
Zond	65kw 100kw	>100/California		$150,000 ($2308/kw)	

107990 kw installed

Figure 4.3.1. Wind power duration curves for Kahuku, Hawaii, with possible application data. Adapted from "Guidebook on Wind Energy, Conversion Applications in Hawaii," Hawaii Natural Energy Institute, University of Hawaii (1981).



4.4 Nuclear Fission

Nuclear fission stimulates many conflicting views, much social debate and political and economic controversy. In the U.S. it is widely regarded as a loser, an attitutde also found in some sections of West Germany, Sweden and a number of smaller European countries. In many others -- Korea, Taiwan, Japan, France, for example, it is seen as a winner. In the U.S.S.R., China and some other countries it is seen as an important energy option to be developed with tight controls that are consonant with central planning.

We believe that nuclear power will play an important role in electric power provision globally, and quite possibly also in providing heat in the temperature range up to 800°C for large industrial applications. This opinion arises not from study of the present state of the U.S. industry, but from what we see to be future prospects and trends elsewhere. The initiative will pass from the U.S., if present trends continue.

Support for this conclusion comes from many sources, but three deserve particular mention. One is the Congressional Office of Technology Assessment study of The Future of Conventional Nuclear Power (in the U.S.), just being completed (fall 1983). Second is an insightful analysis by William Walker and Måns Lönnroth, Nuclear Power Struggles, Allen and Unwin, London (1983). Third are the conference papers from a workshop, "Nuclear Power in the Asia-Pacific Region," at the East-West Center, Honolulu (January 1983), the proceedings of which will appear in 1984 in the journal Energy.

We will focus principally on electric power generation, believing that the future of nuclear power depends on general acceptance of it for that purpose; other applications would then follow. Also we start with a discussion of the U.S. nuclear sector, not only because we are interested in possible U.S. actions, but also because it makes a good point of departure for reviewing the state of affairs elsewhere.

Are the present difficulties afflicting nuclear power only growing pains, or symptoms of a terminal disease? We suggest that most of them are the former (at least outside the U.S.), and that reasonable treatment can cure them. But some are potentially fatal.

4.4.1 Issues with Large U.S. Domestic Content

1. Present U.S. light water reactors (LWRs) are not well matched to future needs. Several sub-issues exist here:

(a) At times of low growth of electricity demand, and also to match smaller electric utility grids around the world, interest turns to smaller reactors, both light water and gas cooled. Such units could capture the effective and improved quality control of factory production, and the economies of construction arising from serial production of identical (or near-identical) units. Moreover, there is a smaller likelihood of large accidents. It was claimed that economies of scale would favor the 1300 MWe reactors now being built, but this has not turned out to be so.

(b) Few U.S. vendors seem interested in building anything but the present line of large LWRs. MIT's Nuclear Engineering Department has held a series of seminars involving the vendors, electric utility companies, and regulatory personnel, which have confirmed this view. Almost without exception, the U.S. vendors see insuperable difficulties in developing anything else: R&D funding, public acceptance, NRC licensing, no markets, etc. Westinghouse and General Electric have joint development programs with Japan, but the initiative seems to rest with Japan.

(c) The U.S. nuclear industry has lost international momentum. The U.S. fraction of the diminishing number of world orders has dropped sharply. See Table 4.4.1 attached (from Lönnroth).

All these look more like growing pains than terminal illnesses, except perhaps for the U.S. sector.

2. Unresponsiveness of the nuclear sector to fears of accidents, consequences, etc. This applies especially to the Atomic Energy Commission and the nuclear industry in years past, but some vestiges continue. This created a climate of suspicion that was justified only in part, but was capitalized upon by critics. The nuclear sector lost its claim to authority, so to speak. To paraphrase the words of Michael Polanyi (Polanyi 1967), the public normally accepts technology not because of a shared sense of the detailed concepts, but by submission to the demonstrated authority and success of technology. Hence, if people ever venture seriously to dissent from technological opinion, a regular argument may not prove feasible. It will almost certainly prove impracticable when the question at issue is whether a certain set of evidence is to be taken seriously or not. Such conflicts between technology and the general public may imperil technology.

The U.S. nuclear sector seems disinclined to pay attention to issues of this sort. This is a potentially fatal disease wherever it occurs. A cure exists: Safe operation for enough years so that the public is reassured.

3. Misjudging the nuclear waste problem. The tale is well known, but seems on the way to a cure in the U.S. via passage of the Nuclear Waste Policy Act of 1982. Again, this looks more like a growing pain, although it has often been presented as a terminal illness.

4. The slower growth of electric energy use. The effectiveness of energy-efficient programs in the post-1973 period, plus shifts in product mix, have reduced electric power growth from its 1900-1970 rate of 7% per year to about 2% per year in 1980 (and even a decline in use in 1982 because of the recession).

Thus the U.S. had an excess operating capacity exceeding 30% in 1982. With presently expected electric power growth rates of even one to two percent per year, this excess will be gone by the mid-1990's, but the nuclear vendors may not stick it out that long, and besides, the technological initiative may have passed to Japan and/or Germany by then. In any event, the present LWRs seem to us not ideal for the period of the 1990's and beyond.

This issue relates to the electric utility sector as a whole, and not the nuclear sector in particular.

5. The over-ordering of nuclear plants in the early to mid 1970's, followed by massive cancellations. This is related to Item 4 above. This ordering of nuclear plants came about not only in response to oil price rises, but also coal price rises (not much publicized) from \$0.38/GJ in 1970 to \$1.50/GJ in 1980 (average to industrial users). This misassessment was duplicated in other countries that now face a surplus of ordered plants: France, Korea, Taiwan, for example. But it appears to be an intermediate-term problem, not a long-term one.

6. The high cost of money. This high cost, especially in 1978-1983, drained financial resources of electric utility companies (and other sectors) that contracted for capital-intensive plants that would take too long to build and/or to recover their cost via operating expenses. The present twelve-year period between first plans and final operations of a nuclear plant does not mean that 12 years interest on the whole cost must be paid. Far from it; judicious ordering of components reduces the interest and escalation charges to what is in effect a few years only. Nevertheless, those money charges account for about half the cost of plants presently going into operation.

If this circumstance of high money costs continues globally and for the long term, many other sectors besides the nuclear one will be in trouble.

7. Many electric utility companies were (and are still) unprepared for nuclear power. The difference in costs and times to completion among nuclear plants in the U.S. is startling, the former varying by a factor of three, and the latter by more than a factor of two. Some electric utilities, not necessarily the largest or best known, have had nuclear plants come in approximately on budget, on time, and they run well. Others, not necessarily the smallest, have experienced large overruns and delays, and operating problems. The nuclear sector is hostage to its least competent reactor operators. The growing realization by the utilities that efficient and safe operation is essential, and that owning and operating nuclear plants is much more complicated than owning and operating coal-fired plants, presses electric utilities in the U.S. to improve their performance. The Institute for Nuclear Power Operations (INPO) was established to deal with these problems, and most of the nuclear electric utilities (both public and private) in countries outside the CPEs are members. However, it remains to be seen how effective INPO will be.

This set of problems is even more difficult for developing countries where the shortage of highly skilled craft personnel, engineers, technicians, engineering and technical services, etc., can lead to serious problems in construction, operation and maintenance. The supply of skilled manpower per nuclear megawatt in Taiwan and Korea is projected to be only about half that in Japan in the 1990's, given present training programs.

In our opinion this lack of in-depth skill in the nuclear-electric sectors of developing countries will be one of the greatest impediments to the growth of nuclear power.

8. The U.S. legal and regulatory morass. This problem is not peculiar to the nuclear sector. Issues are often recycled round and round between the

Federal and State governments, the Congress, and the courts. The U.S. form of government is effective for implementing a consensus already reached, but not so good for reaching consensus quickly. The problem is aggravated by the fact that the U.S. is a very litigious society to the benefit of the legal profession but few others.

These attitudes and difficulties are found also in West Germany, but only to a much smaller extent elsewhere.

9. There is no obvious solution to the potential misuse of the technologies, facilities, and materials associated with civilian nuclear programs for the construction of nuclear weapons. International Safeguards and export controls on sensitive technologies can help, but the ultimate fix is not technical: It lies in reducing the incentives for nations to acquire weapons, not in banning civilian nuclear power. Georgius Agricola wrote in 1556 about whether it is proper to mine the earth for metals because they could be used in weapons:

> The curses which are uttered against iron, copper, and lead have no weight with prudent and sensible men, because if these metals were done away with, men, as their anger swelled and their fury became unbridled, would assuredly fight like wild beasts with fists, heels, nails, and teeth. They would strike each other with sticks, hit one another with stones, or dash their foes to the ground. Moreover, a man does not kill another with iron alone, but slays by means of poison, starvation, or thirst. He may seize him by the throat and strangle him; he may bury him alive in the ground; he may immerse him in water and suffocate him; he may burn or hang him; so that he can make every element a participant in the death of men. Or, finally, a man may be thrown to the wild beasts. Another may be sewn up wholly except his head in a sack, and thus be left to be devoured by worms; or he may be immersed in water until he is torn to pieces by sea-serpents. A man may be boiled in oil; he may be greased, tied with ropes, and left exposed to be stung by flies and hornets; he may be put to death by scourging with rods or beating with cudgels, or struck down by stoning, or flung from a high place. Furthermore, a man may be tortured in more ways than one without the use of metals; as when the executioner burns the groins and armpits of his victim with hot wax; or places a cloth in his mouth gradually, so that when in breathing he draws it slowly into his gullet, the executioner draws it back suddenly and violently; or the victim's hands are fastened behind his back, and he is drawn up little by little with a rope and then let down suddenly. Or similarly, he may be tied to a beam and a heavy stone fastened by a cord to his feet, or finally his limbs may be torn asunder. From these examples we see that it is not metals that are to be condemned, but our vices, such as anger, cruelty, discord, passion for power, avarice, and lust.

We do not pretend that uranium and plutonium are iron or copper, but quote Agricola to show how similar debates have occupied the attention of people for millenia. Applied to nuclear power and nuclear weapons, we see both promise and peril, and the dangerous imperfection of man, susceptible to the sins of avarice, overambition, and hubris. Despite these weaknesses, or perhaps because of them, we believe that resolution lies in seeking states of increasing grace and caritas, and accepting what is in Creation with an attiude of thanksgiving, dedicating the use of these things to the good of all and not for selfish gain. In a sense we are junior partners in Creation and should be careful stewards over that part of it entrusted to us.

4.4.2 Issues that are more International

Let us turn now to some important international trends. U.S. actions in the mid-to-late 1970's to restrict reprocessing of nuclear fuel and other aspects of international nuclear trade had two main effects: (a) it made the U.S. appear as an unreliable (and sometimes incompetent) partner; (b) it stimulated European and Japanese efforts to set up their own enrichment and reprocessing facilities, and to become much less dependent on U.S. nuclear-related technology. The Japanese effort is remarkable; it is now virtually independent of the U.S. technologically. In joint ventures with the U.S. to develop A-PWRs and A-BWRs (see topic No. 1 above), Japan has taken the lead.

Several foreign suppliers seem much more capable of providing complete integrated nuclear facilities than do their U.S. counterparts. Consider the Japanese and German companies. Mitsubishi, Hitachi, Toshiba and Kraftwerkeunion (KWU) have broad experience in building whole plants, in collaborating directly with electric utility and other customers, and providing sophisticated architect/engineering services. They have contacts and contracts worldwide. On the other hand, the U.S. vendors have little equivalent expertise, while the Canadians have demonstrated competence in this area but lack the international connections. Table 4.4.2 (from Lönnroth) shows dramatically the shift in supplying heavy electri power equipment. The Japanese electrotechnical industry has expanded rapidly in the heavy electrical export market, and is by now the single most important exporter. The prospect of the Japanese industry entering the nuclear export market is thus not taken lightly by the competitors.

Where are we left, when all this is said? Nuclear power is the only long-term non-fossil option that utilizes modern technology and that has reached a stage of mid-maturity and substantial impact on the world's energy supply. Its technical troubles appear resolvable, even including those related to nuclear wastes. Its connection with nuclear weapons will remain, to the degree that governments want it to remain so. Training for a nuclear age is insufficient, as it is for wide adoption of any of the other renewable technologies discussed here. The differences in present and future needs, and present and future competence around the world are large. We think that some countries will see nonnuclear options as too insecure, too expensive, or too remote in time to trust completely, and hence will preserve a lively nuclear option, especially on the 50-year timescale of interest in this study.

DESTINATION OF NUCLEAR EXPORTS IN THE WESTERN WORLD (from Lönnroth)

Supplier		1960-65	No. of Units	1966-70	No. of Units	1971-75	No. of Units	1976-81	No. of Units
Canada	OECD	-	-	-	-	-	-	-	-
	Non-OECD	-	-	India	1	Argentina	1	Rumania[a]	2
		-	-	Pakistan	1	Korea	1	-	-
France	OECD	-	-	-	-	Belgium	2	-	-
	Non-OECD	-	-	-	-	-	-	South Africa	2
								Korea	2
F.R. Germany	OECD	-	-	Netherlands	1	Austria	1	Spain	1
		-	-	-	-	Spain	1	-	-
		-	-	-	-	Switzerland	1	-	-
	Non-OECD	-	-	-	-	Brazil	1	Argentina	1
		-	-	-	-	Iran[b]	2	Brazil	1
Sweden	OECD	-	-	-	-	Finland[c]	2	-	-
	Non-OECD	-	-	-	-	-	-	-	-
U.S.	OECD	Belgium	1	Belgium	3	Belgium	2	Spain	1
		Germany	1	Italy	1	Japan	3	-	-
		Japan	1	Japan	6	Sweden	2	-	-
		Netherlands	1	Sweden	1	Switzerland[d]	1	-	-
		Spain	2	Switzerland	3	Spain	10	-	-
		Switzerland	1	-	-	Yugoslavia	1	-	-
	Non-OECD	India	2	Korea	1	Brazil	1	Korea	4
		-	-	Taiwan	2	Korea	1	Philippines	1
		-	-	-	-	Mexico	2	-	-
		-	-	-	-	Taiwan	4	-	-
Total	OECD		7		15		26		2
	Non-OECD		2		5		13		13
Total	U.S. Exports		9		17		27		6
	Non-U.S. Exports		0		3		12		9

Notes:
a. It is now doubtful that the Rumanian plant will be completed.
b. Cancelled at an advanced stage of construction.
c. Finland has also imported two units from the U.S.S.R.
d. Kaiseraugst has yet to receive its construction license.

Table 4.4.2

HEAVY ELECTRICAL EXPORT SHARES (PERCENT)

	All Electric Power Equipment[a]				Turbine generator deliveries (hydro and steam), 1975-87[b]
	1955	1964	1972	1978	
France	6.0	9.1	10.3	10.2	8.0
Germany	18.5	22.6	21.9	22.7	17.2
Italy	1.9	4.6	4.9	4.6	3.0
Japan	1.3	3.8	10.2	15.1	24.9
Sweden	2.5	4.7	3.3	2.4	c
Switzerland	n.a.	5.1	4.8	5.9	13.2
U.K.	22.2	13.2	8.9	8.7	13.2
U.S.	31.9	22.8	17.2	14.2	7.9
Other	15.7	14.1	18.5	16.3	12.5

Source: Surrey and Walker, 1981

a. U.N. Commodity Trade Statistics, SITC 722.

b. This refers to turbine generators installed in, and due for delivery to, the export market between 1975 and 1987. It is a more up-do-date, but narrower, indicator than that contained in the most recent U.N. trade data in electric power equipment. The figures have been derived from the Science Policy Research Unit's data bank on the Western World's power plant.

c. Included in 'Other'.

4.5 Controlled Nuclear Fusion

Our basic conclusion is that controlled nuclear fusion will not make an appreciable contribution to global energy in the next half-century. That said, we hasten to add that the fusion research program has not been wasted because (a) the work is very difficult, so that only recently has it been possible to make assessments which are more than hopes or guesses; (b) most of the field of plasma physics and its many applications (gas lasers, plasma treatment of surfaces, ultra-high temperature chemistry, astrophysics) plus substantial nonplasma developments (large superconducting magnets, for example) came about because of fusion research, and are supported by fusion research funds; (c) we may be wrong.

About $2 billion/year is spent globally on fusion, about one-third spent by the U.S., one-third by the U.S.S.R., 15% by Europe, 15% by Japan, and the remainder by China, Canada, Australia, Poland, and more than a dozen other countries.

The reasons for our pessimism have been presented by one of us (Rose) in a paper prepared for the NSF in 1981, and there is no reason to change its major conclusions in this regard:

1. The plasma physics of confinement is still imperfect; disruptions of ostensibly stable plasmas in large tokamaks do occur, and in a real fusion reactor could be very damaging.

2. The problem of a "divertor" or plasma pump is still unresolved, to keep plasma off the vacuum walls, except where it is designed to be drained off.

3. Substantial improvement has been made in superconducting magnet development (for example 10 tesla -- 10^5 gauss -- in meter-size components), but these will require about 1 meter of shielding from energetic neutrons -- a circumstance well recognized but one that complicates the design enormously.

4. Substantial progress has been made in turning what was a pulsed tokamak design into a steady-state torus via radio-frequency drive of dc plasma currents, but the experiments are still small-scale.

5. The neutron damage problems per unit of energy are a factor of about 100 more severe than they are in fission reactor components.

6. Because of induced radioactivity, repair and maintenance will be more difficult than with fission reactors.

7. This complexity suggests that the price will be high.

8. If these problems _are_ resolved, say in the year 2000, fusion may not be wanted, because

   (a) If nuclear fission proves to be socially unacceptable because of proliferation hazards, too-high technology, or high cost, controlled fusion will be similarly susceptible.

   (b) If nuclear fission is acceptable, fusion will have a few advantages: little nuclear waste, easier siting, no accidents with large public hazards (but perhaps with large costs to the operating electric utility company). These possible advantages seem insufficient to displace an accepted fission-based economy.

Elaborations of this theme are given by (_Rose 1982_). Large design studies have been carried out (_FED-INTOR 1982_); an isometric view of the STARFIRE reference design is attached. These are magnificent reference designs, but they are far from being practical power plants.

A more detailed critique of controlled fusion prospects is given by (_Lidsky 1983_). His conclusions are similar to ours.

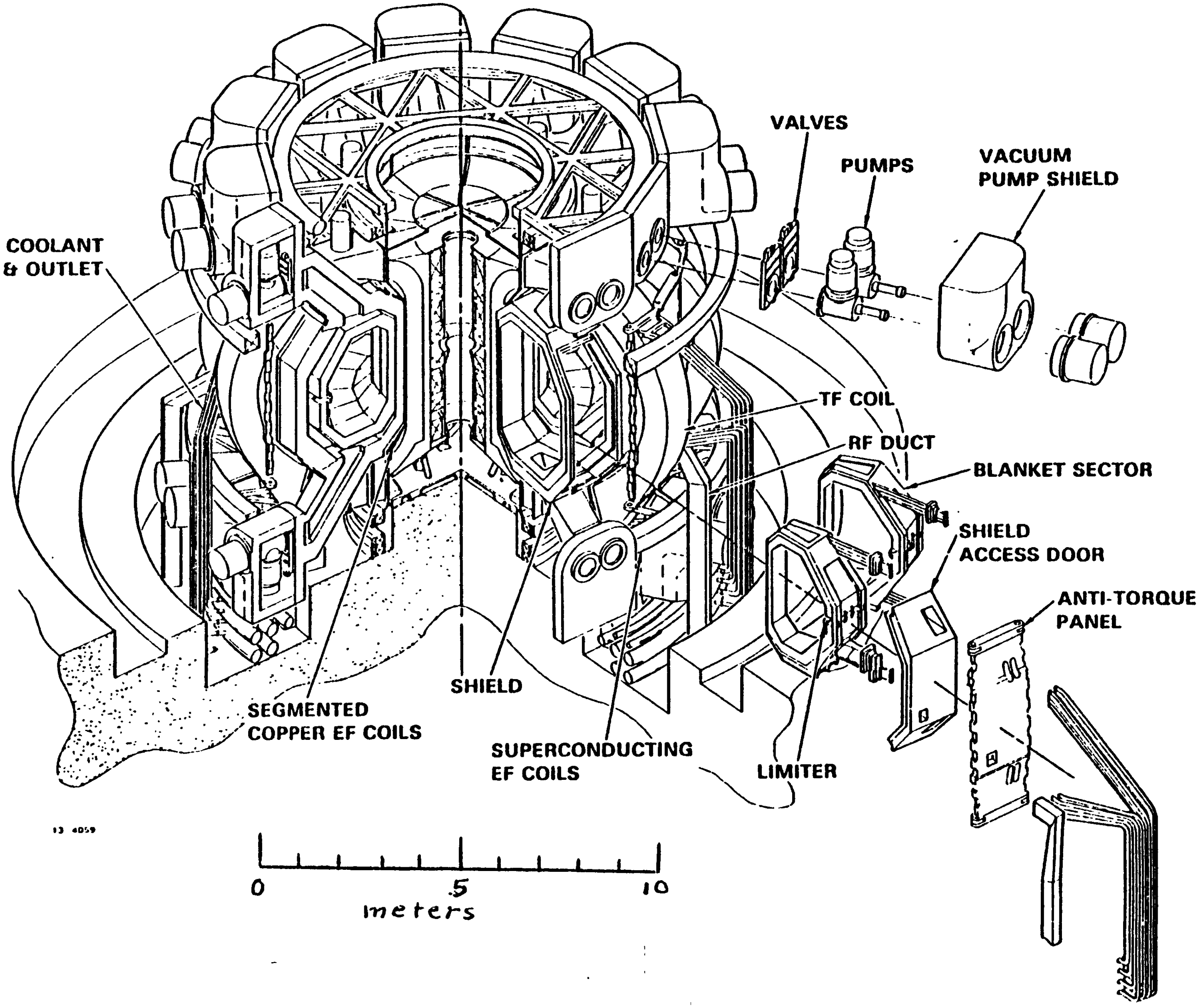


Fig. 4.5.1. STARFIRE reference design - isometric view

4.6 GLOBAL BIOMASS POTENTIAL

4.6.1 Introduction

Biomass is an important energy source throughout the world. Vegetation, together with the winds and oceans, plays a major role in capturing incoming solar energy, storing it, and providing the ecosystem a principal energy source.

Of the 4×10^{24}j of solar radiation absorbed at the earth's surface per year, plant biomass captures about 4×10^{21}j, or 0.1% of this, and about half of that is estimated to appear in plant material of the kind that people might use to greater or less extent as an energy source (Sørensen 1979). This stored energy, were it all to be available, would be roughly equivalent to 320 billion barrels of oil per year, about seven times mankind's total rate of energy use. But the practical upper limits on energy from biomass are much lower.

In the United States, biomass currently provides nearly 2% of annual energy, mostly in the form of wood wastes used by the paper and pulp industry. The Office of Technology Assessment has estimated (OTA 1980) that the share could be increased to about 5% in the year 2000; but in a more recent report, the same OTA points out (OTA 1983) that: (1) the value of wood for construction and as new material for paper and other products far surpasses the value of wood as fuel; (2) extended research and development on using wood and wood waste would make it even more valuable; (3) the long-term environmental impacts of intensive silviculture and other business production can be severe and are not well understood. Thus the conditions that could lead to substantially increased use of biomass in the United States for energy seem unlikely to be realized.

The comparison is sometimes made between energy from biomass in the United States and energy from nuclear-generated electricity, to the effect that they are about the same magnitude (hence that nuclear is and should remain negligibly small or, conversely, that biomass can satisfy the energy demand). Such a comparison is misleading; the biomass estimates are for total heat and, as we see, are unlikely to increase substantially, whereas the nuclear numbers are for net electricity and could be expandable.

Historically in the United States, biomass was even more significant. In 1850, more than 90% of the 1.7EJ gross energy consumption came from wood (Pimentel et al. 1982). As happened in the United States a century ago, a shift to fossil fuels has occurred or is occurring, worldwide today. Even so, it is estimated that over half of mankind still depends on biomass energy, particularly wood, for a significant fraction of total energy use (BNL 1977). Population pressures and competing land-use demands stress forests and agricultural land worldwide. For hundreds of millions of poor people relying on decreasing wood supply, substituting expensive fossil fuels remains beyond their means. As governments around the world try to ease rural energy problems and reduce dependency on imported oil, ambitious tree farm projects and fuel alcohol programs begin, e.g., in Brazil. These have desirable aspects but associated environmental harm and net energy potential should be carefully assessed when planning such projects (Goldemberg 1982).

In this paper, these problems are reviewed and calculations of the global biomass energy potential are presented.

4.6.2 Biomass Resources and Productivities

Biomass energy can contribute importantly to many nations' energy supply although it is limited by the biological productivity of the plants themselves. It has been suggested that most of the United States energy could be obtained from plants on only 10% of the land area; certainly, if 100 million hectares are planted with a crop yielding at least 25 dry T ha^{-1} yr^{-1}, then about 35 EJ gross per year would be supplied. However, it is the purpose of this section to indicate that the sustainable biomass yields that are relevant for energy planning are much lower.

The bulk of biomass energy potential is from forests and crops rather than from, say, manure or algal ponds (see Figure 4.6.1). Hence, forest and crop productivities deserve attention.

The photosynthetic reaction by which plants grow and solar energy is converted to chemical energy:

$$6CO_2 + 6H_2O \text{ ----- } C_6H_{12}O_6 + 6O_2$$

requires 8 quanta of 400-700nm light to reduce each CO_2 molecule to carbohydrate. The energy retained by the carbohydrate, about 480 kJ per mole of carbohydrate, is approximately 28% of the light energy required for photosynthesis. Since this photosynthetically active radiation (PAR) represents 43% of the total solar energy at the earth's surface, the efficiency of the energy retained relative to the radiation reaching the ground would be about 12%--and this would be for perfectly absorbing plants. Accounting for the radiation not absorbed brings the maximum theoretical efficiency to about 10%. Measured peak values are 1% - 3%. Contrast this with actual efficiencies of solar photovoltaics of about 10% and theoretical efficiencies of 26%.

The next question to ask is how much of the photosynthetically acquired energy becomes stored as a harvestable biomass yield. The plants' own respiration reduces the gross primary productivity (GPP, total newly photosynthesized matter) by 20% to 80%. This amount is the net primary productivity (NPP) and is reported in recent global biomass productivity surveys (FAO 1982a, b). Highly stressed plants in deserts may have NPP close to zero, while algae may produce 60 T ha^{-1} yr^{-1}.

However informative NPP may be, it does not account for biomass consumption by the ecosystem itself. The net ecosystem productivity (NEP), accounting for termites (Zimmerman 1982) etc., indicates more realistically the harvestable biomass yield. A mature tropical rain forest will have a negligible NEP, while a sprouting man-made ecosystem such as a young pine plantation may yield one-quarter of the GPP.

Maximum reported growth rates of 100 dry T ha^{-1} yr^{-1} for a Puerto Rican sugar cane and 25 T ha^{-1} yr^{-1} for Euphorbia lathyris (Calvin 1982) correspond to peak seasonal efficiencies of 1.5% to 3% of received radiation (OTA, Smil 1983), which is equivalent to the record yields of corn (OTA). The average yields are much lower, reflecting varied climate and soil conditions and management practices.

Using a large-scale average productivity value, maximum biomass resource limits can be calculated that compare well with more detailed assessments. Since a detailed assessment of the global biomass resource has not yet been done, such a calculated resource limit must suffice. V. Smil's (1983) calculation of the United States' maximum harvestable biomass for fuel is about 15 EJ/Yr, similar to detailed studies by OTA and ERAB that determined a potential of about 10 EJ/yr around the year 2000. Essentially, this represents a yield of 1-1.5 EJ per 100 million hectares of land in the U.S.A.

Studies of Canada's forest biomass potential yield similar results. A supply potential of 120 million dry tons per year about the year 2000, three-fourths of which would be available at 1980 at $2.6 per GJ, could be obtained from 220 million hectares of productive forest land. (Canadian Forestry Service 1981, 1982a,b.) This represents a large area, but 30% of this land is yet to be opened up to commercial forestry. Much of the tropical forest is similarly inaccessible; assuming similar productivities, similar limits of one EJ per hundred million hectares can be expected. Depending on the forest region, Canadian forests have mean annual increments (round wood growth) of 0.3 to 7 m^3 ha^{-1} yr^{-1}, depending on the region. Yields are 1 to 2 m^3 ha^{-1} yr^{-1} in tropical Africa and 2 to 4 m^3 ha^{-1} yr^{-1} in the Asia Pacific region (Sommer 1976).

Before concluding this estimate of global biomass supply, potential agricultural productivities should be briefly addressed. The net primary productivity of cultivated land is about 6.5 T ha^{-1}, lower than that of forest and shrub land, 14 T ha^{-1} (Lieth and Whittakker in FAO 1980). This compares with corn, rice, and wheat yields for the total plant of 7.4, 5.4 and 4.8 T ha^{-1} respectively (Smil 1983); however sugar cane yields much more, averaging 15 to 27 T ha^{-1}. Since forest productivities are generally higher than agricultural ones, it seems reasonable to assess global biomass resource limits in terms of the 1 EJ per hundred million hectares (1 EJ/10^6 km^2) determined above. Table 4.6.1 indicates the planet's land area and limits on potential biomass supply.

Perhaps the world could obtain 130 EJ yr^{-1} (4.6 TW) from well-developed biomass energy supply projects. However, only local assessments will indicate whether this potential will be achievable. Further subsections of this report will indicate some of the competing demands for biomass, the environmental concerns associated with biomass harvest, and related constraints.

4.6.3 Forests

Further support for the forest as the principal source of biomass energy is evident from the UN FAO estimates of agricultural expansion to the year 2000 in Table 4.6.2.

If all of this new land is intensively managed for biomass energy, only a few exajoules would be generated. However, even this is unlikely, given the serious global food problem. So we turn our focus to forestry. What are some of the trends in deforestation and replanting and demands for other materials from the forests?

In 1975, the world consumption of wood and wood products was roughly 25 EJ equivalent (i.e., 2.5 billion m^3). Fuelwood accounted for less than 40% of this. In the 13-year period from 1961 to 1974, world trade in all forest products grew 17% yearly, "far exceeding the growth of total world trade in all commodities, including manufacturers" (FAO 1976). Due to the commercial importance of wood as fiber, tree farms and fuelwood will remain of secondary importance when timber markets are strong. However, the increased demands for timber and fiber will open new previously inaccessible forests and thereby increase access to marginal wood and residues for fuelwood needs. Alone, the commercial value of fuelwood does not warrant the heavy investment in roadbuilding needed to develop a sustainable and well-managed forest project (Hewett 1981).

Moreover, the demands for firewood place severe stress on forests, particularly their perimeters. As the edges of the forests are nibbled away, families spend more and more of their time collecting firewood from greater distances. In the Himalayan foothills of India, firewood collection has grown from a task requiring one hour to one needing a day (Fritz 1981). As this happens, the denuded areas suffer more severe weathering and erosion problems, which may, as in the Sahel, increase desertification.

The extent of the fuelwood shortage is so chronic it is almost beyond the label "crisis." Hundreds of millions of people are affected (see Table 4.6.3) who overcut the woodlands as they attempt to meet their needs and thereby diminish their resources--a certain tragedy of the commons.

4.6.4 Deforestation and Plantation

Concern about deforestation of the tropical forest has received much international public attention. Shifting agriculture poses the greatest concern since more land is cleared than ever restored by plantations or reforestations. The clearing operation can be more serious than logging, which latter can select saw logs and veneer logs, allowing forest cover to remain. Figure 4.6.2 depicts data from the most recent FAO survey of tropical forest resources. For every 10 hectares of forest cleared, only about 1 hectare of plantation will be created. This 10% replacement rate is a global average for the tropical forest and masks the great variation from one region to another. For example, in tropical Asia, the replacement rate is about 25%, but in Africa it is less than 3%. Moreover, often reforestation is distant from the clearing areas. For example, in Brazil tree clearing occurs in the north, but the plantations are in the south. It is a good sign that plantations are being encouraged in many nations. Notably, 40% of the total tropical forest plantations were planted in the 5 years from 1976-1980 (FAO 1982b).

Yet even with ambitious plantation plans, large national programs may not effectively relieve anticipated deficits. India's plantation program of 650,000 ha/yr could result after 20 years in a yield of 30 million m^3 woodfuel/yr, which could provide about 0.5 EJ/yr. Much of this plantation effort is planned for industrial wood. As the share of industrial wood consumption relative to total consumption increases (see Table 4.6.4 and note the reversed consumption situations in developed and developing economies), the fuelwood supply will be further stressed.

As petroleum resources diminish, coal and biomass will be turned to for hydrocarbon feedstocks. Catalytic dehydration of ethanol to ethylene, microbial transformation of lignin and cellulose, and plant breeding techniques to develop plants which will produce specific hydrocarbons are among a number of industrial processes receiving attention for their potential to use biomass feedstocks (Bungay 1981, Calvin 1982, Hydrocarbon Processing 1981). Biomass as a materials supply will introduce further land use competition together with agricultural, forestry, and energy demands. The issue of using land for food or fuel has been well discussed recently (Brown 1980, FAO 1980, Pimentel et al. 1982). A good initial indicator of whether energy crops might hinder food supply is shown in Figure 4.6.3. Where nations experience deficits in both energy and agriculture, using land for extensive energy projects may aggravate present difficulties.

China serves as a good example where biomass energy will be inadequate. Pressures on fuelwood supply are dramatically evident in China. The forest area per capita in China is 0.12 ha per person, much lower than that of Europe (0.3 ha/person) or North America (2.8 ha/person) (FAO 1978, FAO 1982c). The actual forest land area, 122 million ha, covers about 13% of China and 80% of the forests' production provides timber. Less than 4% of the forest land supplies fuelwood; other small wood lots supply roughly an equal amount of fuelwood (FAO 1982c).

Although China has ambitious plans to increase plantations, their planned production 10 years from now will not be sufficient to meet their current or future demand. Current fuelwood demand is estimated at 400 million T (about 4 EJ equivalent), but the supply is less than one-third of this. Twice the current total forest area could be planted and devoted solely to fuelwood, and China still would experience shortage. In conditions of such scarcity, it is not surprising to hear reports of overcutting. In many places, tree plantations are damaged so trees will die early and can be culled for fuel. Moreover, the reported 70 million m^3 of fuelwood which is obtained from 4% of China's forests indicates a harvesting rate of 13 m^3/ha yr, clearly exceeding an average sustainable yield.

4.6.5 Environmental Constraints

Although biomass resources can be renewable and have a lower sulfur content than oil or coal, biomass energy conversion and use have associated environmental and public health problems. Detailed descriptions of these concerns are given in (Pimentel et al. 1982) and (Pimentel et al. February 1983). Of particular concern is the soil erosion and water run-off problems associated with removing forest and crop residues. The economic externalities of such removal can be sufficiently high to negate any benefits of the energy harvest. Calculations presented in Table 4.6.5 based on World Bank watershed rehabilitation projects indicate that the economic cost of watershed damage can be from about \$2/GH to \$$8^+$/GJ of energy obtained from forest cutting.

4.6.6 Conclusions

Biomass energy potential is estimated to be 1 EJ per hundred million hectares, or perhaps 4.6 TW for the world as a whole. We consider this to be a high estimate, although some researchers who count on the widespread use of very high yielding plants may consider it low. Biomass energy potential must be viewed together with competing land use demands for wood, chemicals, and food, and associated environmental problems should be clearly understood before regions embark on large biomass energy programs.

Table 4.6.1

Land Areas

	Million km^2	Biomass Energy Potential (EJ) (gross energy per year)
Africa	30.6	31
Asia		42
USSR	22.4	
China	11.4	
the rest	9.6	
Near East	5.9	6
Europe (east and west, excluding USSR)	10.5	10
N. America		19
Canada	10	
USA	9.4	
Central and S. America	19.9	20
Oceania	8.5	8
Total	138.2	137
(Antarctica and Greenland)	15.4	

Summary and Comparisons:

140 EJ/yr is roughly equivalent to 4.6 TW

Comparing this with predicted energy consumption levels:

40% of a year 2030 Lovins scenario
15% of a year 2030 IIASA high scenario
10% of a year 2030 Hudson Institute scenario

Table 4.6.2

AGRICULTURAL EXPANSION

World's land area:	147 million km^2
World's potentially arable land:	30-40 million km^2
Mid-1970 agricultural land:	15 million km^2
Expansion by A.D. 2000:	2.4 million km^2

Source: FAO 1980

Table 4.6.3

The Fuelwood shortage
(millions of people affected)

Region	1980				2000	
	Acute scarcity		Deficit		Acute scarcity or deficit	
	Total population	Rural population	Total population	Rural population	Total population	Rural population
Africa	55	49	146	131	535	464
Asia and Pacific	31	29	832	710	1671	1434
Latin America	26	18	201	143	512	342
Total	112	96	1179	984	2718	2240

Definitions of categories:

- acute scarcity: sufficient fuelwood cannot be obtained even by overcutting; consumption is below minimum needs;
- deficit: minimum fuel needs are met, but only by overcutting existing resources.

Source: FAO 1982b.

Table 4.6.4

Use of World Forest Resources

Region	Forest area 1975 million ha		Removal 1974-1976 Annual average in million m^3		
	Closed forest	Open forest	Total	Fuelwood	Industrial wood (including that for pulp and paper)
World	2,860	1,070	2,799	1,473	1,326
Developed market economies	693	243	761	57	704
Centrally planned economies	945	185	733	304	429

N.B. Clearly fuelwood supplies would be further stressed as the share of industrial wood supplies in less industrialized countries increase unless industrial wood is obtained from plantations not competing with fuelwood.

Source: FAO 1982a.

Table 4.6.5

Cost of watershed damage due to improperly managed forest removal

Cost of rehabilitation of watershed: \$500/ha - \$1000/ha (1982 \$)
(Data from World Bank projects, ref. John Spears, 1982)

Level of forest removal leading to watershed problems:
13 - 31 m^3 ha^{-1} yr^{-1}
(120 - 290 GJ eq ha^{-1} yr^{-1}
(Data from FAO 1982b).

Energy content of wood: 9.4 GJ/m^3

Economic cost of Watershed Damage (1982 \$/GJ)		
Annual Rehabilitation Cost	Forest Cutting	
	Low yield 13 m^3 ha^{-1} yr^{-1}	High yield 31m^3 ha^{-1} yr^{-1}
\$500/ha	\$4.1/GJ	\$1.7/GJ
\$1000/ha	\$8.2/GJ	\$3.4/GJ

This table indicates a range of costs, noteworthy because they indicate the environmental costs can be large. Proper management practices in advance could prevent the need for corrective rehabilitation. Rehabilitation costs may even be higher than \$2 - 8/GJ depending on terrain, soil type, climate, and the need for dams, etc. to prevent flood damage.

Figure 4.6.1

Estimates of biomass sources available per year
in the USA about the year 2000. (ERAB)

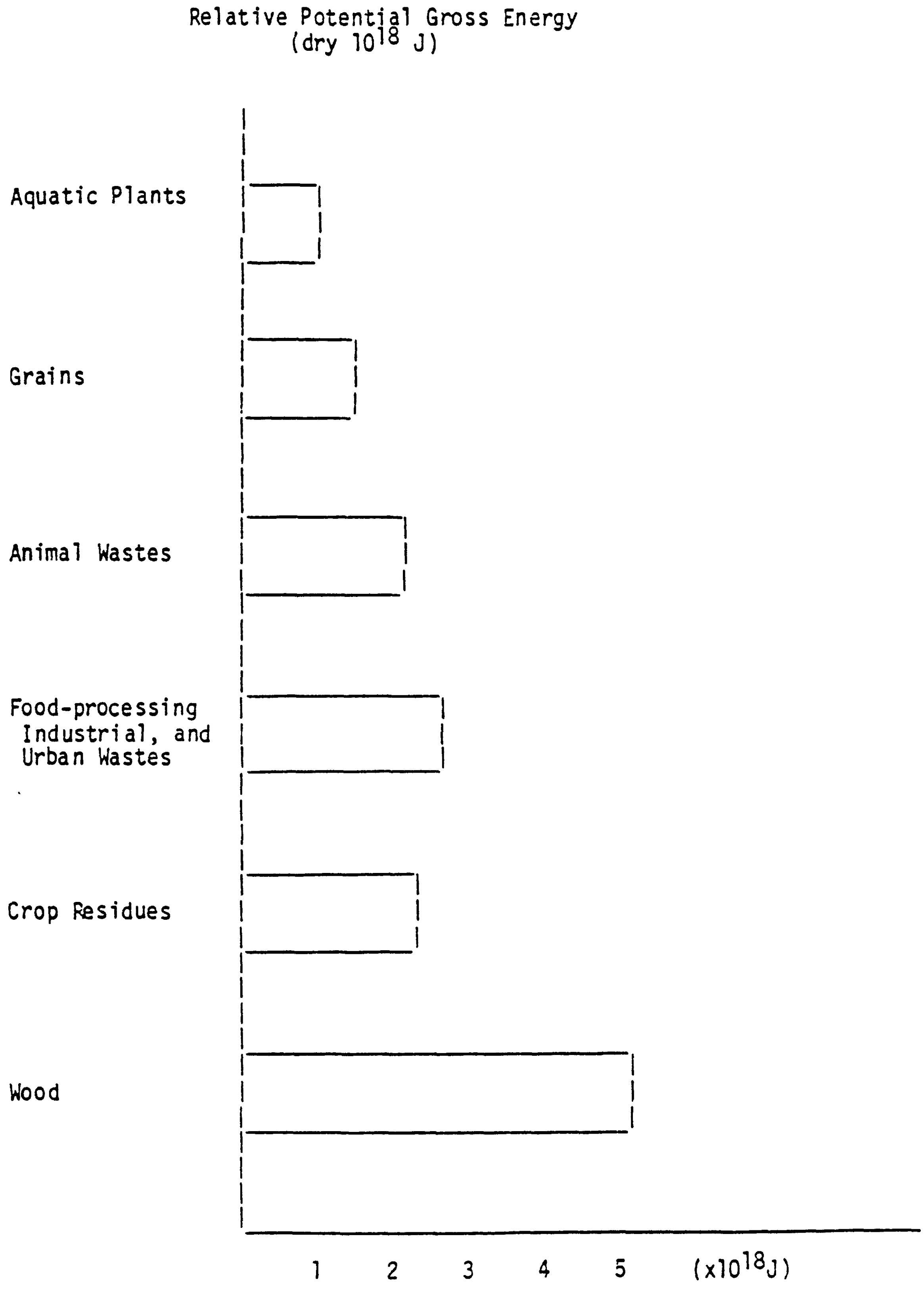
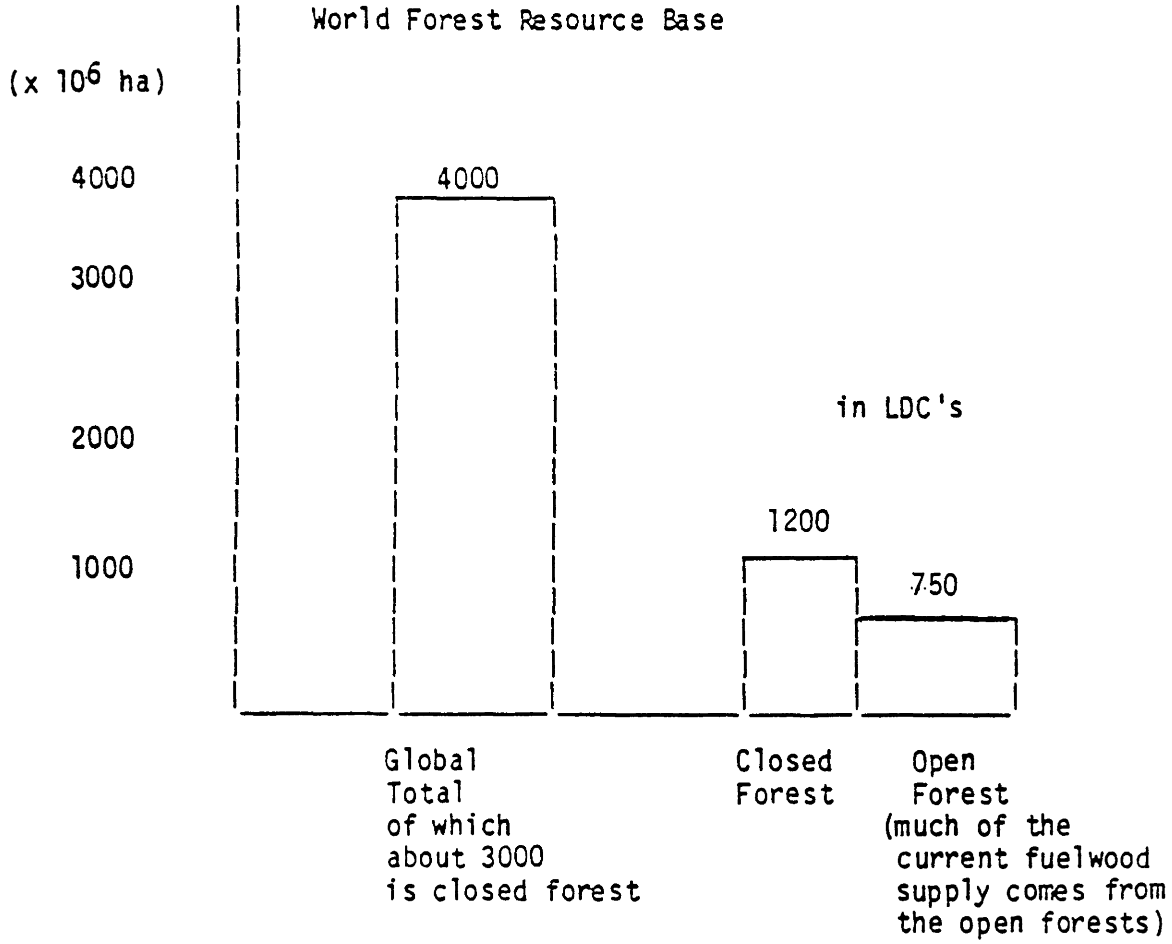
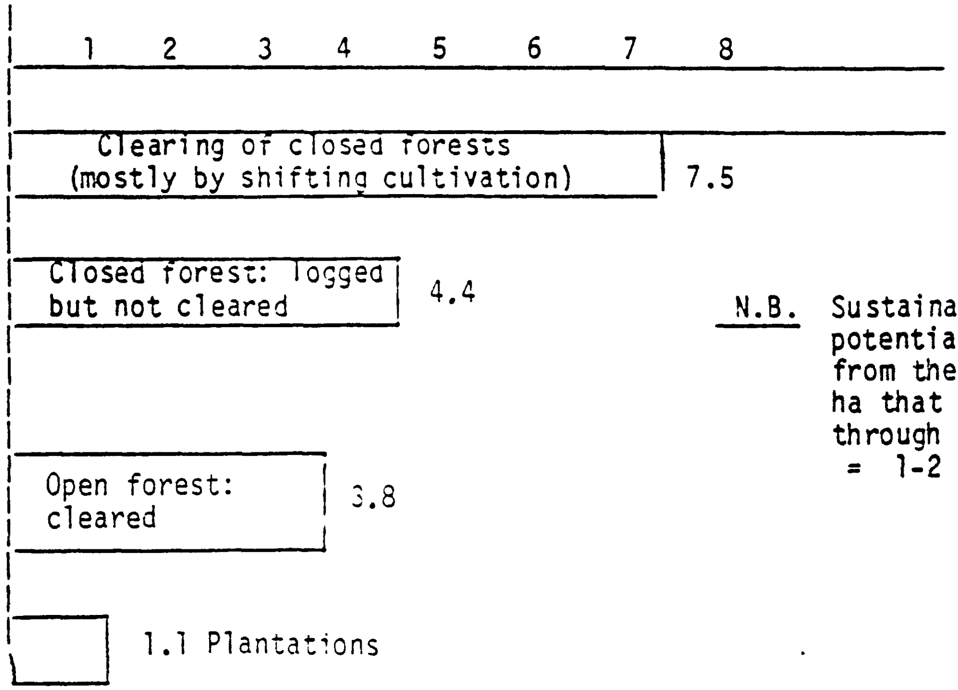


Figure 4.6.2

Tropical Forest Use



Estimates of tropical forest areas disturbed annually (x 10^6 hectares)



N.B. Sustainable energy potential foregone from the 150 million ha that will be cleared through the year 2000 = 1-2 EJ/yr.

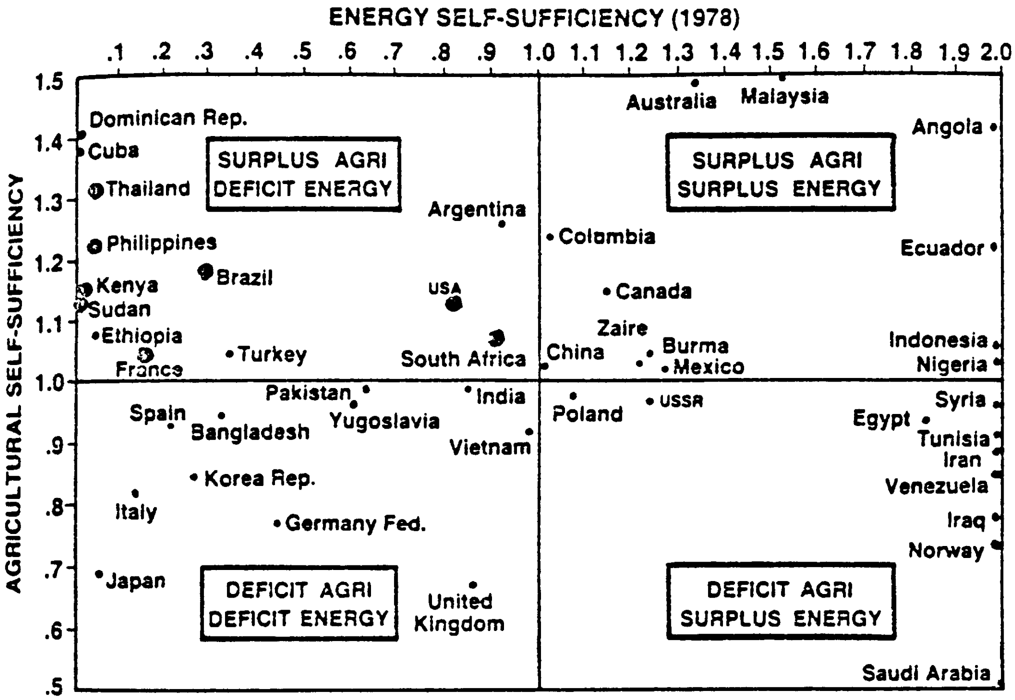


Figure 4.6.3. Energy and Agricultural Self-Sufficiency Matrix for Selected Countries. Large dots indicate countries already engaged in or seriously considering programs for converting food commodities to alcohol. Source: FAO 1980.

4.7 Reducing Energy Consumption by Rational and Effective Use

One of our principal conclusions is that rational and effective use of energy not only can but also most likely will reduce the global demand of energy well below the levels postulated by (say) the IIASA scenarios. This section provides our support for this view.

Speaking of "rational and effective use" in preference to "conservation" is more than mere semantic detail; to many financially constrained groups, "conservation" sometimes sounds like curtailment imposed by the rich upon the poor, whereas the more correct phase makes clear that the activity is applicable to rich and poor societies alike. Extracting the maximum utility from each unit of available energy is a task of global importance.

4.7.1 The Relation between Energy Use and GDP (or GNP)

Energy projections for developing countries generally show the ratio Energy/GDP rising during early stages, then passing through a broad maximum before declining, as sophisticated, highly technological service enterprises replace more energy-intensive production-oriented ones. For example, the IIASA scenarios (Häfele 1981) and a 16 TW low-energy case proposed by Colombo and Bernardini are characterized by the following primary energy-GDP coefficients ε,* for Latin America (LA), Africa/Southeast Asia (AF/SEA), and Western Europe/Japan/Australia/New Zealand (WE/JANZ).

Some Energy-GDP Elasticities

	High Scenario (36.7 TW)		Low Scenario (22.4 TW)		16 TW Case	
	1975-2000	2000-2030	1975-2000	2000-2030	1975-2000	2000-2030
LA	1.04	.98	1.06	.97	.96	.82
AF/SEA	1.15	1.11	1.18	1.19	1.38	.90
WE/JANZ	.70	.77	.65	.73	.04	.10

---

*The elasticity coefficient ε is defined as

$$\frac{E(t_2)}{E(t_1)} = \left[\frac{GDP(t_2)}{GDP(t_1)}\right]^{\varepsilon}$$

where t_1 and t_2 are two given times, E is measured in physical units and GDP is measured in real non-inflated monetary units.

Elasticities $\varepsilon > 1.0$ imply that energe use is rising faster than GDP; the 16 TW case assumes such sharply rising energy prices that energy use is severely constrained everywhere, and that developed countries experience decreased per capita energy consumption due mainly to higher efficiencies of end-use.

The energy being discussed in these cases is energy that reaches the commercial sector; in fact, the ratio E/GDP may not be rising at all, when noncommercial energy, which is largest at early development stages, is included. Thus the rising-falling curve may give the wrong impression, that energy-efficiency techniques are more or less irrelevant at early development stages. The case of the U.S. shows these effects very well. Figure 4.7.1 shows the E/GNP in the U.S. from 1880 (when the U.S. was in a sense like some LDC's today) up to 1980. The data before about 1910 are misleading because wood, a major fuel then, was not included in the accounts, just as many traditional fuels like sticks, dung, grass, etc. are inadequately counted today in LDC's. The three single-year points include the effect of fuel wood, according to the authors of the quoted report. Overall, the ratio E/GNP fell or at worst stayed approximately constant, during the entire 100-year span, and it seems reasonble that most presently developing countries will have a similar experience, especially as energy prices are expected to rise more rapidly in real terms than they did decades or a century ago. The present LDC's will become increasingly important energy users in coming decades, so the likelihood of successful fuel efficiency strategies will be important, as in the developed countries.

The CO_2 problem is generally a consequence of high energy use;* there is a high payoff for effective use, so it is worthwhile to study E/GNP and its changes with time, as follows.

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*Strictly speaking, it is a consequence of high <u>fossil fuel</u> use; here we assume that improving energy productivity reduces demand of all supply sectors.

Figure 4.7.2 shows the growth and occasional decline in both constant-dollar GNP and energy use in the U.S., between 1950 and 1978. Some advocates of rapidly increasing energy supply have used this correlation to support the egregious misconception that "energy conservation" is inherently undesirable because it leads to lowered GNP and other miseries. In that view energy drives both society and GNP.

The system does not work so simply. That is fortunate, because Figure 4.7.2, taken literally, predicts that as energy costs rise and its use inevitably declines, the GNP will surely drop. What the figure really shows is that the short-run correlation is strong; for example, the dip in both arising from the late-1973 through 1974 oil price increases.

Now refer back to Figure 4.7.1. We see that E/GNP was indeed approximately constant from 1950 to 1974, but during that time energy prices declined in constant dollars, implying that if real energy prices had remained stable, E/GNP would have declined with time. The period 1920-45 was such a time, and Figure 4.7.1 shows a decline of about 1% per year. The 1979 oil price rises and the gradual maturation of energy conservation technologies (coupled with an economic recession) brought U.S. energy use in 1982 back to its 1972 level -- 72 quads.

Supporting evidence for this trend comes from elsewhere; e.g. in Japan, the GDP per unit of energy increased by about 30% between 1973 and 1980, after correcting for inflation (EWC 1983). Total energy use stayed about the same, but (significantly) the electric fraction grew substantially, just as it had done in the U.S. and almost everywhere else.

These ideas find confirmation in the sophisticated energy modeling studies initiated for the CONAES studies. Figure 4.7.3 from one of those reports shows the results of several modeling attempts to answer the question: if the E/GNP ratio were forced to decline from its 1975 value to a fraction of that value by the year 2010, by what fraction would the GNP decline from the value it would have had if E/GNP had remained constant? This question, awkward to state, asks in effect about the medium and long-term elasticities, and at what rate energy and GNP can be decoupled. The curve shows, for example, that E/GNP can decline to 0.6 of its 1975 value in 35 years while GNP decreases by only 1.3%, a number surely within the uncertainty of the calculations. This reduction corresponds to a decline of about 1.4% per year in the ratio E/GNP.

4.7.2 Recent Progress in the U.S.

The actual improvements in energy efficiency throughout the past decade have been noted throughout the literature. A summary of the situation as of 1980 is given by (Hirst et al. 1981), and it is worth showing a few of their results. Figure 4.7.4 shows residential energy use 1970-1980. The ORNL energy models were used to project the reduction in residential energy intensity due to price increases. Figure 4.7.4 shows both the projection and the actual energy data. A savings of 12% came about in seven years (1.7% per year) because of price increases. It should be emphasized that the stock of residential structures had not changed very much during this period. Regarding the possibility of further improvements, Figure 4.7.5 shows data from another report, describing specific savings achieved in retrofit studies. The cost-benefit ratio indicated in that figure strongly favors more effective use.

In Figure 4.7.6, Hirst et al. show the improvement in automobile fuel economy from 1975 through 1980. Many small cars now (1983) comfortably exceed the 1985 standards.

It might be argued that this is only a temporary phenomenon, due to end when energy costs stabilize, and the cost of efficiency improvements starts to catch up with energy savings. To be sure, the rate of improvement will slow, but: (a) data show that most capital improvements that have been made to increase energy efficiency have paid back their investment in less than 5 years, sometimes as soon as 1 to 2 years; (b) the thermodynamic second law efficiency postulated by availability analysis is still very low even in the U.S. -- perhaps 10% for the automobile industry, for example (Bazerghi 1982); (c) the technology of rational and effective energy use is much less developed than the technology of provision. Much room exists for continued improvement in the U.S., and in other developing countries as well as the LDCs (Dunkerly 1981).

The most authoritative study of the magnitude and origin of changes in energy productivity known to us is Marlay's study of industrial energy productivity in the U.S. (Marlay 1983). By analyzing the actual material output and energy use in 472 mining and manufacturing industries between 1945 and 1980, he has separated the effects of shifts in product mix, technological improvement, and changes in economic growth, especially in the period 1972-1980. Figure 4.7.7 summarizes some of his findings. During the period 1950-1972, the output per unit of fossil energy input increased by about 0.9% per year, even though most fossil energy prices declined in constant dollars. This improvement was partly offset by an increase in electricity use, leaving a small net improvement overall, consistent with the findings stated earlier.

The period 1972-1980 showed a dramatic improvement, a reduction in fossil fuel use per unit of output of 2.3% per year, not compensated by any increased electric intensity. Much of this improvement featured reduced use of natural gas, as a result of restrictions placed on its use, and reduced use of coal, as industry backed out of coal technologies because of environmental and other considerations. Figure 4.7.8 shows Marlay's summary of the 1972-80 situation, a reduction in energy use by industry of some 22% from what had been projected in 1972 from historic trends, and all this in the presence of substantial growth in output.

One must be careful in analyzing data like these. Many were supplied to U.S. Government agencies (for example, the Federal Reserve Board) only sporadically, and sometimes on a voluntary basis by selected industries (a circumstance now being corrected in part). Figure 4.7.9 shows Marlay's comparison of 1972 Federal Reserve Board data compared with Census index data, for 134 industries from which the FRB collected data. It is easily seen that errors of 5 to 10% can be made, and wrong implications drawn, especially when one is looking for changes amounting to something like 1% per year.

All these studies suggest that energy productivity can be improved at the rate of about 1% per year, with moderate stimuli, and with good information available about how to do it. Thus we have included in our MIT/IEA energy scenarios several with such a rate of improvement worldwide.

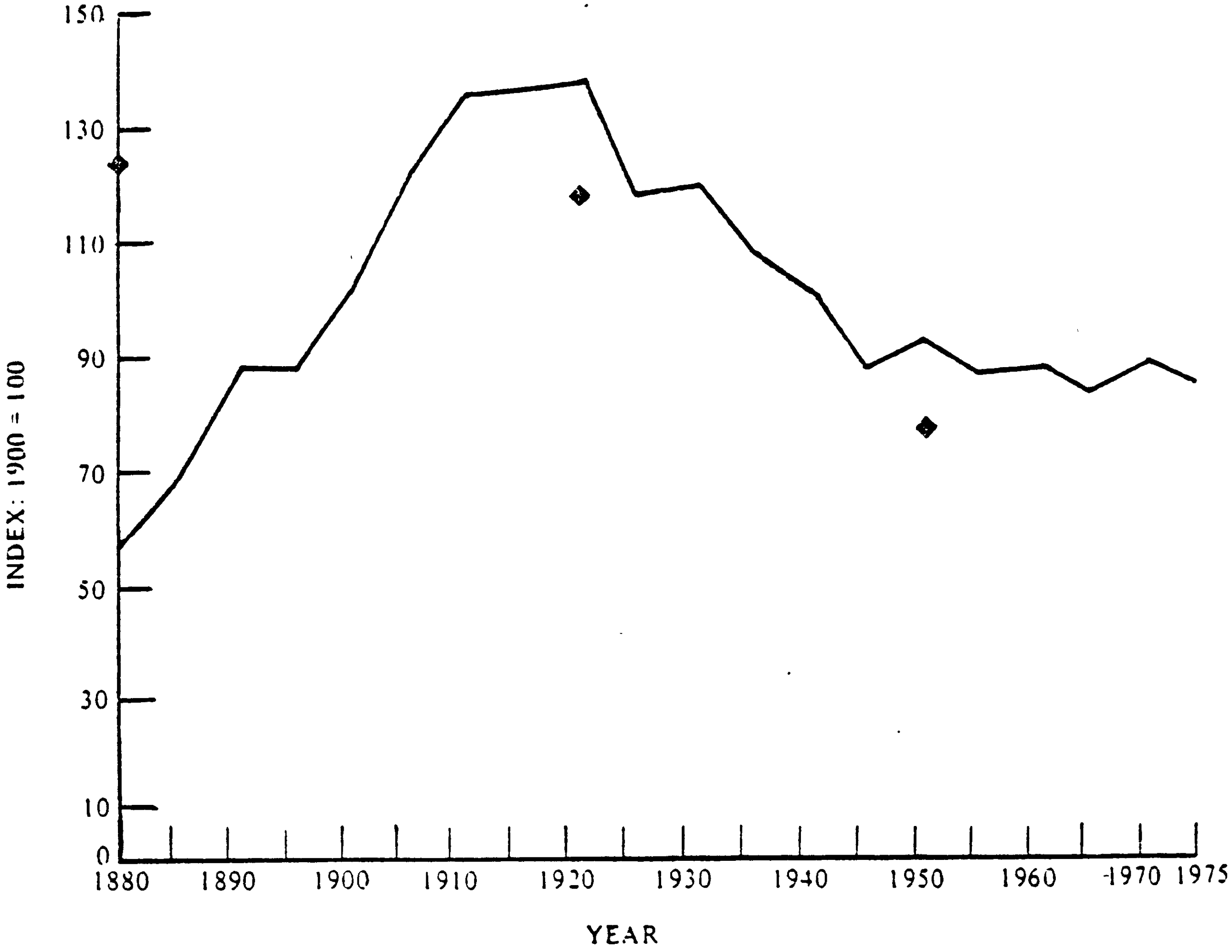

Figure 4.7.1. An index (1900 = 100) of energy consumed per dollar of real gross national product for the United States from 1880 to 1980 shows successive trends of rise, decline, and stability. This plot excludes fuel wood, whose consumption exceeded that of coal into the 1880s. Single-year points that do include fuel wood are indicated for 1880, 1920, and 1950. Source: Adapted from Sam H. Schurr, Joel Darmstadter, Harry Perry, William Ramsay, and Milton Russell, *Energy in America's Future: The Choices Before Us*, Resources for the Future (Baltimore, Md.: Johns Hopkins University Press, 1979). Copyright 1979 by Resources for the Future, Inc.; all rights reserved. Data for 1975–81 from other sources.

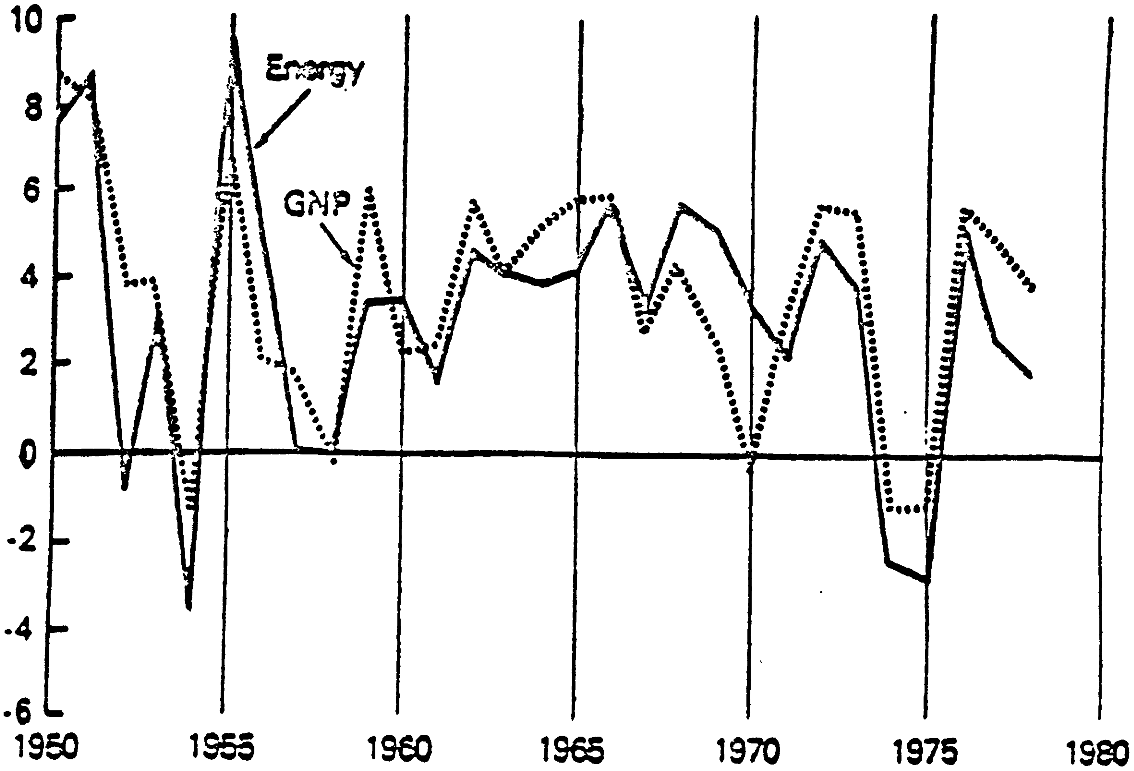

Figure 4.7.2. Annual percentage changes in primary energy and GNP, 1950 - 1978. Data for GNP changes are from the <u>Economic Report of the President</u> (Washington D.C.; Government Printing Office, January 1979). Energy data are from the Bureau of Mines for 1950 - 1974 and from the Department of Energy for 1974 - 1978,

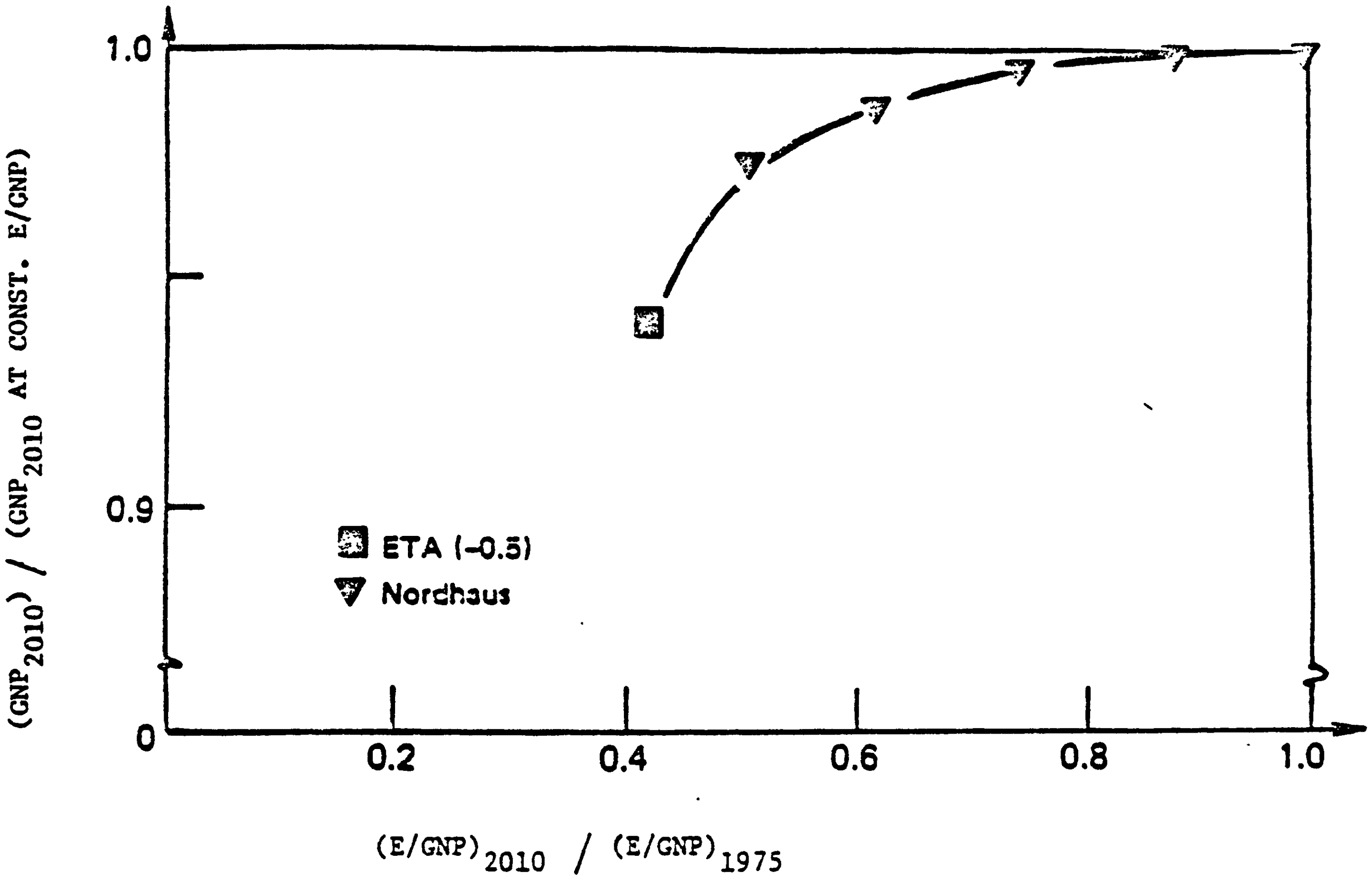

Figure 4.7.3. Estimates of the long-run feedback from energy conservation on undiscounted GNP for the year 2010, with 1975 as base year. See text for discussion. From CONAES supporting Report No. 2 "Energy Modeling for an uncertain Future," National Academy of Sciences - National Research Council, USA 1978, page 109.

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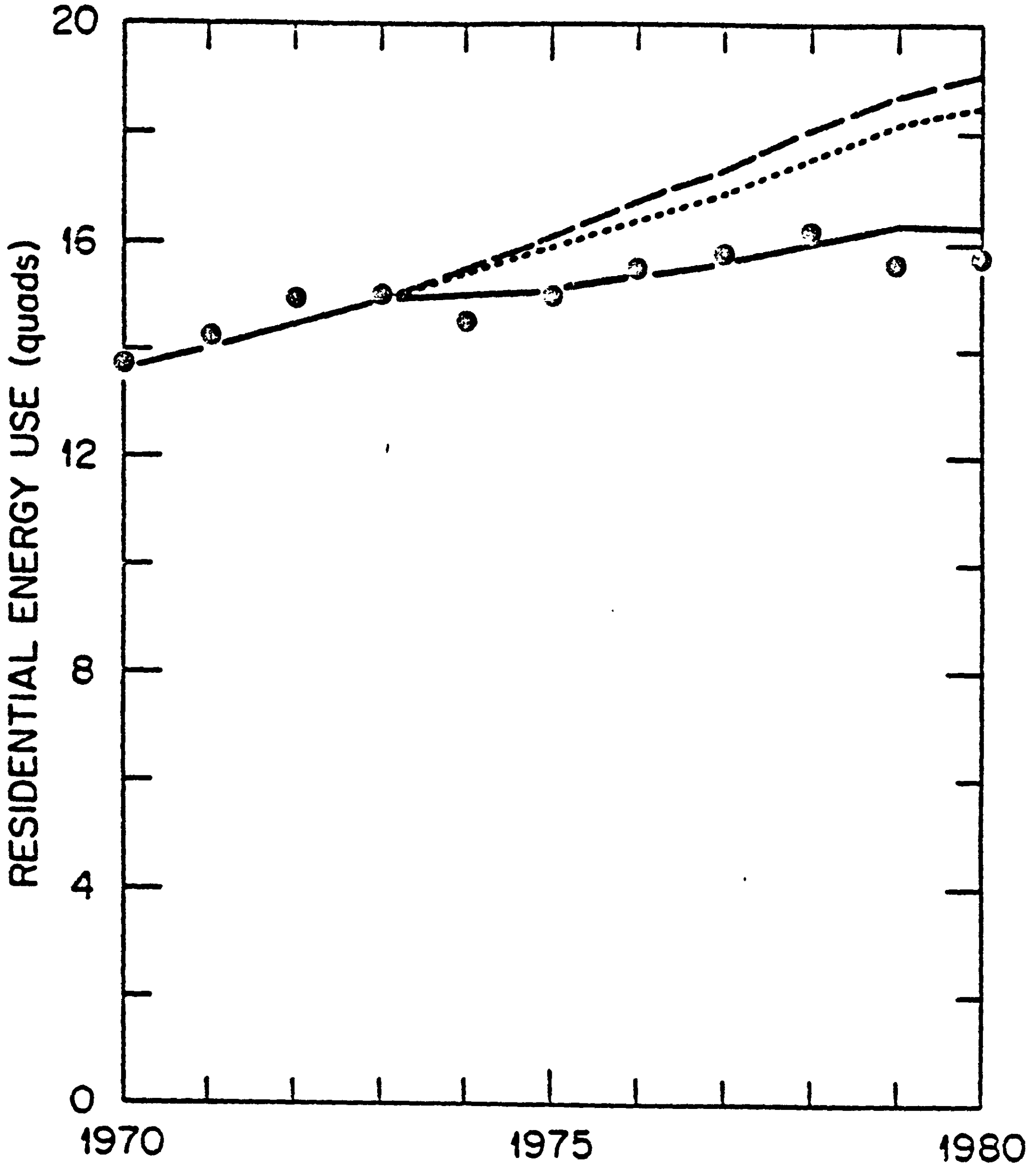


Figure 4.7.4. Residential energy use, 1970-1980. The top projection assumes that GNP grows during the 1973-1980 period at its 1960-1973 rate and that real fuel prices remain constant at their 1972 levels. The middle projection assumes that GNP follows its actual path and that fuel prices are constant. The bottom projection assumes that both GNP and fuel prices follow their actual paths. The dots are actual energy use. Taken from E. Hirst et. al.

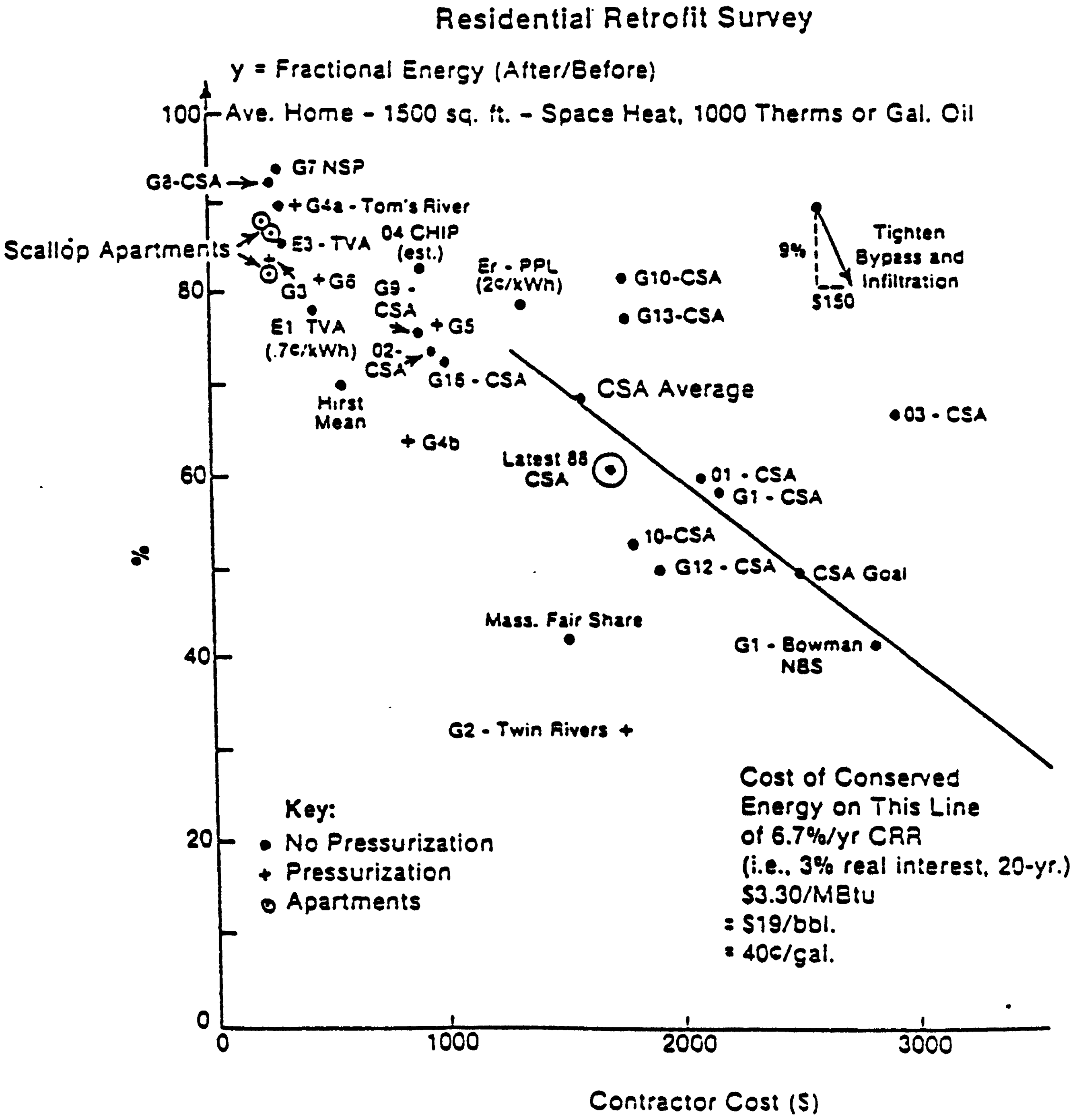


Figure 4.7.5. Results of a survey of retrofitted gas-heated homes in the U.S. From Fig. 2.12 of Report on Building a Sustainable Future, Committee on Energy and Commerce, House of Representatives, U.S. Congress (Committee Print 97-K) April 1981.

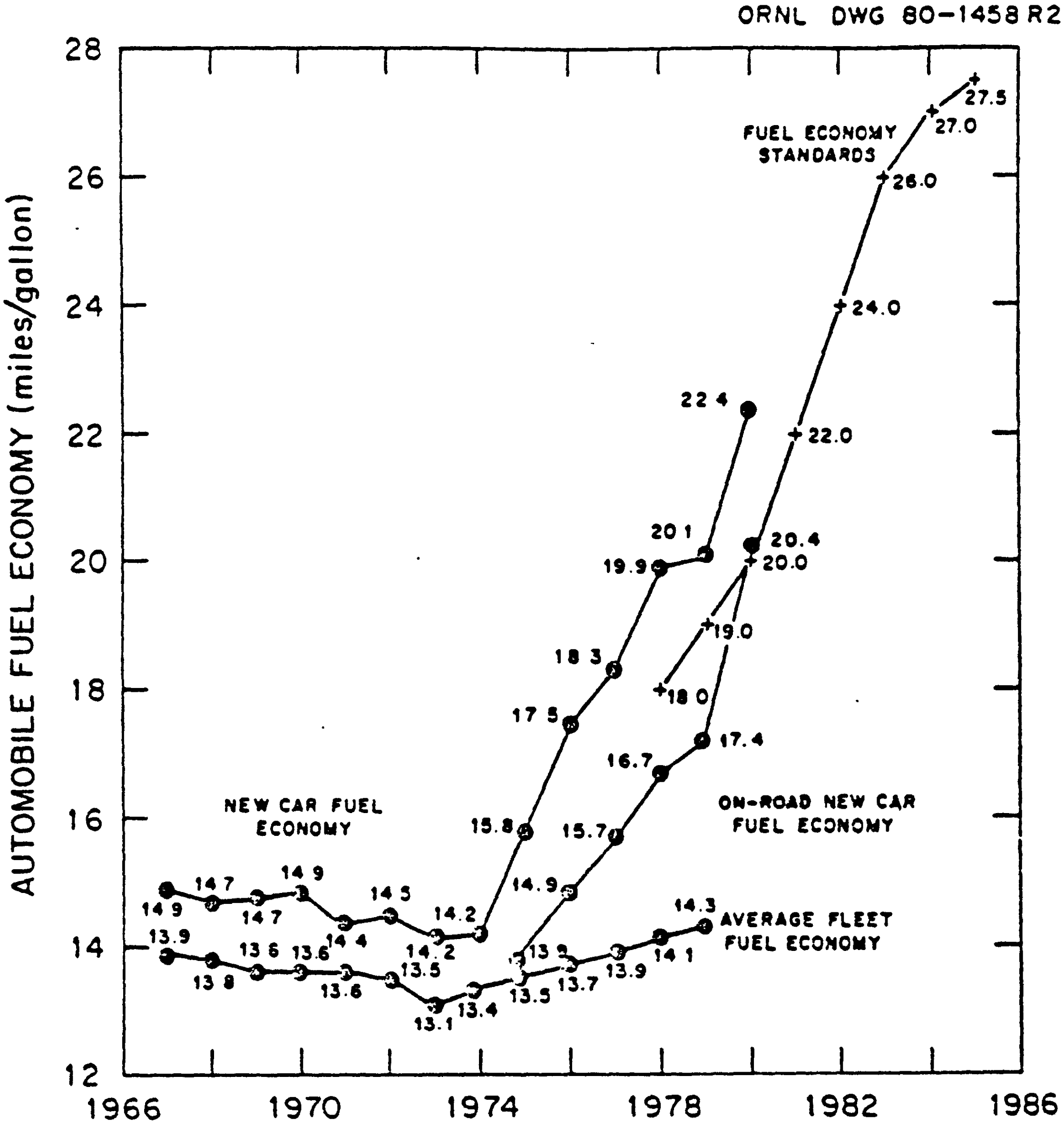


Figure 4.7.6. Automobile fuel economy estimates. The graph shows federal fuel economy standards from 1978 through 1985, new car fuel economy estimates based on the Environmental Protection Agency test procedures for 1967 through 1980, on-road new car fuel economy as estimated by DOE from 1975 through 1980, and fleet fuel economy as estimated by the Federal Highway Administration from 1967 through 1979. Taken from E. Hirst et. al.

Figure 4.7.7. Fossil Fuel Weighted Measure of Output Divided by Fossil Fuel Input, 1951-1980
Mining and Manufacturing

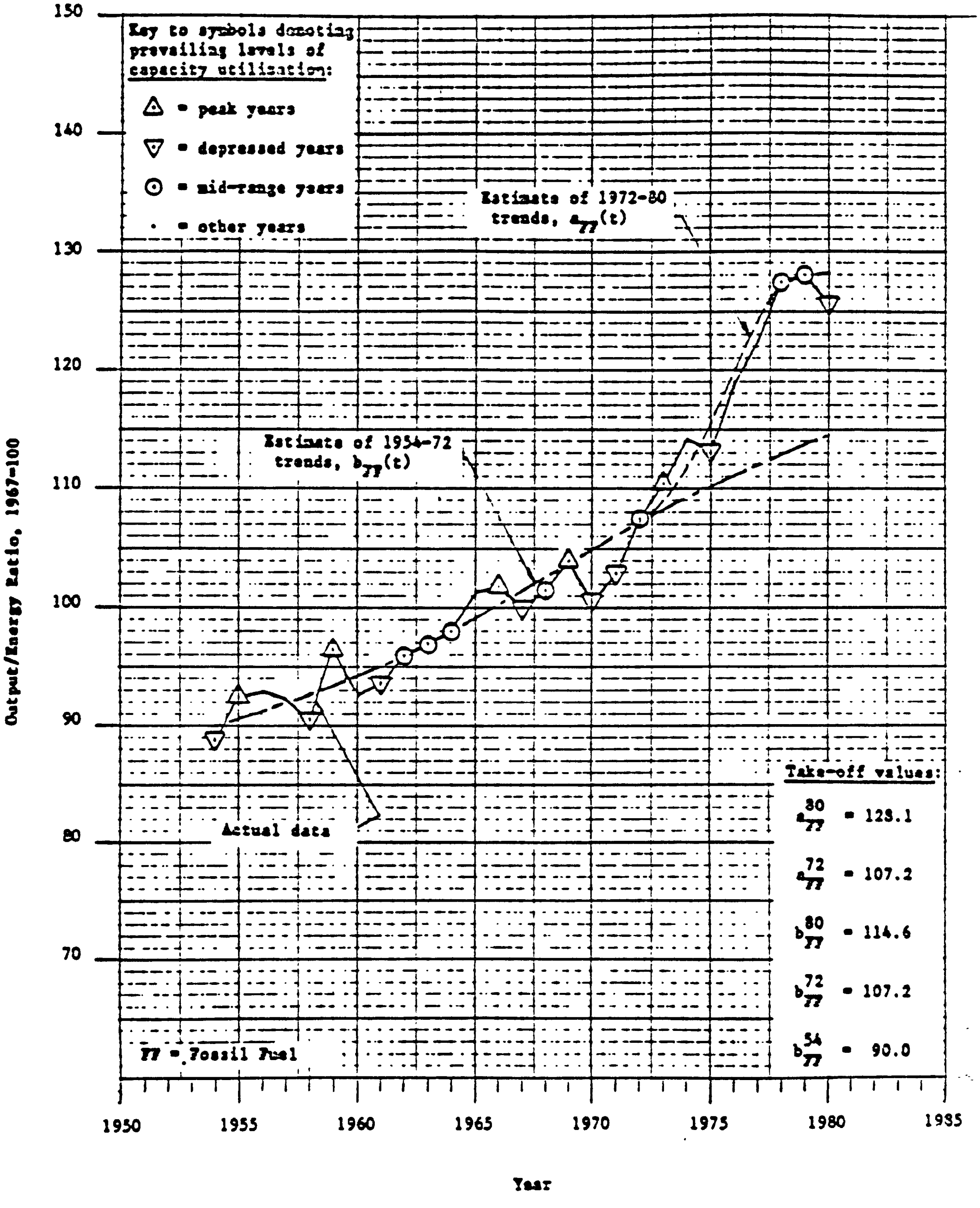


Figure 4.7.8. Changing Trends in Industrial Energy Use, 1972-1980
Mining and Manufacturing

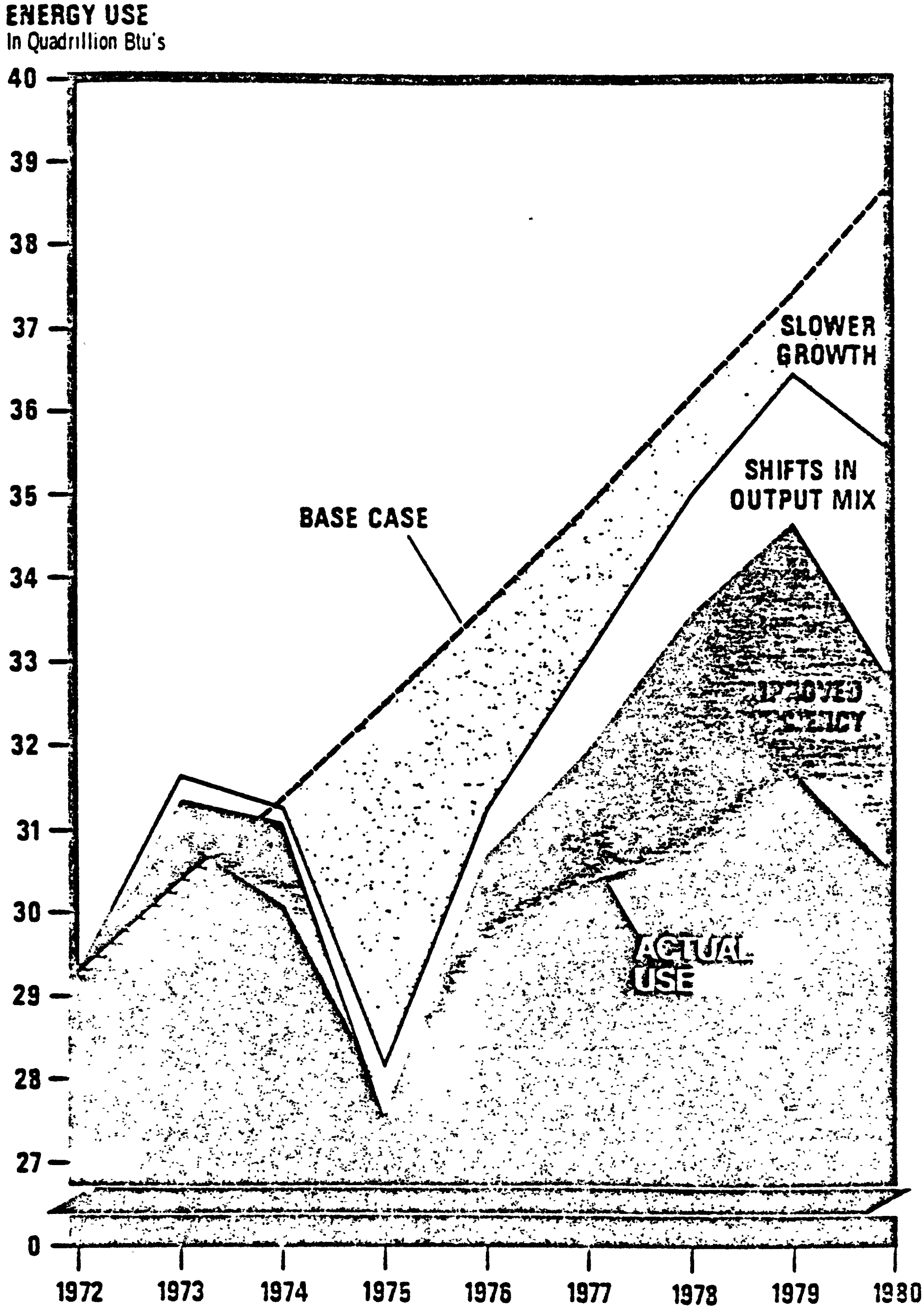
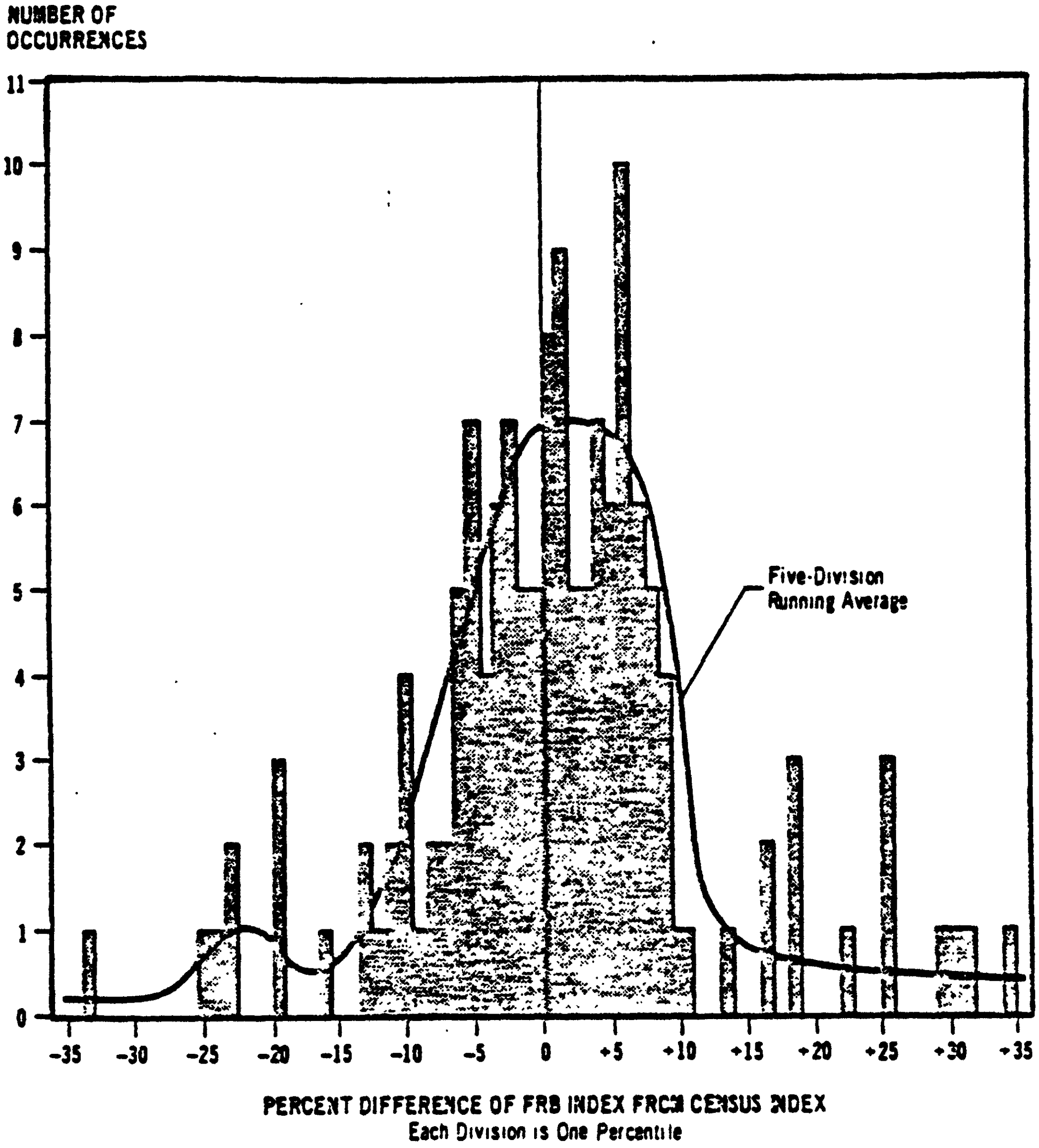


Figure 4.7.9. **Comparison of 1972 FRB and Census Indexes of Industrial Production for Mining and Manufacturing**
For 134 FRB Industries



Histogram shows percent differences between the Federal Reserve Board's Indexes of Industrial Production for 134 mining and manufacturing industries and 134 equivalently constructed Production Indexes from the <u>1972 Census of Manufacturing and Mineral Industries</u>, Bureau of the Census, U.S. Department of Commerce. The FRB indexes exceed those of Census by an average of 1.8 percent, relative to a set of common references in 1967.

4.8 Energy Storage

4.8.1 Introduction

Solar energy without storage is to a first approximation a capital-intensive method of saving on fuel costs at uncertain times; hence storage is critical to making solar power economic on a large scale. However, it is important to note that storage per se does not guarantee that solar will be more economic than conventional supply alternatives. For example, if cheap storage of bulk electric energy became available, it could be used to store solar power for the night, or off-peak night-time nuclear power for the day and early evening. This indicates that storage can be a benefit to conventional as well as to non-dispatchable sources and that a judicious combination of sources could reduce the need for energy storage, hence total cost.

This section concentrates mainly on storing the excess energy output of electric generators and redelivering it on demand. Electric power systems are often characterized as "having no storage," reflecting the view that electric energy is produced in the amount required to be used at a given time. But this is not true in a deeper sense, and incorporating energy storage into the electric supply system can affect its cost, operation, choice of major components and configuration profoundly. Short-term storage affects the need for prompt reserve capacity; longer-term storage provides flexibility in meeting peak demand. Some interruptible consumer use can be looked upon as storage provided by the user (literally true for water heaters timed to operate only off-peak). Storage can sometimes permit using cheap fuel instead of expensive fuel, and can sometimes replace generating capacity. The presence or absence of storage greatly affects the value of renewable, nondispatchable* and/or decentralized energy systems,

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* Sources such as wind and PV whose output at any time is much less predictable than conventional power plants, and hence cannot be dispatched by the electrical systems controller in the same manner.

hence the composition of an optimal electric power system.

This section deals principally with the storage technologies themselves, leaving the issue of integration with other elements of the grid mostly for the next chapter. However, some simple systems concepts will be introduced here, to help show how much of what kind of storage can be useful and have a major impact.

In the context of this study, we are considering the potential for large amounts of storage. Biomass is usually storable, a global resource we estimate to be on the order of some 4 TW (See section 4.6) at most. However, much of its use is liable to be restricted to locations and times that do not match the needs for power on demand in industrialized societies; so to a first approximation, we should look to storage elsewhere. The energy to be stored, in our mainly nonfossil future, is of two principal kinds: electric energy (the natural outputs of nuclear, wind, photovoltaic and most other nonbiomass energy systems), and low temperature heat (for example, in passive solar houses).

Several time scales characterize the operation of an electric power system; Table 4.8.1 shows these time scales, tasks to be accomplished, and how they are met with present facilities.

The principal future storage modes are (in our opinion) electrochemical, hydropower, and compressed air, in decreasing order of importance. Some others, for example flywheels, may find useful applications, but we think that their global effect will be very small. From time to time, the idea of a hydrogen economy has attracted attention, for example in the IIASA studies. That may come about one day, but the only efficient methods of making hydrogen at present (from water, <u>not</u> from fossil fuels) depend on large amounts of very cheap electricity and/or high temperature heat, which in our view puts a hydrogen economy as perhaps a successor to a mainly-electric economy, that would develop with less exotic storage forms. Thus our main priorities are the three mentioned above.

4.8.2 Hydropower as Storage

Compared with future global energy demands, it is a moderate potential resource. Our own estimate of utlimate availability is about 4 TW (120 EJ/year) maximum. Much of the cost of a large hydropower system is in foregone land use, the dam itself (or reservoir, for pumped storage) and other items whose cost does not depend very much on the rate of filling or emptying of the system (e.g. locks in a navigable river). Thus, hydropower systems, just like other energy storage schemes, work most cheaply if the filling and emptying cycle is short: non-flowing stored water increases capital cost, but not revenue. Pumped storage systems are then designed for daily (sometimes weekly) charge and discharge cycles. Natural rivers flow seasonally, so weeks, even months, of storage must be provided; thus the ratio (capital in the storage system)/ capital in the generating system) is higher for natural systems than for pumped storage ones, unless the pumped reservoir is exceptionally expensive, say as excavated caves.

These features of hydropower make it an attractive complement both to nondispatchable sources, and to full-time baseload plants, although the schedule of demand will differ in the various cases. Whether it is natural hydropower or pumped storage is mainly a matter of geography, economics and environmental impact: if generators at a natural dam run only during periods of peak demand, their amortized cost is higher, a situation that applies to pumped hydro systems just as well. About the year 1940, Grand Coulee development in Washington State received its name and location because it was envisaged in part as a large seasonal pumped storage scheme.

At present about 1.4 EJ/year (~45 GWe) comes from hydropower in the U.S.* To put this number in context, we note that about 70% of the rainfall evaporates or is transpired by vegetation before it gets into any river. If every drop that naturally flows downhill in every stream delivered all its potential energy the answer would be about 2000 GWe. The amount present in accessible streams and rivers might be 1000 GWe, but of this only a small fraction is really available, because of many limitations. The CONAES report suggests ≃ 100 GWe maximum.

The U.S. has about 5% of the world's land surface, and collects about that fraction of rain on the land; its topography is slightly more mountainous than the average, but not much more. Thus the 100 GWe figure for the U.S. and 2TW globally are in proportion. However, the U.S. generates about 20% of the world's hydropower; the regions of principal promise are Asia (particularly China), South America and Africa.

We believe that natural dams are liable to be much more important than pumped hydro, as a global average. The sites for pumped hydro, while regionally important, seem too few to dominate, and such installations generally cannot serve any other purpose, such as irrigation on demand, recreation or fish production.

Because of its availability on a multiplicity of time scales and because it can fulfill the role of spinning reserve, hydropower can be an excellent complement to non-dispatchable renewable sources. Consider for example wind/hydro systems; Sørenson (1981) outlines the possibilities well. He describes the results of a study made of the feasibility of combining Danish windpower and Norwegian

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*Note that this is electrical energy; in some accounting schemes, this number is divided by the thermal efficiency of a fossil fuel plant to give the equivalent hydro contribution to primary fossil energy use.

hydropower. Data from three Danish wind years (good 1967 , bad 1963 and typical 1961) with an average Norwegian hydro year were used to show that the maximum annual deviations in water level caused by the power exchange with the wind system were +11% and -5%. Those deviations are small compared with the natural variations caused by differences in annual precipitation.

Regarding this complementarity, we quote from Sørensen's excellent article directly.

> More ambitious wind-hydro systems have been proposed in California and and in Scandinavia. The appealing feature of such schemes is that wind-energy converters embedded in a hydro system of sufficient size may effectively obtain full capacity credit at a very low expense. This hinges on a crucial feature of the regions under consideration for such installations: the average seasonal variation in wind energy is to a considerable extent positively correlated with variations in load and negatively correlated with variations in the water level of the hydro reservoirs. For this reason the impact on the water level in the reservoirs is on average very modest. If anything, the rise in water level tends to occur during the winter, when the wind power is highest and the water reservoirs are being emptied, whereas deficits in wind power leading to withdrawal of water from the reservoirs usually occur in summer, after the reservoirs have been filled by the melting of snow during the spring. Superimposed on these trends is a large amount of borrowing and repaying between the wind and hydro systems on a shorter time scale, ranging from a few hours to a few weeks.
>
> The addition of wind-energy converters to a hydro system with sufficient reservoir capacity may require reinforcement of transmission lines and increased hydro-turbine capacity, but does not require any enlargement of the two main components of the hydro installations: dams and reservoirs. In this sense the wind-energy converters may be given full capacity credit, although strictly speaking the increase in turbine capacity at the hydro installations carries a penalty in power rating. The point is that the power rating is not an adequate measure of capacity either for wind or for hydro installations. For wind turbines the proper measure of capacity may be the average power output at a given site, while for hydro installations it may be the average power of water flow over the year -- neither of which is strongly correlated with the power rating of the generators.

Obtaining capacity credit for non-dispatchable systems increases their value very substantially, because it converts them from being mainly fuel savers to fuel-plus-plant savers. This topic will recur not only elsewhere in this section, but also importantly in Chapter 5 on system operation and integration.

4.8.3 Compressed Air

If pumped hydro with (usually expensive) underground reservoirs are contemplated, the terrain and the electric power system should also be studied to see if compressed air is feasible. The density of overburden rock is about 2.5 that of water, so a gas pressure equal to 40% of the overburden pressure at any particular depth corresponds to a static hydraulic head that high. A well-publicized and successful 290 MWe system operates at Huntdorf, West Germany, utilizing a cavity leached in an underground salt dome. A principal disadvantage is the loss of adiabatic heat in intercoolers during expansion (made up in the Huntdorf system by burning fuel in the expanding air to operate gas turbines). Circumstances favorable to compressed air storage seem less common than for hydro systems.

4.8.4 Electrochemical

The electric energy stored in all the car and truck batteries in the U.S. is about 3 x 10^{14}J; if this were fully discharged during 4 hours each day to contribute to peak electric power demand, the contribution would be about 18 GWe. Such an application is of course impossible; the simple calculation was done to show that much larger storage systems would be needed to satisfy peak demand, and that lead-acid batteries, which even now strain the availability of lead, are not properly suited to the task (beside the fact that these batteries have low energy/kg and power/kg ratios, and the chemical cycles tend to degrade the electrodes physically).

Let us look at the cost. Let the storage system cost = \$$E_1$/kwh, the number of useful cycles = N, the interest rate on money = i, the cycle period = T (measured in the same time units as i), and cost of imput/output power equipment be \$K/kw. Also let a fraction f of the stored energy be drawn out each period, and the cycle efficiency be η. It is then easy to show that the incremental cost S/kwh of storing the electricity is, very closely

$$\frac{\$}{\mathrm{kwh}} = \frac{E_1 iT\ (1+i)^{NT}}{\eta f[(1+i)^{NT}-1]} + K_1 i$$

The first term represents both the initial cost (E_1) and the investment required to replace it at its end of life, NT, on a continuing basis. Note that this cost is in addition to the initial generation cost of the electricity.

A report prepared by the Electric Power Research Institute's UBOAT group (EPRI 1983) gives the following specification for substantial utility application (in a 20 MW, 100 MWhr capacity system):

E_1 = \$80/kwh
N = 7500 cycles
T = 1 day cycle time
K = \$115/kw
f ≈ 0.8
η = 0.65

Suppose i = 15%/yr. Then the incremental energy cost is 7¢/kwh, of which almost all comes from the battery cost, in the first term. If the batteries had only 2500 useful cycles, the cost would rise to about 10¢/kwh. Such a storage system also provides the equivalent of spinning reserve (but more expensively than pumped hydro if it is available).

Another report of EPRI (EPRI 1982) dealing with customer-side industrial application adopts a baseline battery cost of \$212/kwh dc, plus variations both up and down, and correspondingly higher costs for other items. That might be attractive to some users to eliminate high peak demand charges imposed by the electric utility. While interesting for specific industries, and possibly stimulative for yet more economic systems, that application has little relevance to our larger electric storage problem.

The battery cost ($80/kwh in the example above) is the most important item. Where are we now? Automobile batteries are much cheaper ($40/kwh, more or less) but they have limited cycle life, especially with deep discharge, and lead supply is inadequate.

(Kalzhammer 1979) (of EPRI) gives a readable review of the status of lead-acid, nickel-iron, nickel-zinc, zinc-chlorine, sodium sulfur and lithium-iron sulfide battery R&D as of 1979. Of these, sodium-sulfur uses relatively abundant materials, and progress in its development is good. Recent difficulties with their development have been cracking of the beta-alumina ceramic electrolyte tube and insulating seals, together with corrosion at the sulfur electrode, leading to shortened life. The General Electric Company reports (EPRI 1982b) that their type C-45 cells incorporating modified beta-alumina and other improvements have largely overcome these difficulties, and would sell for $45-$60/kwh in quantity (1981 dollars). In the referenced report, G.E. states that the new cells were undergoing extended life test.

A $50/kwh figure applied to our example above would lead to an incremental cost of electricity storage of about 4.6¢/kwh. This number compares favorably with the fuel cost alone of oil or gas for peak generation: at $6.00/GJ in 40% thermal efficiency plants this is 5.4¢/kwh; on the other hand, the cost of coal at $2.00/GJ in the U.S. corresponds to only 1.75¢/kwh. However, if cheap baseload power is available, the storage can replace the plant as well as the fuel. For example, night-time nuclear power at a marginal fuel cycle cost of 1.5¢/kwh added to the 4.6¢/kwh of storage wins over any present peaking system.

Storage would be necessary for large installations of solar or wind power; the costs are higher. For example, electricity from a photovoltaic (PV) installation at $\$1.00/W_p$ total system cost, at 15% interest rate, costs about 8¢/kwh. Wind at $1000/kwe nameplate capacity and 0.4 load factor (optimistic numbers) corresponds to 4.4¢/kwh. The sums of these plus our prospective battery storage (12.6¢ or 9.0¢/kwh respectively, assuming diurnal cycles) compete with peaking power, but are a long way from replacing coal or nuclear baseload if the latter are permitted on the system.

How much storage might be required? A very simple calculation shows fairly accurately what could be accomplished. See Figure 4.8.1. A typical U.S. daily electric power demand looks approximately like a constant average, modulated 30% above and below by a sine curve with a peak at 3 pm, plus higher harmonics and week-end effects. These higher order and weekend effects can be ignored if a 20% ± error is allowed, good enough for this assessment.

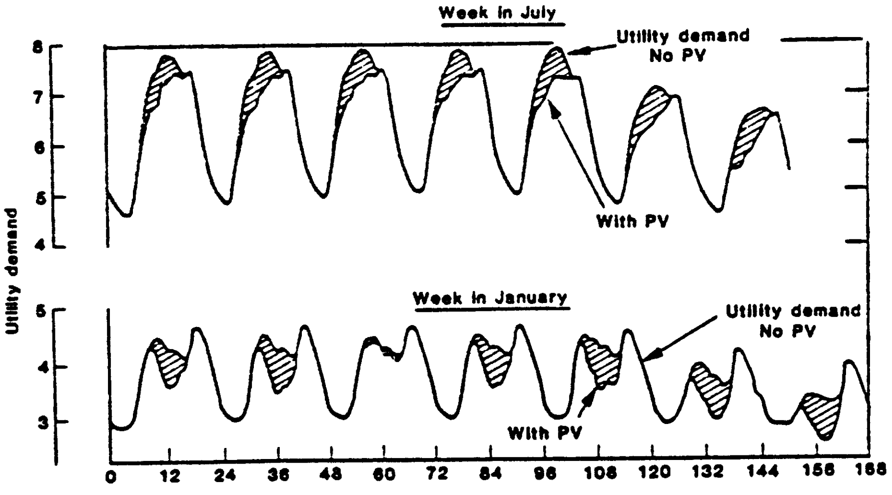
The entire energy content lying above the mean in this case is 9.6% of the daily total, some 5×10^{13} joules or 1.49×10^{7} kwh, if the daily average is 6.1 GWe. The storage system would have to deliver 1.8 GWe peak, rising from and decreasing to zero over the 12-hour period.

The effects of a hypothetical but interesting solar PV system can be easily calculated. Suppose the PV system produces power corresponding to the upper half-sine curve of power demand, but off-set in phase by three hours. The remaining misfit area must be supplied by storage (from the cheap off-peak baseload power). This total amount of energy corresponds to only 2.2% of the daily energy demand. In this 6.1 GWe scenario, some 3.2×10^{6} kwh would need to be generated over a 7½ hour period, at a maximum rate of about 1.2 GWe.

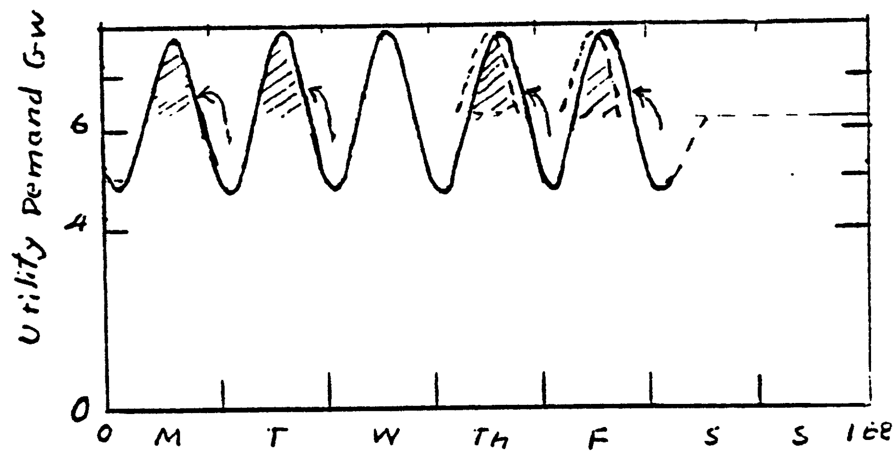
This simple example is not meant to show that PV systems could in fact take over that much of the load; such a system would require enough spinning reserve and/or rapidly accessible storage in order to handle the vagaries of sunshine. What it does show is that the degree of penetration of storage and nondispatchable sources such as PV or wind affects other system components, and that where photovoltaic systems are most useful additions to utility grids, they tend to reduce the value of additions of electrical storage systems, and vice versa. Provided cheap night-time baseload power is available, the two are substitutes for each other. The situation would reverse if PV capacity increased to provide a high proportion of total grid generation. This conclusion has been remarked upon by (Smith 1981) and complicates the development of both renewable and storage systems, the former probably more than the latter. As utility storage systems become available and economically attractive, an outcome we consider likely, so do cheap baseload systems become more attractive, and the market for all peaking and nondispatchable power systems declines.

Table 4.8.1

TIME SCALE	TYPICAL TASK	HOW THE NEEDS ARE MET
0-100 sec.	Frequency control	Governors, steam reserve, dynamic control.
30-500 sec.	Spinning reserve (running spare)	Part-load pumped hydro, system dispatch.
3 min.-3 hrs.	Peak lopping	Unit commitment (gas turbines, low merit fossil plant). Links with other systems.
4-12 hrs. 2-7 days 1-3 months	Load leveling for various periods	Unit commitment (mid-merit fossil plants, spare plant) scheduled maintenance.
1 month-2 yrs.	Long-term loading	Scheduled maintenance.
5-20 yrs.	Long-term demand	Capacity expansion planning.



(a) Simulation by Aerospace Corp.



(b) Simplified model of the July weekdays

Figure 4.8.1. Simulation of a Utility Road profile, with and without photovoltaics in the Southeastern United States

(a) Adaptation by Jeffrey L. Smith [Science, Vol 212, 1472(1981)] of data from Report ATR-80(7694-1)-1, Energy and Resources Division, Aerospace Corp., El Segundo, California.

(b) A simplified model of the July data during weekdays: 6.15 GWe average plus 30% sinewave modulation peaked at 1500 hrs. The above-average shaded parts on Monday and Tuesday comprise 9.6% of the total, and could be met from electricity generated and stored in the slack periods. The hypothetical solar contributions on Thursday and Friday, centered about 1200 hrs, leave only 2.2% of the total demand unmet, to be supplied from off-peak storage.

Chapter 5

ELECTRIC POWER SYSTEM INTEGRATION

5.1 Introduction

Here we consider how both fossil and nonfossil energy sources can best be combined in an electric utility system. This interest in electric systems in our work arises because (a) many of the nonfossil supply options are electric; (b) the electric energy fraction of total energy use grows steadily worldwide. We are particularly interested in what happens with high penetration of "nondispatchable" energy sources, such as solar photovoltaic and wind; they pose novel problems as well as offering new opportunities. The sections on wind, photovoltaic, and storage systems in Chapter 4 touched on them briefly.

We cannot here review in detail the vast literature on how electric power systems are arranged so as to call on various units at different locations and times to match present and anticipated demand, nor do we need to. Our interest is mainly on the effect of new options, on both supply and demand. We will conclude that substantial amounts of wind or photovoltaic power--perhaps 20 or 30 percent of the system capacity--can be incorporated into the utility system, provided some other features that are desirable in their own right are also incorporated. Chief among these are energy storage (e.g., batteries and/or pumped hydro) and load management (e.g. short-term microshedding of interruptible loads). These system developments--storage and management--benefit baseload options such as nuclear power just as well and conceivably even more, because they make off-peak baseload capacity available to meet off-base demands. Thus the very measures that permit extensive penetration of what has customarily been called non-dispatchable power units into the grid also appear to encourage the introduction of the very opposite type of power plants. This is because both non-dispatchable and base load units are very rigid in terms of electric power system operation. The base load units are inflexible because it is very uneconomic to run them at any rate other than full power (and because of that some have not been designed to shift easily from one power level to a different one). The non-dispatchables generate power at a rate totally outside the control of the system's dispatcher. Storage and load management are extremely flexible options and their availability in a power system enhances the level at which rigid options can be introduced, without hindering the system's operational capabilities.

These apparently opposite trends can be reconciled by realizing that <u>both</u> are non-dispatchable, only in different ways: the large baseload units cannot now load-follow to any appreciable extent; storage, load management, peaking units, intermediate-load units etc., in this sense all serve the same purpose--to match the generation and the anticipated load. To be sure, the output mismatches occur for different reasons, with different patterns of fluctuations, and in different parts of the system--the wind dropped, or everyone turned on their television sets--but the need to match provision and use is the same in all cases.

One can then ask which direction, or combination of directions is best. That depends on a host of other important considerations: Cost and expected performance of each particular type of unit; perceived environmental impact: whether small units can be economically added in order to match long-term load growth as closely as possible; size of the grid system; social preference for or against any particular type of unit. Some of those advantages and disadvantages have been discussed in Chapter 4; many of the others are system-specific, hence, not within our present scope.

Despite our intent not to revisit system analysis in general, we offer a brief review of selected topics, in order to establish a basis for the later discussion.

5.2 Demand and Supply Fluctuations, Characteristic Times, and Responses

A useful perspective on systems integration follows from understanding how demand and supply vary both in time and at various levels of demand (i.e., local, subdivision, town, region). Figure 5.1 deals with a hypothetical electric utility system of a few GW total size; in particular it illustrates how the demand (solid lines) might appear, with a nondispatchable source added (dotted lines). For convenience in discussion, let it be wind and, for the moment, assume (unrealistically) that all the windmachines are in one location.

Consider the top diagram of Figure 5.1, where the solid lines show events over one hour. At the 1-kw single residence level, lights get turned on and off, the refrigerator runs, then stops, etc., and we see large fluctuations. At the 100-kw subdivision level, many of those fluctuations are smoothed out, but others may appear, like the peak at 45 minutes when people turned their lights on during a solar eclipse. At the 10-MW level, the demand is further smoothed, but the eclipse (or some other) phenomenon appears here, too. Finally at the 1-GW regional level, the demand is almost smooth, affected somewhat by a few regionally correlated events.

Now consider the behavior of windmachines during this hour (the dotted lines). The figure shows them providing a relatively large fraction (≈30%) of the average demand. For convenience in the discussion, this fraction is administratively allocated among all the users (so that the average wind/demand remains approximately constant throughout the system). The wind blows variably, and not at all sometimes. Most important, this variability is not appreciably diminished as we proceed toward higher levels of integration, from the 1-kw to the 1-GW level; recall that all the windmachines were at the same place. Thus a "noise" appears on the whole system that did not exist before, and the system must cope with this, if the benefits of the wind generation are to be captured.

Next, consider the one day time scale. In the 1-kw house, people go to bed, go out, cook supper, etc. At the subdivision level, these cancel only partly, and the diurnal power demand starts to show through. In this example, we see also a 24-hour power load, because this subdivision included a small industry that operates around the clock, e.g., an electric heater life-test laboratory. At the town level, the average daily pattern dominates, and even more so at the 1-GW regional level. Again, the wind blows, more during that afternoon, but with some calm periods; and, again, this behavior runs through the entire system.

The weekly variation shows daily regularity even at the 1-kw level, but it is noisy, as someone relaxes on Friday but stays up most of the night, cooks a banquet on Saturday, etc. At the 100-kw level and above, the familiar weekly pattern emerges (see also Figure 4.8.1 of the energy storage section for another example). But again, the wind fluctuations penetrate the entire system, and we see no daily pattern, except for a tendency to blow in the afternoons and, by chance, not on Friday.

The one-year picture cannot be so easily illustrated: 52 one-week experiences look on this scale like average levels with noise, although the weekly pattern of demand is there in fact. At the 1-GW level, we see the annual variation of demand (it is a summer-peaking system), and the range of weekly and daily fluctuations. Again, the wind fluctuations penetrate the system from lowest to highest level of aggregation, although they cannot be shown here. But we see that the wind tends to blow well from March to mid-December, and not much in the winter; that happens in Hawaii.

How the combination of the electric utility system and its customers can respond to these and other loads and fluctuations is clear if we spectrum-analyze these data. Figure 5.2 shows how they would appear at the four aggregation levels, but now the entire frequency spectrum is shown (very nonlinearly) from steady operation over the life of the society, to one-second variations.

It is easiest to start at the 1-GW (most aggregated) level. The system never shuts down (the infinite-time component), has a one-year component corresponding to the summer peaking, but also small spectral content up to several times that frequency, because the summer-winter variation is not perfectly sinusoidal. The weekly spectrum is notable, corresponding to reduced demand on Saturday and Sunday; it has distinct harmonics because the fluctuation looks like 5 days on, 2 days off. The diurnal signal is very strong, and so are its first few harmonics, corresponding to daily peaks and valleys. But at higher frequency, there is very little from the demand side. The whole supply side is not shown, but if one large unit were to stop, we would have a high-frequency transient, not easily shown in this figure; the spinning reserve, dynamic control, etc., are built into the system to take care of such events, of which more anon.

At lower levels of aggregation, the principal changes are a broadening of the peaks and spectral content between them; the spectrum becomes more noisy. At the 1-kw level, it has much noise, extending into periods smaller than one hour, a relatively high-frequency region that is almost without contents at the 1-GW level.

Our wind spectrum has two main frequency bands: one year, with some harmonics and variation, corresponding to the annual changes; and diurnal with variation. Also we have higher frequency noise, corresponding to the wind's well-known fickleness. All this wind spectrum penetrates the entire system.

A main goal of system integration, and our goal here, is to reduce unwanted peaks as far as possible and either to cope with or eliminate this spectral noise in the system. Many options available on different time scales are placed on Figure 5.2 on approximately their appropriate ranges. Several may be available to cover any one time period; in fact, the entries recapitulate much of the information contained in Table 4.8.1. of the energy storage section.

How any specific utility system should best respond to fluctuations over different times can only be determined by specific detailed calculations. That would involve performing joint statistical and analytic computations of the real electric demand and wind data over time, data shown allegorically in Figure 5.1. But even without such calculations, we can identify many of the principal trends and possibilities from Figure 5.2.

As an example, consider these hypothetical wind data. The presence and operation of the wind machines allows the total system to deliver any given output more reliably than before because the wind may be blowing when some other generator is forced to shut down. Thus for a given level of reliability, a kilowatt of wind nameplate capacity can displace some part of the conventional system. More precisely, not so many new conventional units need to be added to a growing system, or provided as replacements for obsolete units. However, the substitution is usually much less than a one-for-one tradeoff because the wind may not be blowing when needed. Thus a so-called "capacity credit" exists whose real value requires determining how the system load curve, as calculated without non-dispatchable sources, is modified by their presence, under the assumption that the effect of these sources is to modify the output of the rest of the generating system. That is, by treating both the output of various conventional generators in response to demand--shown by the load duration curve in Fig. 5-3--and their outages as independent random variables, one can calculate the probability that demand exceeds installed capacity minus plant outages as a function of demand.

This brings us to the threshold of several topics, particularly loss-of-load probability (LOLP) and spinning reserve, that have many important complications, the resolution of which depends very much on what degrees of performance and reliability are desired.

In the usual simplified analyses recapitulated here, the data of Figure 5.3 are recast in the form of Figure 5.4, as Curve A of that figure. A standard measure of system reliability is now set by technical, economic and sociopolitical considerations; that is the LOLP, to which the system is supposed to conform. Curve B illustrates the point that by adding non-dispatchable units (in these paragraphs we mean wind and photovoltaic units, that have much impaired predictable availability) to the grid, one can achieve the same LOLP with fewer conventional generators.* The actual capacity credit depends sensitively on the amount and type of conventional generation which is displaced; illustrative data are presented in the next section.

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* But as explained earlier in this paragraph, the capacity credit refers to long run imputed cost saving, because some future additions will not be required.

From the perspective of determining whether there is a feasible maximum penetration of non-dispatchable sources, the important point is that the capturable capacity credit decreases as the level of penetration of the non-dispatchable sources increases for two reasons: (1) With increasing penetration, the output of the non-dispatchables starts replacing that of the less costly conventional generators (e.g., baseload nuclear); this could also be envisaged as the solar economics getting worse, rather than a loss of capacity credit. (2) The larger resulting fluctuations in generating capacity require the addition of more reliable back-up power to achieve the same LOLP as previously specified for the system. That is, the system must now be able to accommodate the loss of the largest plant, the maximum probable increase in load, and simultaneously, the maximum probable decrease in non-dispatchable output. More precisely, adding non-dispatchable sources to a grid increases the requirements for both load-following and spinning reserve capacity. These impacts have become the subject of an increasing literature, some of which we discuss in the next section. However, we can already gain insight into this problem and possible remedies by reference to Figure 5.1. Thus, spinning reserve is responsive to events on the time scale of roughly 0 - 100 seconds, and in Figure 5.2 this corresponds to the high frequency part of the spectrum. If the non-dispatchable sources are co-located, their intermittent output in this part of the spectrum penetrates the system, and it is intuitively clear that spinning reserve must be added on virtually a one-for-one basis with non-dispatchable capacity to maintain a given level of system reliability.

Having written this, we now insert some caveats. First, the LOLP is a planning concept, not an operating parameter; real systems are much more complicated. Second, the emphasis here on the importance of spinning reserve, the implied importance of holding frequency very constant, of exact cycle counts every few minutes, etc. is a conventional U.S. electric system view. Such precise standards do not exist in most other places, and good arguments have been made that they should not, perhaps not even in the U.S. Such expensive precision is not necessary for almost all end-uses for which electric utility systems are built; the few exceptions can be handled in other ways. If the standards are moderately relaxed, the spinning reserve requirements decrease.

Several other ways (besides relaxing unnecessary precision) exist to reduce both spinning reserve and the load-following penalty. One is to disperse the non-dispatchable sources since this tends to even out the effects of microclimates and short-term fluctuations. In the language of Figure 5.2, the steady outputs add directly, but to the extent that outputs of the non-dispatchable sources are uncorrelated in Figure 5.1, the time fluctuations add like noise power, and the effective signal/noise ratio increases. Other means to this end include the addition of short-term storage to the grid and various "homeostatic control" load-management options; e.g., microshedding and power energy rescheduling. We discuss some of the latter techniques in Section 5.3; for a fuller treatment of homeostatic control and its impact on the integration of solar electric technologies see (Tabors 1981). As to storage options, consider; e.g., batteries. At \$200/KWh for the complete installation (see Section 4.8), 300 seconds of battery storage would cost \$200/12 ≃ \$17 per installed kilowatt of wind, a cheap and attractive fix on this time scale.* This would not be an economic option for long outages, but for them we could utilize slower load shedding, hydropower, including pumped storage, peaking turbines, as well as other homeostatic control measures such as spot pricing.

We note that ability to accurately predict wind speed and solar insolations can improve system operation in the sense that the fluctuations in non-dispatchable source output can be handled better. For example, several hours advance warning of a large drop in wind output provides the time required to bring additional steam reserve units up to load, thus reducing the need for additional spinning reserve. This effect is even more relevant in the case of small-scale hydro, where the time lag introduced by the precipitation-runoff process allows more time to predict generation from precipitation data obtained, for example, via satellites using a precipitation-runoff generation model of the hydrologic basins.

5.3 Recent Analyses of Non-Dispatchable Source Integration Issues

Here we briefly review ideas contained in studies at Systems Control, Inc. (SCI 1980), MIT (Tabors et al 1981) and Oak Ridge National Laboratory (Reddoch et al, 1982). The point of view in these studies is similar. However, the analysis of Tabors et al does not include the effect of the

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*We do not propose that batteries could or should charge and discharge on 5-minute time scales, but rather that the arrangements made for longer (e.g., diurnal) storage can at small marginal cost also satisfy these short term needs.

additional spinning reserve and load-following requirement of non-dispatchable source integration which, as we shall see, can be a severe penalty at high penetration levels without innovations in load management.

(a) Capacity and Fuel Credit

Table 5.1 shows the results of adding two levels of photovoltaic generation to a small synthesized utility system as calculated by Tabors et al. (The system capacity for Boston, Miami, and Omaha was about 6500 MW, while Phoenix was 7550 MW). Note the differences: Phoenix is by far the best system match due to high insolation, summer peaking, large mid-day air conditioning load. For small (3.1%) penetration, the capacity credit is 40% of the solar nameplate peak rating, dropping to 34% at 15.9% penetration. On the other hand, Omaha is winter-peaking, a poor match for photovoltaic power.

Note in Table 5.1 that the fuel credit exceeds the capacity credit by about a factor 3. This ratio is in accord with the results of the simple calculation of wind systems (Sec. 4.3) that non-dispatchable units are more fuel-saving than capacity saving, at least with present fuel prices and utility generation mix.

The SCI results are similar in general, but different in detail. For example, for a wind system at Clayton, New Mexico, they calculate the following: 1% nameplate penetration of wind machines can displace 0.46% of the 5000 MW prior system capacity; 10% penetration displaces 4.5%; 30% displaces only 5%.

These results can be expressed in other ways, for example, in terms of the breakeven capital cost of a non-dispatchable system as a function of system penetration. Figure 5.5 shows SCI's calculations for solar PV in Albuquerque NM. These breakeven costs at high penetrations lie near the midrange of our estimates for eventual costs of solar PV (e.g. ≈ $850/kw at 20% penetration, 0.2 effective capacity and 15%/year capital charge rate corresponds to an energy cost of about $18/GJ.)

(b) Taking Account of Load-Following and Spinning Reserve Requirements

The SCI calculations indicate that the addition of non-dispatchable generation to a grid causes an increase in both load-following and spinning reserve requirements that are fairly linear with respect to penetration and very similar for both wind and PV generation. (See Figure 5.6) This is in line with the more qualitative discussions in section 5.2.

The impact of this on the economics of non-dispatchable generation is severe at penetrations greater than 1%. For example, at 10% penetration of wind systems, the breakeven capital cost drops from $993/KW to zero when load-following and spinning reserve are considered. These impacts can be partially ameliorated by spatial diversity; e.g., if the wind systems are dispersed at 25 locations within a 500 kilometer range in the SCI scenario, the spinning reserve requirement is reduced from 18% to 14.5%--the requirement without wind systems is 8%--and the allowable capital cost is again positive at $560/KW.

These reports, the SCI in particular, also make several other relevant observations.

- The operating and maintenance costs tend to be exhorbitantly high for small installations, for example, about 20 mills/kwh, in the several kilowatt range. This is due to the lack of on-site maintenance and the cost of providing it on call from some distance away. Systems 10MWe and above are better.

- The majority of outages are not caused by failures in generation, but in transmission and distribution. This leads SCI to suggest locating non-dispatchable units near the load. If improving service reliability is the goal, it is generally cheaper per kilowatt to improve the distribution and transmission.

It should be noted however that these and other studies suffer from several general deficiencies:

- There is no real evaluation of the benefits possible from spatial diversification (analyses based on single systems).

- There is no evaluation of the potential benefits from a diversified mix of non-dispatchable technologies (photovoltaics, solar thermal, different types of wind machines, etc.).

- There is little consideration of the benefits from storage, not only in terms of added capability to support more stochastic generation, but also on the re-optimized dispatch of the rest of the system and in the case of hydro storage, from enhanced regulation of the hydroelectric system.

To phrase the matter slightly differently, the studies usually freeze the generation mix and style of operation in a pattern more suited to the present techno-economic features, then add the non-dispatchable generators without re-optimizing the system as a whole. The general cause for these deficiencies is the fact that including optimization loops for all these issues into the capacity expansion and/or economic dispatch models used in the studies is a very complex task. The treatment of storage in these models, for instance, has been a hot issue long before non-dispatchable generation came into the picture (Castillo Bonet 1983).

Not unrelated to this discussion is the Public Utility Regulatory Policies Act of 1978 (PURPA) and the various incentives for renewable energy, that favor small decentralized systems. It can be reasonably argued that the purpose of it all is to stimulate development of economical energy from renewable sources. But it should also be realized that these incentives can also act to stimulate installation of systems whose main purpose is to take advantage of these incentives. Tabors et al point out how under some interpretations of PURPA, a larcenous supposed small producer could make money by doing essentially nothing: if the small producer is paid the utilities "full avoided cost," this could mean a marginal cost that is considerably higher than the average: but if the utility has only a single rate for selling, based on the average cost, the small producer could in principle get both money and free electricity from the utility company. However, a comprehensive analysis of practice in the New England region shows that the electric utility companies and small producers manage their mutual affairs quite well, to their mutual (and the public) benefit (Davidson 1982).

5.4 A More Holistic View of the Problem

It appears to us that a somewhat different approach to system integration is needed and indeed is developing.* Consider Figure 5.2 once more. Operations

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* Confirmed in discussions with colleagues at the Massachusetts Institute of Technology, summer-fall 1983.

per unit of energy are usually most expensive in the near right corner of the isometric graph, and cheapest in the vicinity of the far left corner--that is, large base-load plants. One can move in the favorable direction via larger units (keeping in mind the diseconomy of scale that can arise if the units become so few that economic advantages of serial production disappear), or via smoothing the system.

Combined utility-customer load management can do much to smooth the short-term fluctuations shown schematically in Figure 5.2, hence reduce the penalty associated with non-dispatchable components. Here are some relevant data, concerning electric energy use in the U.S. residential and commercial (R & C) sectors. In 1977 and 1980 R & C accounted for 57.5% of total generated electricity, while in 1982 it accounted for 60.1% (DOE 1982); the fraction has remained almost constant since the early 1970's. Table 5.2 from the Oak Ridge National Laboratory (ORNL 1979) gives a breakdown of energy consumption in the R & C sectors in 1977 (note that half the total is electricity, on a primary energy basis). Of the total electric use, water heaters consume 9%, that is, 5.4% of total generated electric energy, and opportunities to operate them off-peak have been recognized for years. Electricity used for all heating and cooling (including hot water and refrigeration) is 60% of the R & C total, and 36% of the entire generated energy. This category includes devices with thermal inertia which can be left to coast for varying times, almost always for minutes, sometimes for an hour or more, without affecting the user adversely. Thus load control can remove much of the high frequency system noise in Figure 5.2 without harming the user. Even if only half this component of the load is in blocks large enough to be worth the trouble of controlling, 18% penetration of non-dispatchable units might be incorporated into a load-dispatched system without having to install additional rapid-response spinning reserve.

Modern communication and control systems make this type of load management possible now, at moderate cost that has been decreasing with time. Schweppe and co-authors, leaders in this field, have described the possibilities (Schweppe 1978; Schweppe, Tabors, Kirtley 1982). A more general review is given by (Morgan and Talukdar 1979). Experiments are underway to test these ideas in practice. For example, the Oak Ridge National Laboratory and the Athens Tennessee Utility Board are now carrying out an experiment on utility control of loads, in that utility district of about 25,000 residents and 77 MWe peak demand (McConnell et al 1982).

Another smoothing alternative is storage on the generation side, as described earlier. This could be by batteries or hydro. The latter has both the advantages of fast start and long term. The performance of a modern bulb-type hydroelectric project at the Grand Coulee Dam in Washington state has been described in detail (St. Onge, Harty, Click 1982). From a cold start, it can be synchronized in 90 seconds; if already spinning, it can go from zero to full load in 45 seconds. Responses of whole power plants to changing loads is reviewed by (Reppen and Ribeiro 1979). Modern oil-fired power plants are also being designed to follow load more quickly than before (Bieber 1979). By such strategies, even larger non-dispatchable penetration can be envisaged.

To conclude this chapter, we recapitulate what we wrote near the beginning of it. If it is possible to modify the system to accept non-dispatchable power via addition of control and storage either at the generator or user end, then it should be possible also to apply the same techniques to use baseload power during peaking periods. This latter option appears to us likely to be much cheaper in most locations, because on an energy basis the off-peak power is very much cheaper than non-dispatchable sources developed or even envisaged up to now. In other words, many of the present analyses of how to incorporate non-dispatchable units into otherwise conventional grids may be far from an economic optimum.

To put the matter somewhat over-simply for the sake of emphasis, we can fairly easily envisage a modest penetration (10%?) of non-dispatchables incorporated into the grid, with the associated penalty taken up by relatively inexpensive strategies such as load shedding of particularly simple items. Beyond that, the costs of incorporation rise, and above some higher level (30%?)baseload plus storage will be preferable, at least from this systems point of view.

Which alternative is best depends on a holistic view which accounts for diverse factors: cost per unit of electric energy, size of the system (i.e., is it large enough for economical base-load units), on regional opportunity to use non-dispatchable sources to best advantage (i.e., solar PV in Albuquerque or wind in Hawaii), and on social and/or environmental preferences of one system over another. But in any event, storage and load control appear as essential ingredients in all good choices. Given that, subsequent analyses and comparisons become much easier to make.

TABLE 5.1

Region	Nameplate Capacity		Effective Capacity		Capital Credit	Operating Credit	Breakeven Cost*
	1	2	3	$4 = \frac{[3]}{[1]}$	5	6	7 = [5] + [6]
	(MW)	percent of utility system	(MW)	percent of nameplate	(1980$/Watt)		
Miami	200	3.1	59	29.5	.316	1.080	1.396
Miami	1200	18.3	185	23.8	.280	1.032	1.312
Boston	200	3.1	71	35.5	.286	.806	1.092
Boston	1200	18.3	304	25.3	.238	.790	1.028
Omaha	200	3.1	19	9.5	.139	.465	.604
Omaha	1200	18.5	74	6.2	.108	.461	.569
Phoenix	200	3.1	80	40.0	.287	1.257	1.524
Phoenix	1200	15.9	407	33.9	.263	.803	1.066

*The breakeven cost is the amount the utility would be willing to pay, per watt, such that the utility is no better or worse off after installation of the system.

Table 5.2 U.S. energy consumption by sector, fuel type, and end use, 1977 (10^{15} Btu)

	Electricity[a]	Gas	Oil	Other	Total
		Residential			
Space heaters	1.25	3.64	2.26	0.54	7.69
Water heaters	1.17	0.87	0.14	0.08	2.26
Refrigerators	1.49				1.49
Freezers	0.64				0.64
Ranges/ovens	0.52	0.31			0.83
Air conditioners	1.10				1.10
Lights	0.96				0.96
Other	0.68	0.48			1.15
Total	7.81	5.30	2.40	0.62	16.12
		Commercial			
Space heaters	0.37	1.94	1.90	0.35	4.56
Air conditioners	2.03	0.16			2.19
Water heaters	0.04	0.09	0.10		0.23
Lights	2.23				2.33
Other	0.85	0.20			1.05
Total	5.62	2.39	2.00	0.35	10.36

[a] Electricity is reported as primary energy (11,500 Btu/kWhr).

Sources: The ORNL Residential Energy Use Model and the ORNL Commercial Energy Demand Model, as quoted in Ref.(ORNL 1979)

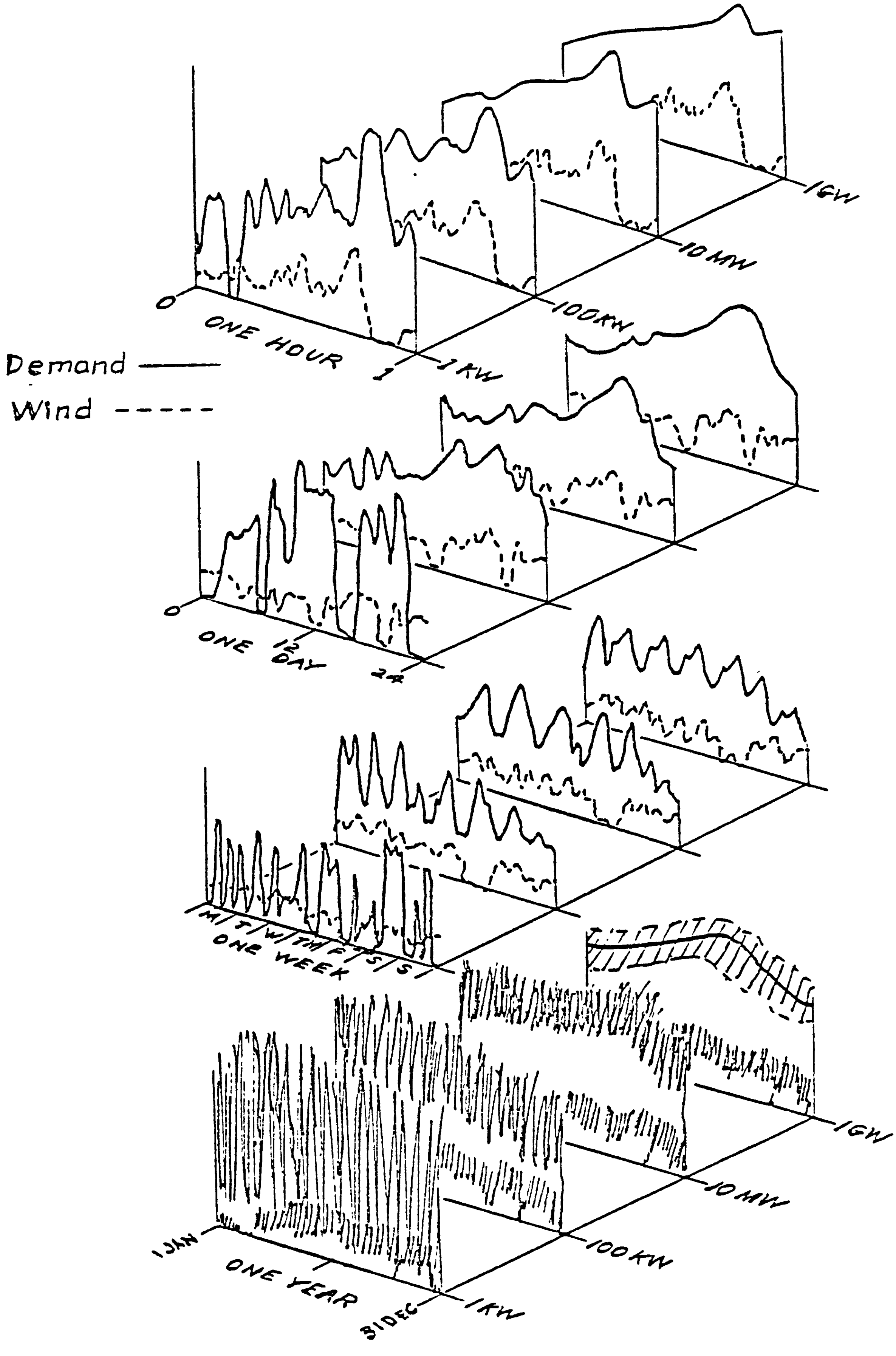


Figure 5.1. Experience of a hypothetical electric utility system, at four levels of aggregation (single residence, subdivision, town, region), on different time scales. The solid lines are electric power demand; dotted lines are output of a wind generator. See text for discussion.

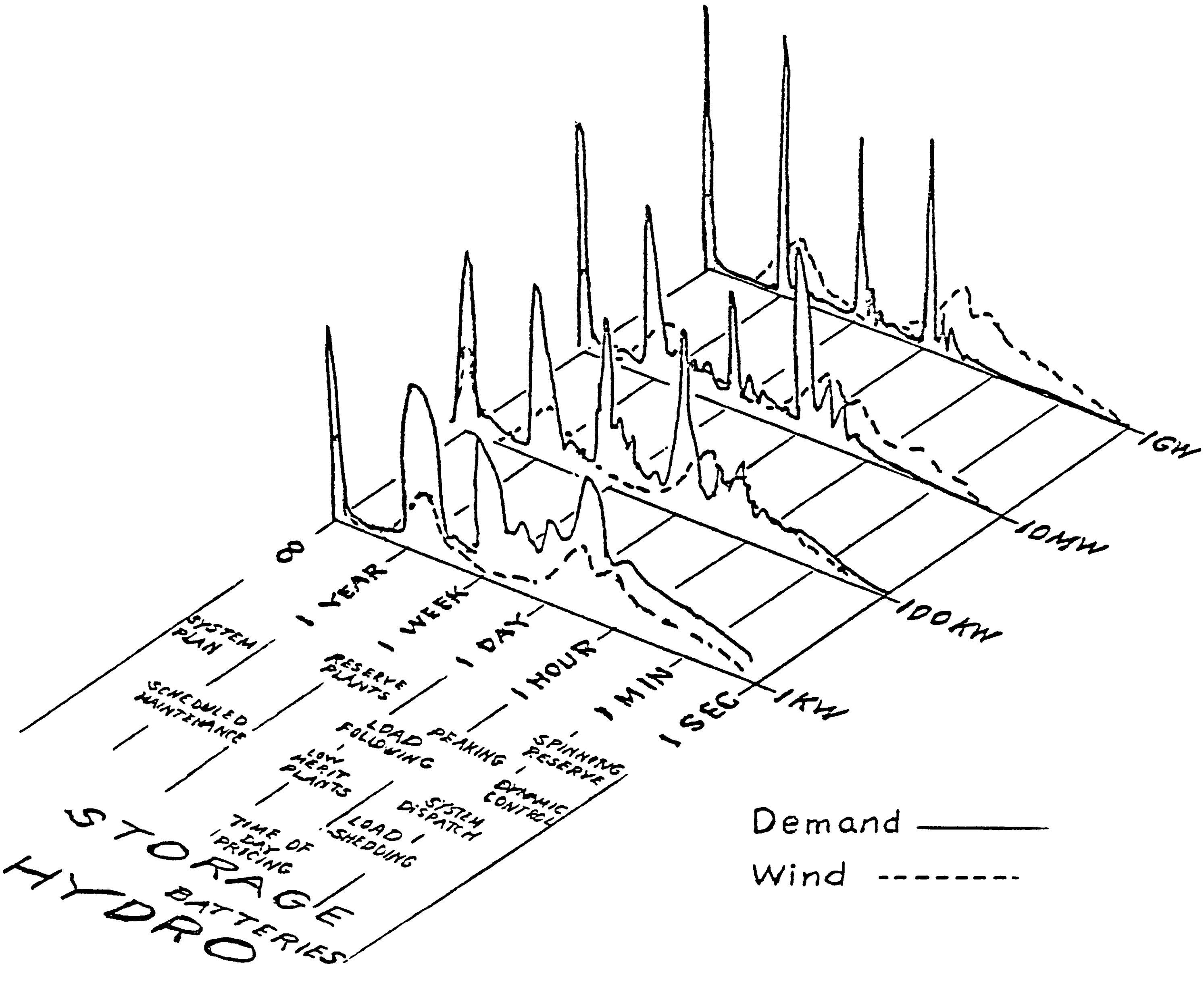


Figure 5.2. Spectrum analysis of the "data" of Figure 1, showing characteristic times and options for system response.

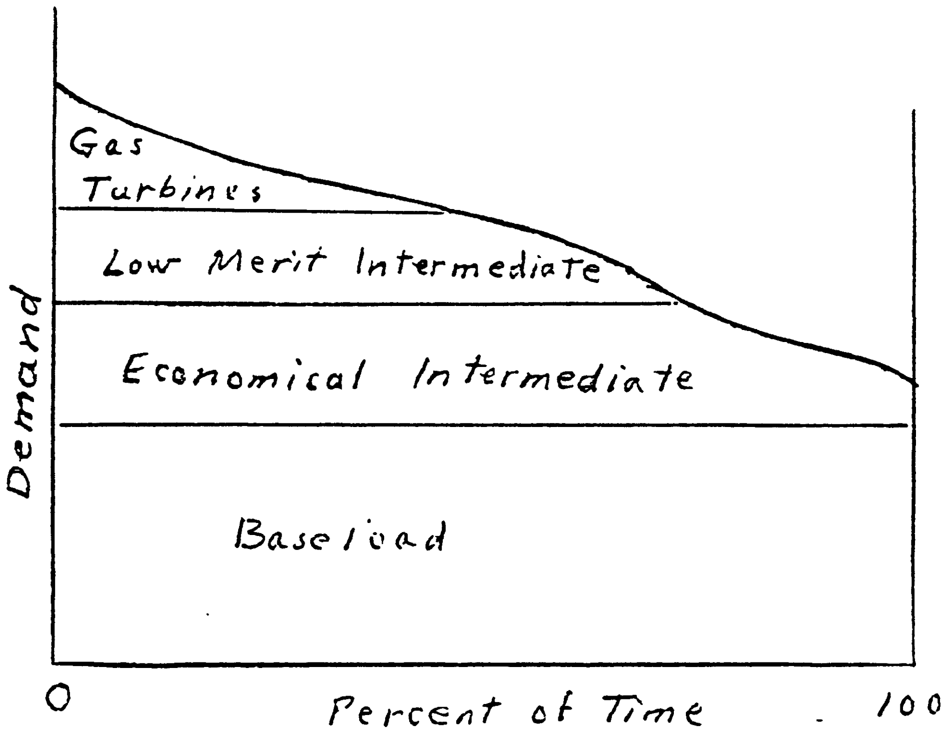


Figure 5.3 Load duration curve

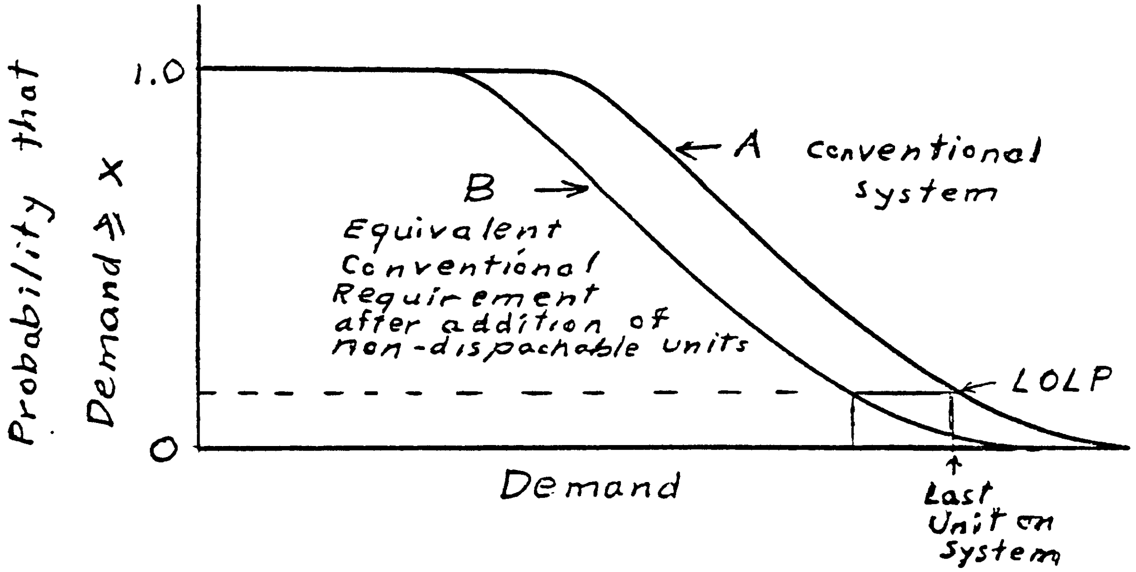
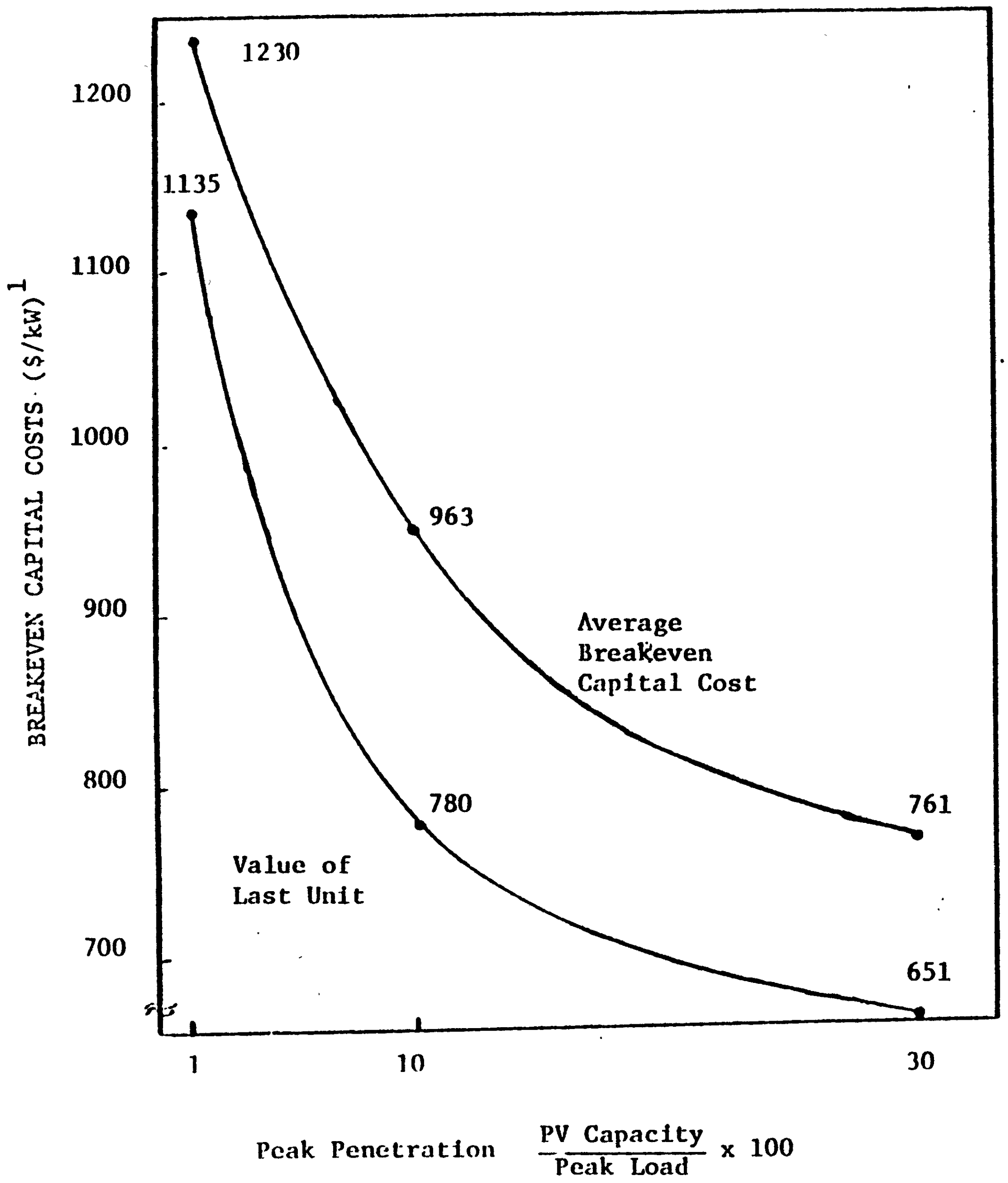


Figure 5.4 Equivalent load duration curve

LOLP ≡ Loss of load probability

Figure 5.5 BREAKEVEN CAPITAL COSTS FOR FLAT-PLATE PV SYSTEMS AT VARIOUS PENETRATION LEVELS



Assumptions:

Photovoltaic System Description:

Cell Type	Silicon
Cell Area	50 m^2
Cell Efficiency at 28°C .	11.5%
Inverter Efficiency . . .	87%
Tilt Angle	20° South Facing
Site:	Albuquerque, NM
Latitude	35°N
Data Source	National Climate Center
Data Type	SOLMET TMY
Data Frequency	Hourly
Utility System Model: . . .	EPRI Summer-Peaking Scenario 'E'
Peak Load	5000 MW
Load Temperature Adjustment Based on SOLMET TMY Albuquerque Data	

Economic Assumptions:

Annual Fixed Charge Rate 15%

[1] \$/kW assume standard operating conditions of 28°C, 1 kW/m^2 incident radiation, inverter efficiency of 87%, and cell efficiency at 28°C of 11.5%.

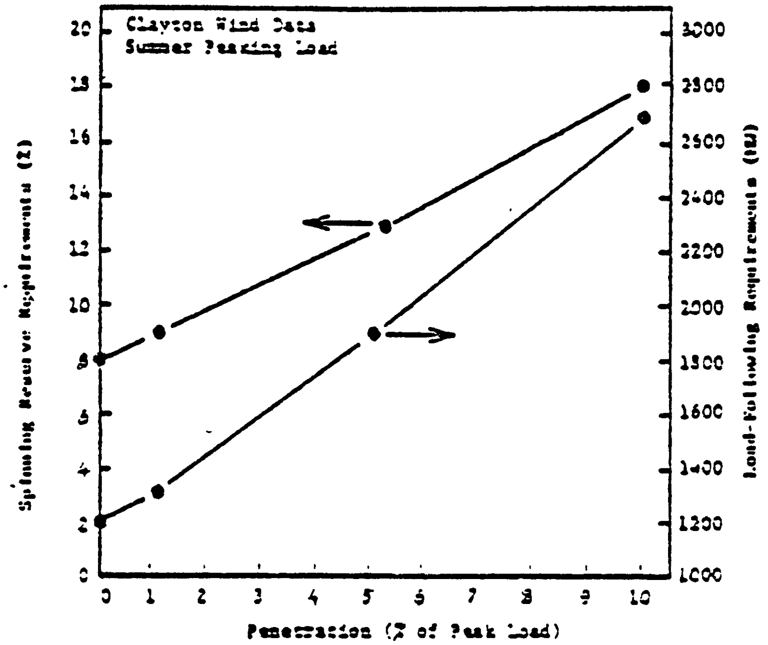


Figure 5.6 Load Following and Spinning Reserve Requirements versus Penetration of MOD-OA Wind Generation Capacity (From SCI 1981).

Chapter 6

DISCOUNTING AND CO_2

In evaluating the impact of alternative energy policies on CO_2 and global climate, we inevitably have to compare outcomes at widely separated points in time. There is considerable dispute over how this ought to be done. One frequently suggested methodology is to calculate a present value of the future costs and benefits of specific projects or policies, using an appropriate "social discount rate." This methodology has generated enormous literature and much controversy. The purpose of this chapter is not to review this literature, but briefly to consider its relevance to the CO_2 problem as we understand it at present.

We conclude that discounting may be used in two ways. One of these is helpful in thinking about the CO_2/climate problem; the other is not. Discounting is helpful when considered as an explicit, technical/mathematical way to represent preferences for different outcomes at different times. Moreover, there are technical reasons why most economic models require discounting or some other limit on the value of future resources. Without such a representation of time preference, most economic models of investment and growth reach the paradoxical conclusion that society never enjoys the fruits of its labor but continually anticipates an enormous spree of consumption in the future.

The unhelpful use of discounting is in simple net present value calculations in relation to large and complex social decisions. Present value calculations in the private sector almost always involve incremental projects whose size and effects are small compared to the whole economy.

Moreover, the costs and benefits involved are more or less readily measured in money terms. In these circumstances, present value analysis (i.e., discounting) is useful in order to assess the financial impacts of decisions. On the other hand, CO_2/climate impacts are, potentially, large enough that they cannot be considered incremental. More importantly, we cannot completely express these impacts in money terms. As will be demonstrated, these problems invalidate the assumptions which would make a simple net present value analysis appropriate.

It should be noted that in addition to the economic problems with discounting there are many people who consider social discounting invalid on ethical grounds. This study does not address this argument. Instead, the arguments summarized below imply that the proper evaluation of future costs and benefits remains an uncertain and controversial economic issue and introduces another source of uncertainty into decisions about CO_2.

6.1 Problem Setting: What Does Discounting Do?

The basic discounting issue can be formalized using a model with only two periods. Suppose in period 0 you have available for consumption an endowment of goods of different types $x_j^0, j = 1,\ldots,m$. In period 1, in the future, your endowment will be x_j^1. You, as well as the rest of society, have a number of trading and production opportunities by which endowments today can be transformed into endowments in the next period. For example, if a part of your endowment consists of seed corn, you can (1) consume it now, (2) plant it and grow corn to consume in the next period, or (3) sell it to a farmer, who will plant it, harvest it, and sell you (or someone else) corn in the next period.

In order to determine what opportunities to take you need to consider the rates at which you are willing to trade off consumption in this period for consumption in the next period. Other individuals, with different endowments and opportunities, do the same. The marginal rate at which you are willing to exchange one unit of commodity j in period 0 for some commodity j in period 1 can be expressed as an interest rate, ρ_j. This rate is called your "own rate of interest." Everyone else in society has similar own rates of interest, too.

In principle, there are an infinite number of these interest rates. However, it is a fundamental theorem of economics that in fact they will all be the same under certain circumstances.* In particular, we have the following:

> Proposition 1: If (1) one of the commodities in the economy is money, (2) there are no taxes, (3) everyone has perfect foresight about the future, and (4) there are no transaction costs;** then (1) the own rate of interest for all commodities purchased by an individual will be the same, and equal to the so-called "consumption rate of interest," (2) all individuals' consumption rates of interest in a period will be equal, and equal to the (marginal) rate of return on any private investment in that period.

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[*] The original idea is in Fisher (1930, reprinted 1977).

[**] In addition to these conditions, a formal statement of Proposition 1 would put certain restrictions on individuals' preferences and firms' production possibilities.

To illustrate this proposition, consider Figure 6.1. It shows the choices and preferences of an individual for consumption (say consumption of corn) in periods zero and one. The convex curve pp' is called the "production possibility frontier." It depicts the combinations of consumption which can physically be produced in the two periods. Moving along the curve, one trades off consumption in period one against consumption in period zero. The (negative of the) slope of a line drawn tangent to pp' gives the rate of substitution between consumption in the two periods. For instance, if the seed-yield ratio on the last acre of corn planted in period zero is 10, then the marginal rate of substitution is 10 (bushels in period one per bushel in period zero). The corresponding consumption rate of interest is 900%, i.e., $10 = 1 + r$, where r is the consumption rate of interest.

Also shown in the diagram is an indifference curve, II', for an individual. An indifference curve has a similar interpretation to a production possibility frontier--all points along the curve are equally preferable. (Points above and to the right of the curve are all more preferable, while points below and to the left are less preferable.) One can define marginal rates of time preference by the (negative of the) slope of an indifference curve. To avoid cluttering the diagram, only one indifference curve for one individual has been drawn in Figure 6.1. Actually, one must imagine a family of indifference curves for each individual, and that they are all present (although not shown) in Figure 6.1.

Obviously, nothing said so far guarantees that the marginal rate of time preference (slope of the indifference curve) will equal the marginal rate of substitution (slope of the production possibility frontier). Proposition 1 says, however, that they will be equal if trade is permitted. Without going into details, trade among individuals establishes a common rate at which consumption in one period can be exchanged for consumption in another period. (If there were no such common rate, opportunities would exist that would allow individuals to buy at one rate and sell at another, making a sure profit. But competition should rule out any such profit opportunities.) The effect of trade is to establish a line such as LL', which is simultaneously tangent to the production possibility frontier and the indifference curves of everyone in the market. The (negative of the) slope of the line LL' establishes the market rate of interest. Because of the mutual tangency, everyone's marginal rate of time preference equals the market rate, as does every marginal rate of substitution in production. Since an interest rate is just another way of expressing a trade-off ratio, the interest rates also are all equal.

Notice also that the individual in the figure is better off with trade than without it, which is why the indifference curve itself does not touch the production possibility frontier. In effect, the individual has borrowed so as to consume more in period zero, and less in period one.

There is a second proposition which is relevant for discounting:

> <u>Proposition 2</u>: Suppose the conditions of the first proposition hold, and that then an additional way is found to transform goods incrementally between period 0 and period 1. (That is, only small changes in goods held by individuals in either period will occur.)

> Furthermore, suppose it is possible to redistribute the outputs of this transformation so that some individuals are better off and no individual is worse off through using it. Then the present value of the benefits of the transformation, evaluated at current prices and at the market rate of interest, will exceed the present value of the costs.*

The implication of Proposition 2 is that if we evaluate a project using present value, at market prices and interest rates, we will make efficient choice from society's viewpoint if we accept projects whose net present value is positive and reject those whose net present value is negative.

6.2 Complications

The propositions are unexceptional as stated. Their problem is that their premises do not hold. In particular, the world contains:

- Risk
- Taxes
- Transactions costs
- Projects which are not incremental

These complications are responsible for the controversy about whether or not the discounting is applicable, and if so what interest rates and prices should be used. Consequently, if net present value analysis is applicable at all it must be under much more limited circumstances than those implied by Proposition 2.

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* For full proof of this proposition see (Varian 1978), p. 218.

The search for specific cases where discounting is applicable has generated an enormous literature. Most of this is concerned with the so-called "second best" problem: when to use discounting if risk, taxes or transactions costs are present, or when changes are not incremental. It is evident the climate change produced by a CO_2 doubling or tripling is not expected to be an incremental one. Thus, even if there were perfect markets, no risk, and the like, it might not be appropriate to use discounting to make judgments between alternative policies. For a discussion of the stability and resilience of societies in the face of climate perturbations, see (Smith 1982) and (Timmerman 1981).

6.3 Technical Issues: Lind's Work

The complications reviewed above have led economists to adapt the basic methodology of social discounting to particular situations. Such is the subject of a recent book edited by Robert C. Lind (1983) and sponsored by Resources for the Future*.

Lind's conclusions fall into two groups: the first are general, and the second relate to picking a particular discount rate. The first set of conclusions are more important for CO_2 than the second.

Lind's first general conclusion is that when taxes, risks, and the like are considered, a single social rate of discount cannot be used for every project. This is another aspect of what we said above, namely that

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* The book is the outgrowth of a symposium originally held in 1975, at which a number of leading economists presented papers. However, the symposium apparently did not produce a consensus on when discounting was appropriate, or what rate to use. Lind was therefore asked to write additional material for the book summarizing the others' work and reconciling it where possible. The result is a book whose technical level is rather advanced, but which reaches some rather simple conclusions about the technical utility of discounting.

if discounting is useful it can only be under special circumstances. These circumstances will require different discount rates in different situations.

Lind's second general conclusion also is the same as ours: that it is generally incorrect to adjust for risk or opportunity costs by changing the discount rate. One of the best discussions of this point is in Robert Wilson's essay in the book. Briefly, discounting is inappropriate because the result of a present value analysis using a "risk-adjusted" discount rate may contradict an analysis using the theoretically correct method of adjusting for risk, the so-called "certain equivalent." The certain equivalent of any random payment is the payment which, if received for certain, would make an individual indifferent between accepting the certain and the uncertain outcome. Adjusting the discount rate for risk implies that the certain equivalent is proportional to the mean of the outcomes. However, Wilson shows that there are many cases of practical significance where this is not the case.

Lind considers what the appropriate discount rate should be if risk is not a factor. While this seems inconsistent, there are several reasons for doing it. First, the book is specifically concerned with energy projects where government support is or may be sought. This is arguably a special instance of the general problem, i.e., evaluating a privately unprofitable project as to its suitability for government subsidy. Second, the background of this volume and the preceding symposium suggests that the individuals involved were under pressure to produce a consensus on discounting and an appropriate rate. Anyone involved in energy policy during the period from 1975-83 will attest to the fact that the discounting question seemed to come up with extraordinary frequency. There may have been considerable pressure to produce a "defensible" value for use in project evaluation.

Against this background, Lind takes a sensible approach. He begins by saying that the social discount rate should not be used to adjust for risk or the existence of taxes.* Lind then says that the social rate of discount should equal the social rate of time preference on riskless investments. The social rate of time preference is an abstraction. It is the rate at which society in the abstract would exchange present for future consumption.

(As an aside, economists generally agree that consumption is the key quantity to which all choices ought to be reduced. That is, consumption streams are what is relevant, and discounting is one way to specify an explicit preference function for consumption streams.)

The next step is to infer a value for the social rate of time preference on riskless investments. Lind appears to assume that this rate should equal the individual rate of time preference for riskless investment. (The individual rate of time preference is the rate at which an individual will exchange present for future consumption. If Proposition 1, or some variation of it holds, then all individuals have the same rate of time preference.) Lind then uses market interest rates on riskless securities (specifically, US Treasury bills and bonds) to determine that the individual rate of time preference for a riskless investment is somewhere between

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*Taxes themselves are less important than the fact that government investment displaces private investment and consumption. The money, of course, is raised by one form or another of taxation.

0 and 2% on a real, after tax, basis.*

Lind's next detailed conclusion relates to the difference in private investment and public investment impacts on future consumption. Here, Lind uses an adjustment factor called the "shadow price of capital." The shadow price of capital is the present value of the future consumption associated with one dollar of private investment, discounted at the social time preference rate. The value of this quantity depends on how the government taxes consumption and investment, and on individuals' and firms' marginal propensities to save. Calculation of the shadow price of capital needs to consider the fact that private investments generate future consumption, some of which is saved and some of which is reinvested. Therefore, the shadow price of capital depends on the savings rate and the private rate of return on investment. Lind concludes that the marginal real, after-tax rate of return on a private investment is 4-6% (based on historical market rates of return on a diversified stock portfolio). With this as a basis, he calculates a shadow price of capital of about 3.8. That is, every dollar of federal subsidy which displaces private investment should be treated as if it "cost" $3.80. If the federal supply is raised by a tax on disposable income, the shadow price is applied to the portion of income that would have been saved.

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* If the time horizon is infinite, there is good reason to question any nonpositive time preference rate. This is because if the time preference rate is zero, one would be willing to pay any amount in the present for an investment that paid an infinitesimal sum indefinitely. Like the original St. Petersburg paradox of D. Bernoulli, there are a number of ways of resolving this one without invalidating the use of the zero discount rate. However, many <u>models</u> of the CO_2 problem are formulated with an infinite time horizon. These models require a positive discount rate if the mathematical expressions for utility are to have a finite value.

6.4 Relation to CO_2 Problem

The Lind book highlights several factors that are relevant to our consideration of the CO_2/climate change problem. The first of these is the need to focus attention on how consumption is affected throughout the whole economy. For example, a number of studies of the CO_2 problem have shown that high rates of economic growth (i.e., high consumption) and high rates of CO_2 emission tend to go together. A project-level evaluation might miss this interaction.

A second point is that even though discounting procedures may be imperfect, decisions must nevertheless be made, and that using a discount rate is an explicit way to evaluate outcomes at different times. By changing the rate one can see whether or not a decision is sensitive to particular preference patterns. I think this use of discounting is helpful in making an informed decision.

Indeed, discounting doesn't go far enough in providing appropriate, flexible weights. The problem is that it is often very hard to think about what a weight should be when the time period is very long. Below, we suggest an evaluation procedure which includes discounting but provides additional flexibility in evaluating future outcomes. For an application, see the discussion of the energy model due to Hamm in Chapter 2.

This procedure uses a finite and comparatively short "time horizon," T. Discounting over consumption, or the utility of consumption, would take place during this time horizon. At the end of the horizon there would be an additional "terminal value" function whose arguments were the stocks of goods and bads (e.g., non-fossil power plants and atmospheric CO_2) left for the future. One example of such a formulation is as follows:

$$\max_{c} \int_{0}^{T} e^{-rt} u(c)dt + S[x(T)]$$

where c is consumption, r is the social rate of time preference, t is time, T is the planning horizon, u is a function determining the utility flow, x(T) is a vector of final stocks and inputs, and S is a function determining the value of x(T) in the objective.

This objective function is somewhat unique. A value function for final outputs and stocks, S[x(T)], is frequently not included in objective functions because either an infinite time horizon is used or, if a finite horizon, T, is considered, stocks are valueless after T. We feel that the use of a time horizon, T, and value function for final outputs and stocks S[x(T)], provides additional, valuable flexibility in the analysis.

The inclusion of the function S[x(T)] in the objective provides several specific advantages:

1. Though there is disagreement over the appropriate short-term discount rate, disagreements seem much greater about discount rates out to infinity. The objective function suggested here allows consumption in the short and intermediate terms to be evaluated separately from costs and benefits in the distant future.
2. This formulation requires decision-makers to determine the values they place on resources reserved for future generations. This may be a simpler task for decision-makers than determining their infinite horizon discount rate.
3. By changing the values we place on resources left to future generations, we can examine if those values significantly affect present decisions. That is, this formulation allows sensitivity analysis over the value of resources left to future generations.

6.5 Summary

To summarize, traditional discounting may be appropriate to situations involving evaluation of an incremental project. Whether it is appropriate, and how to do it if it is, depend on the circumstances surrounding the project. However, traditional discounting is probably not a very valuable tool for making decisions about CO_2 policies at the present time. This is because the effects of CO_2 on climate are not well understood, and may be very large in relation to present and future consumption. Discounting is helpful if it is used to summarize explicitly certain aspects of one's tradeoffs between present and future consumption. However, sensitivity of a policy to the discount rate would suggest that extra care is needed in making the decision.

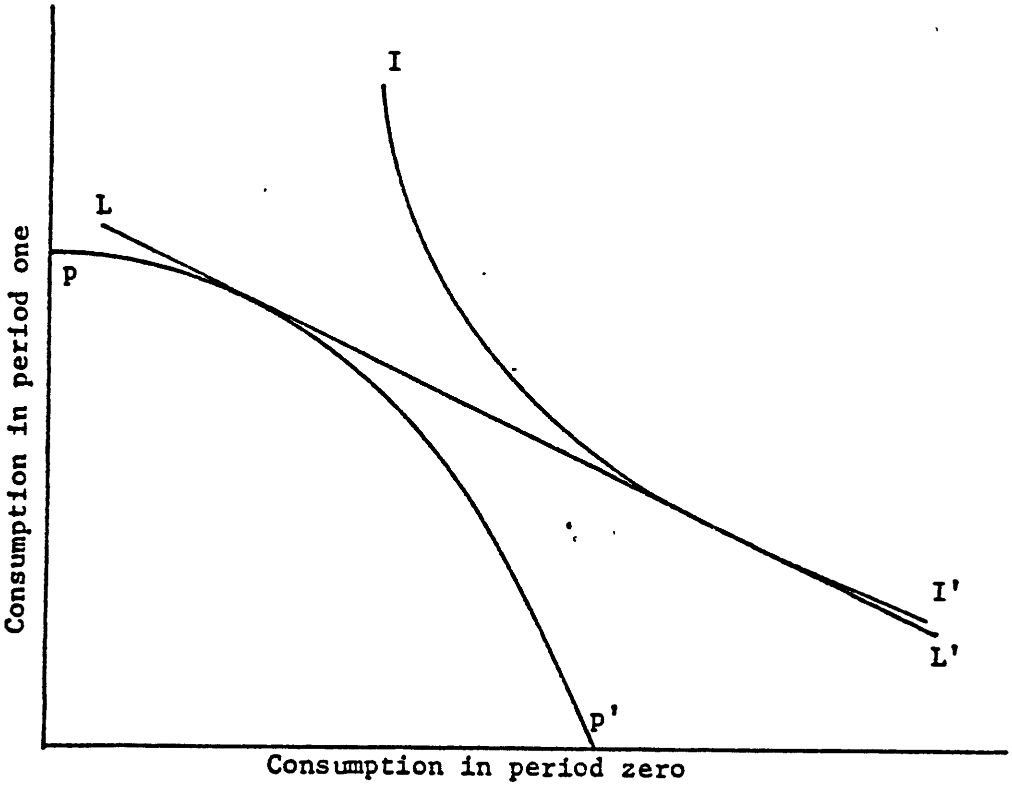

Figure 6.1 Illustration of Proposition 1

Chapter 7

MATERIAL DEMANDS AND CONSTRAINTS

7.1 Introduction

The question arises: what material demand would various energy scenarios make? Different energy technologies require markedly different mixes of steel, concrete, glass, etc. and it will turn out that the renewable technologies generally require larger amounts, principally because the energy sources are more dilute, so larger facilities must be built to accommodate them.

Similar analyses have been done before. For example, the Bechtel Corporation (Gallagher and Zimmerman 1976; Gallagher, Caruso et al 1976), the Westinghouse Company (Love 1976), University of Pennsylvania (Malenbaum et al 1973), and the U.S. Department of the Interior (US DOI 1976) all forecast material requirements. But as the technological options and the projections of energy use change, the prospective material requirements also change. Therefore, this is a continuing process and this analysis takes its place in this chain of assessments.

The materials to be considered are steel, nonferrous metals (mainly aluminum and copper), concrete, glass, and silicon. In many of the applications requiring simple structural materials, steel and aluminum are substitutable, and options exist for building many things out of either metal or concrete. Glass and silicon will be needed for solar PV systems, at least in the present most technologically advanced systems. The possible need for and supply of some other less common materials will also be mentioned.

Our procedure was to collect and analyze the material requirements both as reported in the literature and as obtained by a partial industry survey, and then to make a best estimate in each case. This was done for all the energy supply technologies of interest: fossil (oil, coal), nuclear, hydro, and solar power. From this the requirements for each of the following 15 scenarios were calculated: IIASA Low, IIASA High, Colombo and Bernadini, Lovins, and the eleven MIT/IEA scenarios (cases: A,B,C,D,E,F,H,J,K,L,M). The energy mixes for the MIT/IEA scenarios have been described in Chapter 3 and the others are taken from the literature. These requirements have been calculated as annual averages during the years 2000-2025. This 25-year period appears to pose the most severe demands since during that period the most materials-intensive technologies, the renewables, are forecast to grow most rapidly.

Some general observations to place the detailed calculations in context are as follows. A comparison of the scenarios shows that IIASA High projects a large demand for coal, synfuels, and nuclear power; thus, there are large demands on steel and concrete. By contast, in Lovins' low-energy scenario the sources are mostly renewables; this imposes large demands for cement, nonferrous metals, glass, and silicon. These two are more or less the extremes, so if IIASA High and Lovins avoid material constraints then IIASA Low and Colombo and Bernadini will also have no constraints. From examination of the MIT/IEA Case projections it is not obvious which scenario will present the most severe material constraints. However, Case H projects significant utilization of solar energy, while Case E projects significant utilization of both solar and nuclear energy.

7.2 Material Requirements per Unit Energy

Appendix E of this report lists the various estimates of material requirements for coal electric, synfuels from coal, LWR-fission, photovoltaics, hydropower, wind electric, and biomass, to build plants that will produce one EJ per year (≈1 quad/yr). This is electric output, except for synfuels and biomass, which are assumed to be burned for their heat energy. Oil and gas are not included due to the projected decreased reliance on them. Many of the large ranges given in the appendix represent the possibility of exchanging steel for aluminum (or concrete) etc. Thus a set of "reference" requirements are needed, and these are listed in Table 7.1.

The scenarios as worked out do not distinguish among solar PV, wind, and biomass. Photovoltaics will probably be the dominant solar technology, thus we assume all of the projected solar energy to be PV's. Although the material requirements would differ if solar energy systems were considered to be thermal-electric, the difference would not be significant since the metal and concrete requirements for PV and thermal-electric systems are, in general, very similar. The material requirements for wind energy systems are moderate, but so are the projections for wind energy. If the material requirements for wind energy are used in the Lovins' scenario, which projects the largest increase in wind systems, the materials demand would fall within the range already specified by the other scenarios. Therefore, the requirements for wind systems were not considered in the projected materials demand. Similarly, biomass, which has small material requirements and whose total contribution to energy supplied is constrained (see Section 4.6) was not considered.

7.3 Global Material Requirements for the Scenarios

Appendix E also gives a breakdown of the material requirements by energy source and the resulting total material demands for each scenario. These totals are also given in Table 7.2 in metric tons and as a percentage of 1980 global production, the latter being listed in Table 7.3. A few points should be noted when examining the tables:

1) The values refer only to new additions, not to maintenance or replacement plants. In effect, any operating plant is assumed to last forever. Thus the actual requirements will be larger than shown in the table. As an example, scenarios in which the rate of coal consumption is decreasing (IIASA Low and Lovins et al) show requirements for coal plants as being zero. This assumption is adequate for our purposes, because (a) the largest material demands are for systems not presently existing, e.g., solar photovoltaic; (b) the most rapid changes appear to be taking place in about 25 years, which is less than the lifetime of most plants of this type; (c) we seek rough estimates only in order to be able to distinguish material-frugal from material-intensive options.

2) This table does not include oil, gas, wind or biomass systems. Materials required for oil and gas facilities are relatively insignificant and the projected demand for wind and biomass systems are very small.

3) Nonferrous refers mainly to aluminum, considered substitutable for steel, as described earlier, for photovoltaic plants. Thus, the projected production rates for both steel and aluminum will not be required in the year 2000.

4) The percentage of 1980 glass production refers only to the percentage of rectangular flat glass produced in 1980 (6.1 million metric tons), used mainly for doors, windows, greenhouses, etc. The total glass production in 1980 for the world was approximately 11 million tons.

5) The 1980 silicon production in Table 7.3 is the amount of semiconductor grade polysilicon produced in the world outside the centrally planned economies. (Snyderman 1981).

Overall, the requirements for steel and cement appear as though they will not pose a barrier for implementation of any of the scenarios; but nonferrous metals (mainly aluminum), glass and silicon will impose significant demands on the respective industries. Each of the materials projected is reviewed separately below.

7.3.1 Specific Materials

STEEL. Global raw steel produced in 1980 was 708,400 thousand metric tons. The projections of steel needed in the year 2000, range from 1.7% to 12.0% of the 1980 production level. The most demanding use per unit power capacity is in solar photovoltaics, and the worst case is H (nuclear moratorium, cheap solar power). Case H requires 12.0% of 1980 steel production by the year 2000. Of this 12.0%, the steel needed for PV systems accounts for 92%.

The steel demands projected in the scenarios are not expected to pose any problems. Excess capacity exists in the United States now (72.9% utilization of capacity in 1980) (Amer. Metal Market 1981). Worldwide, 715 million metric tons of steel were consumed and according to Lenhard Holshuh, secretary-general of the International Iron and Steel Institute, consumption will increase by 2.7% in 1982 (Brown 1981). Furthermore, steel production in the United States alone is expected to increase to more than 180 million metric tons by the turn of the century (U.S. Bu. Mines 1980). The basic raw materials, iron ore, coke, and limestone, are abundant and widely distributed throughout the world.

CEMENT. Concrete is the most versatile and widely used structural building material, and is about 20% cement. The materials to make it are commonly available.

The projected demand for cement in all the scenarios is a substantial amount, yet all the projections are a small percentage of present production rates. The percentages range from 2.1% for Colombo and Bernadini to 20.7% for MIT/IEA Case H. Similar to the steel projections, most of the concrete required is for foundations and structural components of solar photovoltaic systems. All of the scenarios except for IIASA Low, IIASA High, Colombo and Bernadini, and Case A, project solar as the energy source requiring the most concrete, thus the most cement. In summary, no supply problems are anticipated in meeting the projected cement requirements.

NONFERROUS METALS. As mentioned previously, the need is principally for aluminum in structural materials, and that mainly for renewable energy supplies; solar, PV and wind. A glance at Table 7.2 shows that the annual needs would be at least 17% and as high as 460% of 1980 production, if aluminum is the chosen material. Because steel can in principle be substituted for it, the first reaction to these numbers is that aluminum will not be used to any great extent, but rather more plentiful steel will be used. To be sure, such substitution will certainly occur, but the demand for aluminum is likely to strain the supply nevertheless. The reason is that the solar installations will be mostly untended, outdoors. Aluminum requires much less protection against corrosion, and will be the material of choice in many cases.

As expected, Case H, the nuclear moratorium scenario, projects the largest nonferrous material requirements--over four and a half times the 1980 production rate. The second highest projection of 271% of 1980 rates is for a more probable projection--Case E. All of the scenarios except two project nonferrous demand to be at least 50% of 1980 production rates. Aluminum and copper are each reviewed separately.

(a) ALUMINUM. Present production of primary aluminum is heavily concentrated in the industrialized regions. Three fifths of the world production is from the United States, the U.S.S.R., Japan, Canada, and West Germany. However, production is expected to shift heavily to countries with large bauxite reserves: Australia, Brazil, and Venezuela (U.S. Bu. Mines 1980). In particular, Latin America will experience dramatic growth in all stages of the basic aluminum industry--bauxite mining, alumina production, smelting and use of aluminum (Altenpohl 1980).

The United States' total annual primary aluminum capacity at the end of 1980 was 5 million metric tons, up 4.2% from 1979. In 1981, global primary aluminum was produced in overcapacity and 3 million metric tons were stockpiled (Kramer 1981). Furthermore, capacity additions will occur more rapidly in the next five years than in the previous five years (U.S. Bu. Mines 1980). Thus, production rates will be significantly higher by 2000. Over the period from 1970-1980, world production increased 59 per cent, an annual growth rate of 4.8%. However, world production of primary aluminum in 1980 was up 5.5% from 1979. If global production continues at this rate until the year 2000 (excluding copper production), then only the demand projected by three scenarios (MIT/IEA Cases E,H,J) will not be matched.

Although future U.S. aluminum requirements cannot be met by domestic resources of bauxite there is an adequate supply in nonbauxitic materials in the United States. But, at the present time no industrial plants exist to treat the nonbauxitic materials. Although large quantities of bauxite are imported, there are substantial reserves to meet domestic demand to the year 2000. In addition, aluminum recovery from scrap is an important contributor to the domestic aluminum supply. From 1970-1980, scrap accounted for about 22% of the total U.S. aluminum supply (Aluminum Assn. 1980). Furthermore, the world reserve of bauxite contains almost 5 billion metric tons and is sufficient to meet forecast world demand through the year 2000.(U.S. Bu. Mines 1980). Consequently, no supply problems are expected.

(b) COPPER. Total land-based resources, including hypothetical and speculative deposits, are estimated to contain 1,480 million metric tons of copper. An additional 690 million tons are estimated to exist in deep sea nodule resources. (U.S. Bu. Mines 1980). Future demand for copper is projected to increase, with the electric utility industry being a major consumer, but the copper resources will be adequate. However, current supplies at current prices are inadequate to maintain demand by the year 2000, even with scrap recovery maintaining a 1979 rate of 35%/yr of total production. (CIPEC 1979). As a result new supplies will be sought and developed, lower grade ores will be mined, and the price of copper will rise. (GE 1977). Due to this increase in price, copper will become substituted in many applications, including aluminum for conducting electricity, steel for shell casting, and plastics for plumbing (U.S. Bu. Mines). For the near future, new mining and smelting capacity coming on-stream will maintain a period of sufficient supply (Kramer 1981). Although limitation on the supply of high grade copper is foreseen, it is not expected to constrain the implementation of any of the energy scenarios.

GLASS. Either glass or plastic can be used to cover photovoltaic modules. Soda-lime glass, borosilicate glass, acrylic, Poly-n-butylacrylate (PnBA), Mylar, Teflon, Lexan, and Saran have been considered (Minnucci et al 1976; Carmichael et al 1976; Carroll et al 1976; Dennis 1980; Liang et al 1981). Glass is more resistant to weathering; it will retain its clarity for a longer time. If glass is washed regularly, the amount of light transmitted is expected to remain within 5% of that at the time of manufacture for a period of twenty years or more, whereas plastics will lose 25% and more of their transmissivity within several years (SERI 1982).

Raw materials for glasses are abundant and accessible. But the demands for it would strain the supply in the large PV scenarios. The glass industry is divided into three main divisions according to its products: flat-glass, containers, and special glass. The flat-glass division is relevant to our needs.

The percentages listed in Table 7.2 pertain to 1980 production of flat-glass. The majority of all glass produced is soda-lime glass; it is cheap, and is used in windows, bottles, and mirrors. As can be seen from the table, additional glass manufacturing facilities will be required to meet the projected demands, even though raw materials will be sufficient. In addition, new manufacturing processes may be needed. The most likely scenario not to be affected by glass requirements is Colombo and Bernadini, followed by IIASA Low. The remaining scenarios may encounter problems in attaining the projected solar energy supply because of the glass requirements. However, the amount of glass required may be reduced by using Fresnel lenses which can be made of plastic. These lenses can serve the purpose of both a concentrator and an encapsulating cover.

SILICON. The dominant solar cell technology is based on single crystal and polycrystalline silicon. The rates projected by the scenarios represent the amount of silicon needed to meet the projected solar energy supply.

The 1980 world production of metallurgical silicon was approximately 2800 thousand metric tons, but the volume of semiconductor-grade polysilicon consumed in the world outside the centrally planned economies was only 2775 tons (Snyderman 1981). Furthermore, the quantity of polysilicon required worldwide in 1979 for solar cells was a mere 44 mtons (Snyderman 1979). In this analysis the total semiconductor-grade polysilicon production can be considered for comparison, since this material is applicable in both the electronics and solar industries. Present production is a factor of 100 to 2500 short of early 21st century needs, in all the scenarios.

As of mid-1981 there were twelve silicon producers in the western world: 4 in the U.S., 5 in western Europe and 3 in Japan (Chemische Ind. 1981). Essentially a complete silicon cell manufacturing industry must be established. If the semiconductor-grade polysilicon industry continued growing at its present rate of 50%/yr to the year 2000, the projected demands of all the scenarios would be met, but no other industry ever grew that fast, for that long, as attested to by Edelson and Lee.*

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* For a brief description, see the bibliography accompanying the solar photovoltaic assessment.

When considering the material requirements for photovoltaic cells it is important to realize that various other materials can be substituted for silicon wafers. These materials include thin films and compound semiconductor cells. A second point to realize is the design of the photovoltaic array affects the amount of silicon needed. Less silicon is needed to produce a given amount of energy with a concentrated array than with a flat-plate array; a shift that transfers the burden of supply to the glass and plastics industries.

In conclusion, silicon is the material most likely to pose the barriers to implementation of the energy scenarios. This is due to the projected rates of solar energy. The most viable energy future is projected by Colombo and Bernadini which has the lowest projection of solar energy.

7.4 Conclusion

Overall the following can be concluded: the projected demand for steel, nonferrous metals, and cement are seen to be small or moderate compared to present day production rates and no great supply shortages are foreseen. The largest problems arise with respect to solar PV systems, in particular for glass and pure silicon (and by inference, other semiconductor materials). Although projected glass demand is very large, 1980 production must expand at about 10% per year to meet the highest projected requirements in 2000 of MIT/IEA Case H. That scenario is somewhat extreme to be sure (nuclear moratorium, good success at developing cheap PV systems); many of the solar scenarios would give trouble to the glass industry, a massive industry with much inertia. The production of silicon cells needed for the photovoltaics may pose the largest barriers on implementation of the scenarios.

The silicon industry must grow at 25%/yr for 20 years to sustain the lowest solar energy projection and at the current 50%/yr to meet all the scenario projections. That does not mean that the lowest solar scenario futures (Colombo and Bernadini) are the most likely. The whole pure silicon industry is too small to have much leverage over the world's energy supply. Rather, it appears to us that the industries that produce materials for solar cells will grow very fast.

Table 7.1

Best Estimates of Material Requirements for Energy Technologies
(Thousands of metric tons per EJ/yr)

Technology	Steel	Concrete[a]	Nonferrous[b]	Glass	Silicon
Coal Electric	1500	5500	30	-	-
Synfuel from Coal	600	*	30	-	-
LWR-fission	2500	15000	125		
Photovoltaics[c]	20000	210000	30000	12000	1800
Hydroelectric	3500	60000	200	-	-
Wind Electric	8000	35000	1000	-	-
Biomass[d]	4500	12000	*	-	-

- These quantities are relatively insignificant.

* Data not available

[a] Concrete is a mixture of sand, gravel, water, and cement. Cement is approximately 20% of the total mass.

[b] Nonferrous refers mainly to aluminum and copper.

[c] Steel and aluminum are substitutable as construction materials.

[d] Values are for conversion plants.

Table 7.2

Annual Projected Materials Demand for 2000-2025
(10^6 metric tons per year, (% of 1980 production)

Scenario	Steel[a]	Cement[b]	Nonferrous[c]	Glass[d]	Silicon
IIASA Low	19.1(2.7)	29.7(3.4)	7.4(28.8)	2.6(42.6)	0.39
IIASA High	32.7(4.6)	46.5(5.3)	13.8(53.8)	5.0(81.9)	0.76
Colombo & Bernadini	12.3(1.7)	18.8(2.1)	4.3(16.8)	1.6(26.2)	0.23
Lovins	24.6(3.5)	54.1(6.1)	34.3(134)	13.7(225)	2.05
Case A	23.7(3.3)	41.2(4.7)	12.1(47.1)	4.6(75.4)	0.68
Case B	25.1(3.5)	47.9(5.4)	13.7(53.4)	5.2(85.2)	0.77
Case C	26.3(3.7)	52.4(5.9)	19.6(76.4)	7.6(125)	1.13
Case D	41.5(5.8)	80.1(9.1)	39.0(152)	15.4(253)	2.30
Case E	62.1(8.8)	129.8(14.7)	69.6(271)	27.5(450)	4.12
Case F	23.3(3.3)	45.6(5.2)	14.5(56.5)	5.5(90.2)	0.83
Case H	85.4(12.0)	182.6(20.7)	118.0(460)	47.0(770)	7.06
Case J	44.4(6.3)	92.4(10.5)	50.4(196)	19.9(326)	2.99
Case K	23.9(3.4)	45.2(5.1)	17.7(68.9)	6.8(112)	1.03
Case L	40.5(5.7)	84.6(9.6)	44.9(175)	17.8(294)	2.66
Case M	47.1(6.6)	99.0(11.2)	54.6(213)	21.6(357)	3.24

[a] Percentage given is for 1980 raw steel produced.

[b] Cement is 20% of concrete mass.

[c] Refers to aluminum and copper, but it is mostly aluminum due to solar photovoltaics.

[d] Refers to rectangular/flat glass only.

Table 7.3

1980 Global Material Production[a]
(Thousands of metric tons)

Raw Steel	708400
Cement	882545
Primary Aluminum	15363
Refined Copper	10300
Flat Glass	6056
Silicon[b]	< 3

[a] Production rates are listed by region in Appendix G.

[b] Semiconductor grade polysilicon produced in the world outside the centrally planned economies.

Chapter 8

INTERNATIONAL LAW AND THE CO_2-CLIMATE PROBLEM

8.1 Introduction and Discussion

Dealing with the CO_2 climate problem requires both national and global consensus. That does not mean political forcing, certainly not a priori. Things do not work that way. Building international consensus in one region, let alone globally, is an incremental activity, as the protracted negotiations on prohibiting the catching of whales, acid rain, and the Law of the Sea attest.

International laws and conventions are more subtle things than, say, national criminal law. They tend to express agreed attitudes, and the very process of working toward them - international meetings, discussion papers, debates, etc. serves to raise the consciousness of nations and people, and to create a climate of opinion and understanding. In this spirit of constructive incrementalism we write this chapter.

Among the many conclusions that flow from serious CO_2 - climate studies, two stand out as germane to starting a debate on this topic. They are robust, and represent the majority view by far:

A: The climate modelers are not wrong by such a large factor that they have been calculating effects of CO_2 buildup when in fact those effects are very much smaller. In other words, if a lot of coal is going to be burned in the next century, serious climate changes, leading to shifts in agricultural productivity, political disruptions and mass migrations will occur in due course.

B: Enough of those changes will be deleterious that there will be winners and losers, both within given countries (e.g. shifts in U.S.

> Midwest agricultural productivity, inundation of part of Florida), and internationally (shifts of monsoon rains, shifts of global agricultural productivity, etc.). Disputation among groups about these matters does not require full documentation. The perception of winning or losing will trigger the disputation. The existence of such perceptions will be enough to warrant serious international attention.

Apart from doing nothing about the problem, or just "research," which is practically the same, (a trivially inadequate repsonse) we see just three major classes of events that affect the outcome.

1. So much coal is not burned after all, for non CO_2-climate reasons. For instance, there could be greater economic attractiveness of some other energy provision strategy or of conservation, or large, non-CO_2 social costs associated with coal.

2. Developing adaptive strategies for crops, living patterns, coastal zone development, etc.

3. Attempting to make international agreements to limit coal use because of expected climate change, and/or to compensate losers and make other adjustments via international law.

A few comments about the first two options are in order, before we discuss the third, which is the main topic of this chapter. Regarding option 1, the relative prospects of coal, solar, nuclear power, and fuel efficiency were discussed in chapter 4. Those analyses explored various dimensions of the choice: technical, economic, environmental, and socio-political; we will exhume such issues here, to the extent that they bear on international conventions; the acid rain question is excellently educational, and will be a principal topic of discussion.

As for option 2, we see, as do many others, the benefits of developing plants - indeed whole biosystems, if it can be done - that are more resistant to climate fluctuations. Those involved with the managed biosphere point to great success - wheat now grown successfully in Northern Alberta for instance. Those involved with the unmanaged biosphere - foresters, for example - are less sanguine about timely benefits, pointing out that forests are pretty resiliant as it is, because they change their detailed makeup slowly as they adapt to changing conditions; furthermore, the time constants of mature forests are centuries, uncomfortably long for these CO_2-climate questions of concern today.

But other implications of option 2 seems to us less productive: for example, while it is possible technically to build dikes around the U.S. (for instance), it would not be possible to do that for many other countries around the world. Thus the rich/poor, winner/loser problems would be vastly aggravated.

Thus we come to this chapter's principal topic, international conventions, agreements, etc., but of course the three options will not be exclusive. Difficulties with one will trigger responses of the other two, and the real future will contain a mixtures of all three that changes with time, geographical location and particular details.

This essay contains material about other experiences with transboundary pollution, principally but not exclusively air pollution, from which we seek insights on what to expect in the CO_2-climate case. No substantial material in international law now deals directly with CO_2-climate. This is not surprising; laws generally are enacted in response to specific challenges to which some finding can be beneficially and constructively applied. For CO_2-climate, there are not yet any well-recognized data to cite, no states, corporations or individuals to hold accountable, nor are there likely to be any for a decade or two.

Nevertheless, some useful literature has appeared. Westview Press assembled a book of essays (Nanda 1983), and articles have appeared in many places, which will be referred to later on.

Two noble principles, and a third less-noble one, seem to guide much of both the discussion and (lack of) action. These are:

1. A principle of equitable use with respect to shared resources.

2. A principle of national responsibility for damage that a country causes to the environment of other states.

These first two principles reflect the principle of old Roman law sic utero tuo ut alienum laedas (use your property in such a way as not to injure that of another). Such views are consonant with what philosophers, naturalists and theologians have preached since ancient days about the necessity and benefits of long-term stewardship over the earth, some by pragmatic arguments, others describing Earth as a part of created order, to be loved because God made it. The messages were similar: take care or troubles will come. We admire such sentiments; they often form an almost invisible but strong foundation upon which public attitudes and laws are built. Granting all that, we are concerned here with how things are turning out in actual practice. Compliance with those two principles has been spotty, leading to the third (lack of) principle:

3. Nations will not usually respond to pleas about international air quality (or other commons) unless it is in their own national interest, and act as if they had no international obligations.

However, this third principle, depending as it does on perceptions of national interest, is susceptible to change via development of new global perceptions, and threats of economic or other retaliation. Thus arises pragmatic hope.

It is both timely and useful to review progress over the last half-century in dealing with transboundary pollution, with the object of asking whether it would be reasonable to start analyzing the relevance of present and prospective international law as it might apply to CO_2-climate. The process of legal adjustment is slow. Additionally:

1. Experience with other selected problems tells us about how long it takes to receive data affectively, as distinct from academcially.

2. We detect what appears to be a slow secular shift in national and international environmental law from simple compensation for proven damage toward anticipatory negotiations. If so, the outlook for timely attention to CO_2-climate improves.

Acid precipitation makes a case study applicable to both these points; but other transboundary pollution events also apply.

8.2 Some Early Years, 1909-1940

The earliest exhibit we present is the Boundary Waters Treaty of 1909 (BWT 1909) between the U.S. and Canada, relating mainly to the Great Lakes, but not exclusively. Although concluded and observed mainly for management and utilization, the treaty even in those days stated that the boundary waters were not to be polluted by either party to the detriment of the other (Article IV). An International Joint Commission (IJC) set up as part of the treaty has successfully bridged the gap between agreement in principle and implementation of specific actions.

Failure to keep Great Lakes pollution under control, especially in Lake Erie, led to much more detailed agreements in 1972 listing specific standards and abatement techniques. Then in 1978 a new accord included also atmospheric deposition (Great Lakes Treaty 1978).

We see in this example an early intent to anticipate future damage, and in the sequence of agreements a developing sophistication in international law that reflects the increasingly sophisticated technological and scientific "state of the art." This important point, to be reintroduced throughout this chapter, suggests that as our present climatic predictive powers increase, so will our time horizons move further ahead, perhaps even far enough to handle CO_2-climate in a timely way.

The Trail (British Columbia, Canada) Smelter case is revealing and important. That large plant, owned by Consolidated Mining and Smelting Ltd., located on the Columbia River at Trial, polluted the air of the downstream valley, damaging fruit crops miles away in Washington State. Damage occurred mainly in the 1920's, and in 1928 the U.S. referred the question to the IJC, which reported in 1931, leading to an Arbitration Tribunal in 1935, and compensatory payments in 1935 and 1938 by Canada to the U.S. In the Tribunal's final decision, we find this:

> The Tribunal therefore finds ... under the principles of international law, as well as the law of the United States, no state has the right to use or permit the use of its territory in such a manner as to cause injury by fumes in or to the territory of another or the property or persons therein, when the case is of serious consequence and the injury is established by clear and convincing evidence (Trail Smelter 1941).

The last clause and the specific payments ($350,000 and $78,000) have often been cited as supporting two narrow principles:

(a) Compensation for past damage only, with no anticipatory features;

(b) Only specific monetary considerations were allowed -- for example no account was taken of environmental or nonmarket values. The United States attempted at the time to have such considerations included, to no avail.

To be sure, such interpretations reflect prevailing attitudes of the early 1930s, a time of somewhat simple views toward science, technology, and industry.

The motto of the 1932 Chicago World's Fair, "Science discovers, technology provides, man conforms," seems to have been accepted as a matter of course at the time.

But this much-referenced Trail Smelter case has more in it. Article II of the Convention states that the Smelter will refrain from causing damage in the future, to such an extent that the Tribunal shall determine; this combined with the substantive findings of past damage, should be interpreted as a recipe for future action (Weston et al 1980).

8.3 Acid Precipitation: Establishing the Fact

Before discussing the international (or national) responses, it is necessary first to show that the problem is real and can be fairly well quantified.

As the National Resource Council points out (NRC 1983), the largest source of acid deposition in the U.S. and Canada is sulfur oxides. Figure 8.1, from that source, shows these SO_2 emissions; most of them come from burning coal. Roughly speaking, the region is bounded by Northern Alabama on the south, Southern Canada (principally the province of Ontario) on the north, a line a little west of the Mississippi River, and the Atlantic Ocean. The region is about 1500 km on a side, 2.3×10^6 km^2. In it, almost 500×10^6 tons of coal were burned per year in the late 1970's, with an average sulfur content of about 2.0%. Ore-smelting and other operations brought the total SO_2 emissions in that region close to 18 million tons. The prevailing winds blow from west to east, about 750 km per day, and on the average it rains (washing out much of what is in the atmosphere) once in five days. The rainfall is about 1 meter/year. What is the average acidity of the rain?

We need a little more information, and can afford to be carefully cavalier in deriving an approximate answer. Much of the SO_2 will be converted to SO_3

in the air, often aided by adscrption on fine particulates which make reasonably good catalytic surfaces, and by water vapor. Thus, the SO_2 tends to convert to sulfuric acid (H_2SO_4) the same way as it is made commercially; much of it combines with alkaline particulates present in the air. Assume that half the acidity so disappears. Also, the two-day travel time across the region and the five-day rain-out time imply that 60% of it drifts off the east coast (to seek a fate to be mentioned in a later section). Not all of it waits for rain, but about 30% falls out by dry deposition. This contributes substantially to acidity at ground level, and affects things on and near the ground, but we will not include this complication.

We can now proceed. The annual average sulfur production over the area is 4.0×10^{-3} kg/m^2, and 20% of it (one-half of 40%) is effectively H_2SO_4 rained out in the area itself. It is dissolved in 1 m^3 of water, doubly ionized, i.e. $H_2SO_4 \rightarrow 2H^+ + SO_4^{--}$. Thus we find a molar density $[H^+]$ of hydrogen ions in the water of 4.9×10^{-5} moles/liter. Nitrogen oxides from both vehicles and power plants add on an additional 30% approximately bringing our total now to 6.4×10^{-5} moles/liter. The conventional measure of acidity or alkalinity being the quantity

$$pH = - \log [H^+] ,$$

we finally get the answer of pH = 4.2. The pH of pure water is 7.0, and of rainwater saturated with atmospheric CO_2 is about 5.6. A pH of 4.2 corresponds to 25 times the acidity of CO_2-saturated rainwater. While we cannot expect this average number to be very accurate, derived with assumptions that are individually inaccurate by as much as a factor of two (but some of the errors tend to cancel), it should give an idea of what to expect.

Now inspect Figure 8.2, taken also from the NRC report. The range of pH values and the geographic distribution corresponds fairly well with our sample calculation. What goes up must come down. While more authoritative and better documented than before, these results are not new; nor have they been hidden from public view. In 1974, Scientific American published similar results measured by 1600 high school students through the U.S., and in 1979 published another confirmatory article.

Effects of acid deposition have been extensively documented--in particular acidifying lakes, reducing or eliminating fish populations, modifying the transformation of forest litter and of soil materials, stunting plant growth and affecting plant growth via complex nutritional pathways (Likens et al 1974, Glass et al 1976, Cowling and Lindhurst 1981, Hutchinson and Havas 1980).

Data like those illustrated here and given in more detail in the literature give rise to what is often called the Long Range Transport of Air Pollutants, the origin of the otherwise inscrutable acronym "the LRTAP problem."

8.4 Some Institutional Responses to Acid Precipitation, etc.

With this in mind, what are we to make of such articles as "Tracking the Clues to Acid Rain" in the EPRI Journal (EPRI 1979), published at the same time as the article in Scientific American; the EPRI Journal states that

> The idea has been publicized that fossil fuel combustion is the main source of the sulfates and nitrates that can produce acid rain. Acid rain has been given as the primary reason for acidification of surface waters, for decline in fish populations, and for decreasing forest productivity.
>
> The data on acid rain effects that were collected over the past two decades have validity, but the conclusions drawn from them are highly inferential. Too few avenues of the acidity network were traveled; too few scientific disciplines were included in tracking the facts.

That is, the closet the EPRI author comes to identifying any source at all for the rain. It is a mystery, the article says.

Some industry-based analyses are more direct. The journal Chemical and Engineering News published an excellent summary in 1981 (Ember 1981) disagreeing with the EPRI view, supporting the NAS position and the one offered here.

Despite statements that it is (or is not) too soon to act, the principle of anticipatory action appears to have gained considerable ground and international acceptance since the 1930's and 1940's.

The move toward anticipatory action was gaining ground during the 1960's and 1970's and a summary of most of it can be found in articles by (Whetstone 1980), (Maclure 1983) and Nanda (referenced earlier), and some of the material recorded there is used here. Dealing more specifically with water but applying in principle to the air also, the Helsinki Rules (ILA 1966)hold that states benefitting from an internationally shared resource must temper their utilization reaonably and equitably; liability can be incurred on the occasion to act reasonably, and appropriate reparations and compensation are due for physical damage.

The principal of anticipatory response received further support in 1972. Acid precipitation from England, the German Ruhr, and lately even more from East Germany and Poland falls on Scandinavia, where the lakes tend not to be buffered with limestones, hence vulnerable to acidification. As its contribution to the 1972 UN Conference on the Environment in Stockholm, the Swedish government prepared and distributed in 1970-71 its own report on the existence, effects, and sources of acid rain in Sweden (Brolin 1972). Evidence of this and other submissions led to Principle 21 of the 1972 Stockholm Declaration on the Human Environment, including the passage:

> States have, in accordance with the Charter of the United Nations and the principles of international law, the sovereign right to exploit their own resources pursuant to their own environmental policies, and the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other states or of areas beyond the limits of national jurisdiction. (UN 1972).

In addition, Principle 22 of the same declaration called for anticipatory cooperation and development of rules of liability and compensation:

> States shall cooperate to develop further the international law regarding liability and compensation for victims of pollution and other environmental damage caused by activities within the jurisdiction or control of such States to areas beyond their jurisdiction.

In 1979, the U.N. Economic Commission for Europe (ECE, an association of 35 nations including the U.S.S.R, the U.S. and Canada, not to be confused with the European Economic Commission, or "Common Market") signed a convention on Long-Range Transboundary Air Pollution (ECE 1979), those content shows both the hopes and the difficulties. It emphasizes pollution by sulfur oxides and their transformation products; the Director of the ECE's Environment and Human Settlements Division summarizes some of tis features in these words (Bishop 1980):

- The Convention is the first legal instrument which directly applies, on a broad regional basis, Principle 21 of the Declaration of the Stockholm Conference; this principle expresses the common conviction that states have, inter alia, "the responsibility to ensure that activities within their own jurisdiction or control do not cause damage to the environment of other states or of areas beyond the limit of national jurisdiction."

- Despite its title, the scope of the Convention has a somewhat broader connotation; it addresses itself throughout to problems of "Air pollution, including long-range transboundary air pollution."

- The Convention legally binds the contracting parties to "endeavor to limit and, as far as possible, gradually reduce and prevent, air pollution, including long-range transboundary air pollution."

- In this connection, each Contracting Party "undertakes to develop the best policies and strategies including air quality management systems and, as part of them, control measures compatible with balanced development, in particular by using the best available technology which is economically feasible and low- and non-waste technology."

- Pending ratification of the Convention,* the Signatory States have (through adoption of the accompanying resolution) formally taken an unusual and far-reaching decision. Specifically, they have decided to initiate, "as soon as possible and on an interim basis," the provisional implementation of the Convention and to carry out the obligations arising therefrom to the maximum extent possible, pending its entry into force. In this respect they will seek, inter alia, "to bring together their policies and strategies for combatting air pollution including long-range transboundary air pollution."

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*Twenty-three of 24 required ratifications were achieved by July 1982 (Amasa S. Bishop, private communication).

The ECE looks upon this Convention as an important advance both in the development of international law and in the development of effective institutions. The Convention, recognizing the pollution problems, describes avenues of cooperation in monitoring and research, but sets no standards, obligates no one to any abatement policy, has no mechanism for enforcement of any future regulations, and delineates no responsibility for compensation for damages. Regarding transnational claims for redress of perceived real damage, recourse can be had to the International Court of Justice (ICJ) as before.

Up to the present time, the ICJ has been permitted to rule on cases like this only after all involved nationals have consented to the action. But change is in the air; Appendix F contains a copy of a uniform ("model") law designed with this very problem in mind: once the various states have signed it, citizens or organizations of one state can press for action in another signatory state, without petitioning for permission. More on this point later.

At about the same time, U.S.-Canada bilateral discussions on acid precipitation had made progress. On the U.S. side a 1978 Congressional Resolution that the Department of State initiate negotiations toward a formal air quality agreement with Canada (C.R. 1978) led to several events. After preparatory meetings, the two governments issued a Joint Statement on Transboundary Air Quality (DOS 1979). It showed a common determination to reduce or prevent transboundary air pollution, and outlined a "substantial basis of obligation, commitment and cooperative practice in existing environmental relations."

These negotiations led to a Memorandum of Intent (Int. Env. Rep. 1980). Maclure (referenced above) summarizes the principal advances well:

> Through the MOI, the United States and Canada reiterated their "common determination to combat transboundary air pollution in keeping with their existing international rights, obligations, commitments, and cooperative

practices," specifying a number of treaties, conventions and declarations subscribed to by the two nations.

Significantly, the MOI discusses the grave -- and still growing -- ecological implications of the situation by stating the existence of a "concern about actual and potential damage resulting from transboundary air pollution ... including the already serious problem of acid rain," noting:

> Scientific findings which indicate that continued pollutant loadings will result in extensive acidification in geologically sensitive areas during the coming years, and that increased pollutant loadings will acclerate this process

and that:

> environmental stress could be increased if action is not taken to reduce transboundary air pollution.

With these concerns identified, the MOI expresses the Governments' joint intention to develop and facilitate the conclusion of a bilateral cooperative agreement on transboundary air quality. To this end, a detailed plan of interim actions is established that both aids negotiations and advances efforts at controlling current pollution. These interim actions include the creation of a Coordinating Committee to effect preparations for the conduct of negotiations, and a resolution to apply enhanced pollution control and management measures. The long-standing practice of bilateral notification and consultation on proposed industrial development and policy changes is also to be expanded, as is the exchange and coordinated development of pertinent scientific information and research.

The MOI interim actions provide for the establishment of technical and scientific Work Groups to assist the Coordinating Committee in its negotiations. The Work Groups are to function in five general areas: Impact Assessment; Atmospheric Modeling; Strategies Development and Implementation; Emissions, Costs and Engineering; and Legal, Institutional Arrangements and Drafting. The Work Groups' terms of reference provide for reports in each of their respective subject areas to serve as a basis for proposals for inclusion in a transboundary air pollution agreement. The specific tasks of the Work Groups are described in the MOI, including the mandate of the Legal, Institutional and Drafting Work Group to "develop the legal elements of an agreement such as notification and consultation, equal access, non-discrimination, liability and compensation."

The Legal, Institutional and Drafting Work Group submitted its report in the summer of 1981, presenting "an initial effort to draw together available information on international and domestic legal matters which may pertain to the negotiation of a cooperative agreement to deal with transboundary air pollution" (U.S.-Canada MOI 1981). The report's contents include a review of multilateral principles and practices, bilateral obligations and their implementation, and an overview of domestic authorities (both U.S. and Canadian) in the field of air pollution.

Maclure comments that this material has set the course toward the desired conclusion of a U.S.-Canadian air quality agreement. The Canadian Government in late 1982 and early 1983 expressed a feeling of frustration that since 1981 the U.S. had not cooperated satisfactorily (if at all), and the U.S. was suddenly demanding specific actionable evidence, as well as ecological and environmental analyses, measurements of emissions and deposition, etc. Such a U.S. attitude stands in striking contrast to the view that it tried to have adopted in the 1930's with respect to the venerable Trail Smelter case, at which time the U.S. tried to make the debate more general, in opposition to Canada's wishes. Such a switch is an example of the principle cited before, that attention to and adherence to ideas of global environmental protection change with circumstances.

Besides these notable cases, a growing literature dealing with anticipatory response to transboundary pollution is developing. (Bilder 1976) concludes that while international law does not presently (1975) impose general obligations on states to avoid disputes, in the special field of international environmental law a principle of dispute avoidance via notification and consultation appears to be developing. The Organization for Economic Cooperation and Development (OECD) in a 1975 document (OECD 1975) recommended that member states notify others of activities creating significant risk of transboundary pollution, exchange of information, scientific cooperation and joint establishment of monitoring systems, and goes on to state a Principle of Equal Right of Hearing, that citizens in one country who may be affected by the environmental impacts of proposed projects should have the same rights of standing in judicial and administrative proceedings as do citizens of the action state. The 1974 Scandinavian Convention (Scandinavian 1974) provides for abatement and compensatory relief and also gives non-citizens equal access to agencies and domestic courts.

Of course, the legal outlook is not entirely clear. The U.S. Clean Air Act does not address specifically the problem of long-range acid deposition; Section 115 allows the EPA to order special emission limitations for any pollutant if it endangers the health or welfare of a foreign country, but only if the endangered country provides a reciprocal agreement concerning emissions that might harm the United States. Apart from whether that section is invoked, the reciprocal arrangement could be used to hobble implementation: prevailing winds and rivers to not blow or flow reciprocally.

8.5 Application to CO_2-Climate

While few of the conventions, agreements, etc. so far cited deal directly with CO_2, many of them could be interpreted as not excluding it. Furthermore, we see a slow but more-or-less steady progress toward the idea of anticipatory action, and a softening of hitherto national attitudes toward sovereignty. The ECE, Scandinavian and other conventions cited earlier support that view.

Other general considerations and recent actions either support such an attitude or help to build a foundation for it. In this latter category, we note that injunctions to preclude land uses that would cause unreasonable pollution have been available in English law since the Industrial Revolution; the principle has been long accepted in the American and Canadian legal system. It formed part of the base for setting up the International Michigan-Ontario Air Pollution Board in 1976 (by the IJC).

To be sure, CO_2-climate is a heavier problem than other transboundary pollution issues. Who is the defendent: The U.S.? The U.S.S.R.? OECD? Assigning responsibility for acid rain in Scandinavia has been frustrating enough; CO_2 will be worse, perhaps impossible in any narrow sense. It is a very long-time problem, with intergenerational aspects that daunt economic discounters, as well as lawyers. It would be very hard to agree on quotas. Perhaps it would be easier to seek some sort of advance agreement that winners should compensate losers; but will the bill be paid when it comes due?

Several international organizations have paid attention to parts of this problem. One of the first to come to mind is the United Nations Environmental Program (UNEP); it has no formal mandate to develop law, but having the responsibility to implement the 1972 Stockholm resolutions, it has a <u>de facto</u> obligation to propose rules, actions, etc. In our view it would be the most logical organization to lead global CO_2 discussions, except for a proclivity for UN organizations to become paralyzed by politicization in the too-narrow sense.

Working in collaboration with UNEP but separate from the UN is the World Meteorological Offices (WMO). In 1979, the Eighth World Meteorological Congress established a climate program, stimulated primarily by acid rain, but secondarily by CO_2. While mainly attended by professional meteorologists and climatologists, it did receive some institutional recognition, and recommended introducing acid rain and CO_2 issues into international agendas. Another nongovernmental organization ("NGO"), the Scientific Committee on Problems of the Environment ("SCOPE"), founded in 1969, has a long-term global scientific program, including CO_2 effects, complementary to WMO activities. The International Institute for Applied Systems Analysis (IIASA) has also touched upon the topic.

Other regional and national activities are worth citing. In 1979, the OECD Council on Coal and the Environment recommended that member countries try to work on defining appropriate fuel uses and CO_2 emission levels, to minimize deleterious climatic change. The Economic and Social Commission for Asia and the Pacific (ESCAP) has been active on regional environmental issues. The International Law Association also comes to mind. Any or all of these organizations could play important roles; careful intellectual work needs to be done, yet publicly enough to command attention as well as respect.

Some proposed and extant laws already move us toward increased international responsibility. U.S. Congress Senate Resolution 49 in 1977 related to internationa environmental impact statements; its proposer, Senator Clayborne Pell, would have required EIS's for major national undertakings that could affect the international environment.

Most important perhaps, although not dealing with the air at all, is the Law of the Sea, because it established a principle of global managements of the global commons, contains broad proscriptions against pollution, and requires notification of plans for activities liable to pollute. It has many "requirements" rather than exhortations. Signatories can be brought before the International Court of Justice, with or without consent. Of course, the sea has many fixed resources, so many incentives exist to write laws for their use, that do not exist for the atmosphere. Nevertheless, if the attitude of the ECE or Scandinavian transboundary air pollution conventions were combined with the legal structure of the Law of the Sea, the global CO_2 problem could probably be addressed vigorously in the world's courts.

Pessimists will point out that the Law of the Sea is in trouble, and so are acid rain conventions of all kinds. That is so, but the troubles seem to us temporary rather than permanent, in the nature of growing pains rather than symptoms of terminal disease.

The question arises: is the time about right to review the situation in international law, at least to the extent of seeing how well equipped it is now (and is liable to become if the trend toward looking ahead continues) to deal with the CO_2-climate issues, if and when they arise? Several points are germane.

1. Timing of discussions should recognize response lags. A response lag of about one decade appears for simple cases (e.g. Trail Smelter) and two to three decades for complex ones (acid precipitation), from development of technically plausible data or analyses to constructive action. Global CO_2 is yet more complex -- tropical and temperate zone countries, rich and poor ones, not just relatively homogeneous OECD ones, for instance; more ambiguity about costs and benefits; consequences that come only much later in time; no group presently affected adversely.

Furthermore, when viewed at any one time, development of new perceptions about transboundary pollution seems to come very slowly, and the idea of effective anticipatory action agreements may seem as remote as January dreams of summer beaches. However, summer does come.

2. Observational data exist for acid rain, but not yet for CO_2-climate (but none are yet expected). However, increasing technological and scientific sophistication may lead to substantive information in a decade.

3. The CO_2-climate models are probably as good as, perhaps even better (for their purposes) than the regional acid rain transport models.

4. If history is any guide at all here, any long delay in amelioration will not be the result of the lack of appropriate amelioration techniques, but of waiting for favorable economic circumstances and for development of appropriate laws to apply the techniques. The record is quite clear here:

- SO_2 scrubbing techniques were developed in less than a decade; cheap coal cleaning techniques have been available for many decades.
- Toxic waste problems are mainly economic and legal, not fundmentally technical.

- Automotive emissions were reduced rapidly, auto safety systems were introduced rapidly, and more energy-frugal cars all came along in about one decade, once decisions had been made to go for them.

5. CO_2-climate and acid rain are not the only things for which we need to review the need for and status of international environmental law. Consider for example Mediterranean pollution and disposal of wastes in the ocean (to which the Law of the Sea already applies).

6. The process of amelioration, if required, will surely be long and complex, requiring the development of consensus about global commons.

From all this, we conclude that the CO_2-climate topic is ripe for preliminary exposure in international legal forums; given the trend in thinking, some state is likely to raise the issue soon anyway, particularly in terms of and in conjunction with developing non-fossil energy sources, in order to satisfy a number of other resource constraints. It is much better to be in front of the discussion than behind it.

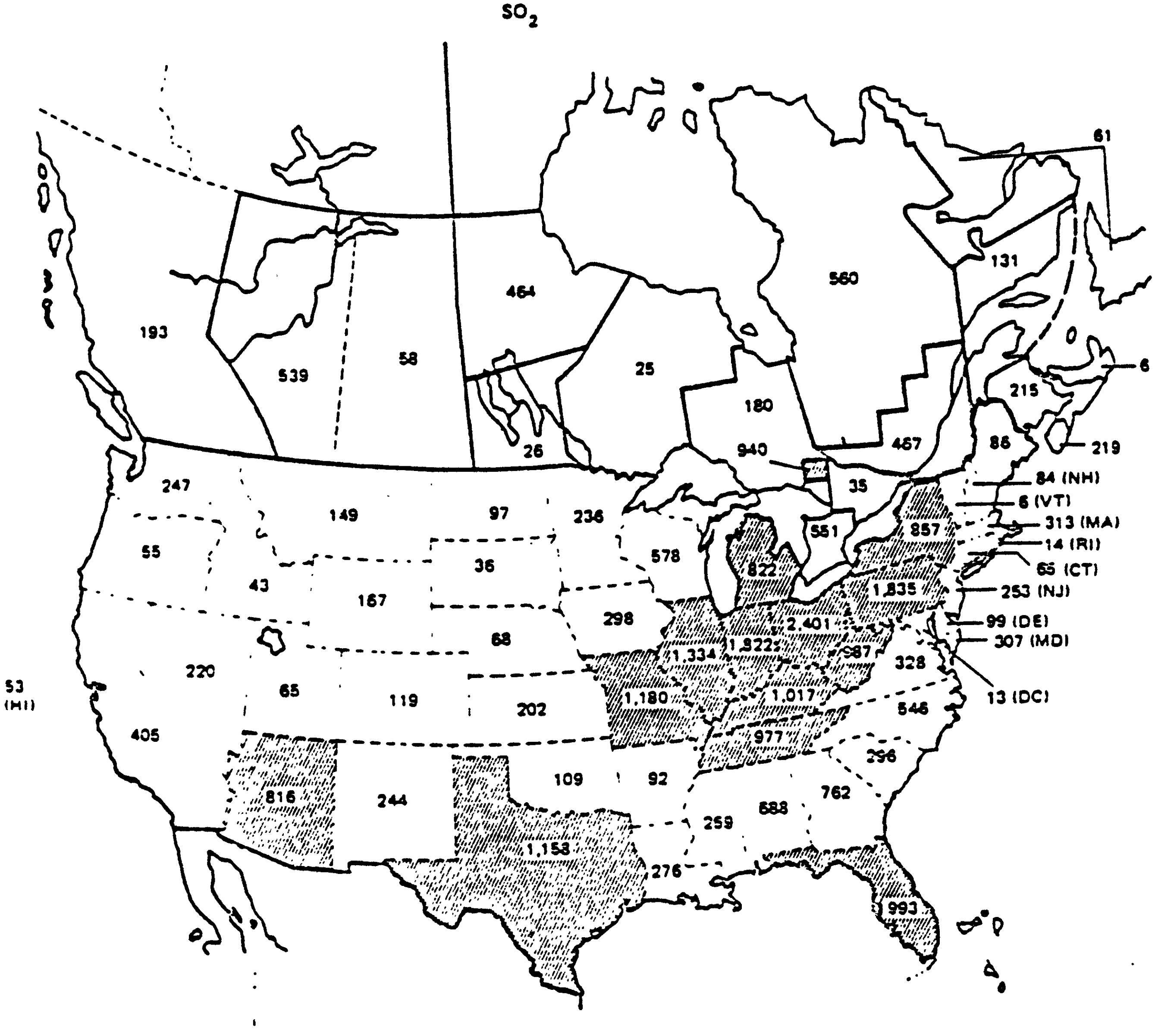

Figure 8.1 SO_2 emissions in the United States and Canada in 1980 (thousands of metric tonnes/year) From Acid Deposition: Atmospheric Processes in Eastern North America, National Academy Press, Washington DC, (1983) (their Fig. 1.2)

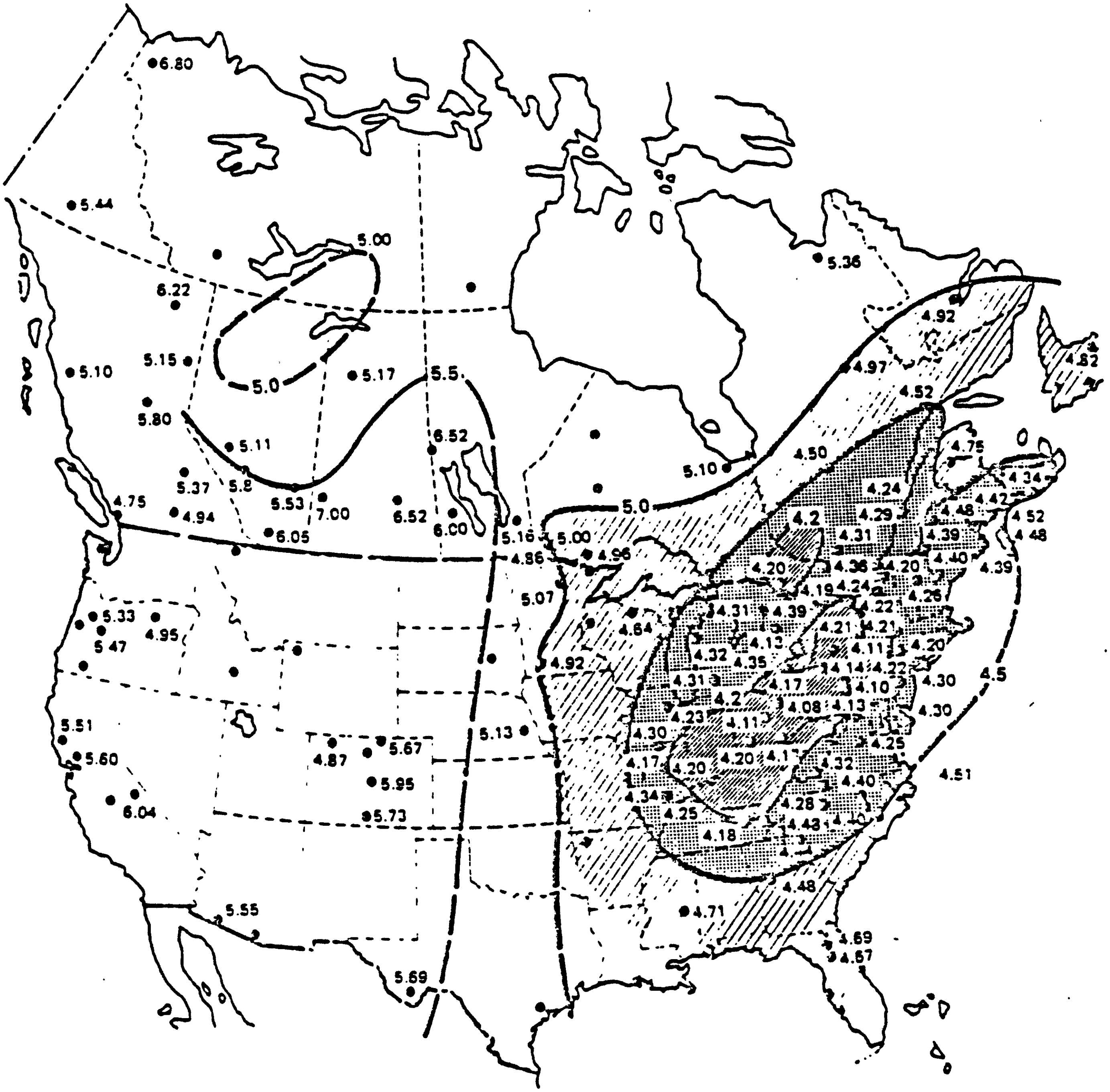

Figure 8.2 Annual mean value of pH in precipitation weighted by the amount of precipitation in the United States and Canada for 1980. From *Acid Deposition: Atmospheric Processes in Eastern North America*, National Academy Press, Washington DC, (1983) (their Fig. 1.1)

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CO_2-INDUCED CLIMATE CHANGE

APPENDICES

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APPENDIX A

LIST OF INPUTS TO THE

INSTITUTE FOR ENERGY ANALYSIS ENERGY MODEL

(THE "EDMONDS-REILLY" MODEL)

INPUT PARAMETERS

Note: l = region, I = primary energy type, M = period, R = elasticity, P = price, KK = aggregate fuel, J = secondary fuel, k = sector, Y = income.

Input	Applied to	Symbol	Comments
Price Development			
World Prices	Fossils: oil, gas coal Global	PI	One price (1975$/GJ) for each fossil fuel. It represents a global price in base year 1975.
Transportation Costs	Fossils: oil, gas, coal Global	TRI	One price (1975$/GJ) for each fossil fuel. It represents a global transportation cost in base year 1975.
Import/Export	Fossils: oil, gas, coal Each region	NXIL	This NXIL has a value of 1 or -1, where 1 indicates exporter and -1, importer.
Trade Barriers	Fossils, each period Each region	TXILM	Factor applied to fuel prices
Energy Taxes	Oil, gas, coal & electricity Each period, each region	TXJLM	Taxes on final consumption
Regions			
Actual Population	Each region, base year	ZL	Actual population (in thousands) in year 1975 of each region
Base GNP	Each region, base year	GNPBL	Gross nation product in millions of 1975 $ for year 1975.
Population	Each region, each period	ZLM	Projected populations indexed with 1975=1.00
GNP	Each region, each period	GNPPCM	Projected economic activities (GNP's) indexed with 1975=1.00 (per capita)
Refinery Parameters			
Conversion efficiency	Oil, gas, coal Global	CIJ	Ratio of Joules of primary energy in to Joules of energy product out (exclusive of fuels used as energy by the refinery
Mark-up cost	Oil, gas, coal Global	HIJ	Accounts for cost of refining and distributing energy products

Input	Applied to	Symbol	Comments
Electricity Parameters			
Generation efficiency	All fuels	GUI	Ratio of Joules of energy in to Joules of electricity out (GUI should equal 1 for nuclear, solar, and hydro)
Non-energy costs	All fuels, each region	HUIL	Reflects non-energy costs 1975$/GJ. (fixed or capital costs)
Logit substitution	Oil, gas, coal, nuclear, solar	RUI	Parameter governing conversion response of utilities to price increases of a given technology (Hydro is fixed)
Multiplicative factor	Liquids, gas, solids each region	PAUIL	Adjusts refined fossil fuel price to account for different fuel types and distribution costs.
Utility fuel share weights	Oil, gas, coal, nuclear solar. Each region, each period.	BSUILM	Ranges from 0 to 0.2.
Technological change parameter	Liquids, gases, solids, electricity. Each period. Each region.	TJKLM	Read as an index with 1975=1.0. Additive. An increasing value over time implies energy savings per unit output. The OECD regions are disaggregated into 3 sectors: residential/commercial, industrial, and transportation.
Resource Constrained Technologies (Exhaustible)			
Cumulative production	Oil and gas. Each region	AIL	Cumulative production of conventional fuels to base year 1975 (EJ).
Shape parameter	Oil and gas. Each region	BIL	Determines the shape of the logistic function.
Resources	Oil and gas. Each region	RESIL	Total conventional resource (EJ) in each region.
Gas Flaring Parameters			
Flaring fraction base year	Gas. Each region	FLRL1	Fraction of gas supply being flared in 1975. Flaring = Burning + Reinjection.
Ultimate flaring fraction	Gas. Each region	FLR2	Ultimate fraction of gas that will be flared in each region.
Years to FLR2	Gas. Each region	FLR3	Number of years to reach the ultimate flaring fraction.

Input	Applied to	Symbol	Comments
Renewable Resource Constrained Technologies			
Orientation Paramenter	Hydro. Each region	HYDRO1L	Orients production path in time of logistic function
Shape	Hydro. Each region	HYDRO2L	Determines the shape of the logistic function.
Resource	Hydro. Each region	HYDRO3L	Resource (EJ) amount available in each region.
Price	Hydro. Each region	HYDRO4L	Production price in 1975$/GJ
Electricity share	Hydro. Each region	HYDRO5L	Electricity share of hydro in each region.
Backstop Technologies Unconventional oil, unconventional gas, coal, nuclear, solar = BT			
Base breakthrough price	BT. Each region	CIL1	Price below which there is no production in 1975 ($/GJ).
Ultimate breakthrough price	BT. Each region	CIL2	Ultimate price (1975$/GJ) below which no production exists.
Years to CIL2	BT. Each region	CIL3	Number of years to reach ultimate breakthrough price.
Elasticity	Unconventionals & coal. Each region	RIL	Supply price elasticity referenced at and base quantity and reference price.
Base Quantity	Unconventionals & coal. Each region	BESILM	Amount of resource (EJ) available for production at a "normal" price.
Reference Price	Unconventionals & coal. Each region	DILSET	Price (1975$/GJ) of BESILM, but expressed as a ratio to CIL. [CIL x DILSET = "normal" price].
Synfuels (from coal)			
Conversion Efficiency	Syncrude, syngas	GCI	Ratio of primary Joules in to energy product out.
Base year add on costs	Syns. Each region	HCILT1	1975 $, mark up cost in 1975.
Ultimate add on costs	Syns. Each region	HCILT2	1975 $, ultimate mark-up cost.
Years to HCILT2	Syns. Each region	HCILT3	Number of years to reach ultimate add on costs.
Elasticity interpolation	Syns.		RCI Elasticity control parameter, allows for intermediate years.

Input	Applied to	Symbol	Comments
Energy Service Input-Output Coefficients for oil, gas, coal, electric (sectors = Res/Com, Ind, Trans for USA, WE/CAN, OECD-PAC; Aggregate for other regions.)			
Energy transformation	Each sector: Aggregate:	GJK GJ	Energy price = (GJK) x (secondary energy price) + HJK
Non-energy transformation	Each sector: Aggregate:	HJK HJ	Non-energy cost of secondary fuels
Base consumption weights	Sectors for each region	SJKP	Undimensioned. Specifies a share of service by fuel type in 1975.
Base service energy consumed	Sectors for each region	BSKL	Amount of energy used by a sector in 1975.
Scale Parameters	Sectors each period	BSJKLM	Undimensioned parameter scaling the logit function
Elasticity	Each sector, aggregate fuel type	RPKK	End-use price elasticity
	Each end use energy, each sector	RPJK	End-use substitution elasticity
	Aggregate sectors aggregate fuel	RPK	General end-use price elasticity
	Aggregate sectors each fuel	RPJ	General substitution elasticity
Income Elasticity	Each sector	RYKK	End-use income elasticity of demand
	Each sector	RYJK	End-use income substitution elasticity
	USSR and all non-OECD regions	RYKT	General end-use income elasticity
Energy-GNP		RY	Feedback elasticity on GNP

Input	Applied to	Symbol	Comments
Carbon Accounting			
C-Coefficients	Combination of oil, gas, coal, coal liquefact coal gasificashale prod. biomass	COI	Teragrams of C released per exajoule
Base flared gas burned	Each region	SBURNL1	Fraction of the flared gas which is burned (as opposed to reinjected) in 1975.
Ultimate flared gas burned	Each region	SBURNL2	Ultimate fraction of flared gas burned.
Years to SBURNL2	Each region	SBURNL3	Number of year to reach the ultimate fraction of flared gas being burned.
Shale fraction	Each region Each period		Fraction of backstop technology from shale
Feedstock fractions	Oil, gas, coal. Each region	SFEDIL	Share of each fossil fuel used as a feedstock
Biomass			
Price/share combos	Price, share, waste, energy farms	BIOPSM	Fractions of total biomass resource available at a particular price.
	Waste, energy farms. Each region	BIOLM	Max resource amounts available.

APPENDIX B

THE IEA BASE CASE
AND THE MIT/IEA VARIATIONS

```
          *****                                      *****
          *******************************************
PRICE DATA DEVELOPMENT
  FOSSIL FUELS
    WORLD PRICES (PI) AND TRANSPORT COSTS (TRI)
    (IN 1975 DOLLARS PER GJ (GIGAJOULE))
        OIL                       GAS                    COAL
     PI        TRI        PI        TRI        PI        TRI
   1.8398    0.1397     0.6256    2.8458     0.5121    0.3409


             IMPORT/EXPORT STATUS (NXIL)
   (NXIL=1 INDICATES EXPORTER; NXIL=-1, IMPORTER.)

        OIL        GAS        COAL          REGION
        -1          1           1            1 US
        -1         -1          -1            2 WEUR+CAN
        -1         -1          -1            3 JANZ
         1          1           1            4 EUSSR
        -1          1           1            5 ACENP
         1          1          -1            6 MIDEAST
         1          1          -1            7 AFR
         1          1          -1            8 LA
        -1          1          -1            9 SEASIA


TXILM -- TRADE BARRIERS  (SCALE FACTOR APPLIED TO FUEL PRICES)

  OIL --  TXILM
 1975      2000      2025      2050
 0.9800    1.0000    1.0000    1.0000    USA
 1.4800    1.4800    1.4800    1.4800    CANADA&EUR
 1.1000    1.1000    1.1000    1.1000    JANZ
 1.0000    1.0000    1.0000    1.0000    EUSSR
 1.0000    1.0000    1.0000    1.0000    ACENP
 0.1000    0.4000    0.7000    1.0000    MIDEAST
 2.1500    1.5000    1.0000    1.0000    AFR
 1.0700    1.0200    1.0000    1.0000    LA
 0.8500    1.0000    1.0000    1.0000    S&E ASIA

  GAS -- TXILM
 1975      2000      2025      2050
 1.0000    1.0000    1.0000    1.0000    USA
 1.8000    1.8000    1.4000    1.2000    CANADA&EUR
 1.8400    1.5500    1.2500    1.0000    JANZ
 1.0000    1.0000    1.0000    1.0000    EUSSR
 1.0000    1.0000    1.0000    1.0000    ACENP
 0.5000    0.7000    0.8500    1.0000    MIDEAST
 1.0000    1.0000    1.0000    1.0000    AFR
 1.0000    1.0000    1.0000    1.0000    LA
 1.0000    1.0000    1.0000    1.0000    S&E ASIA

  COAL -- TXILM
 1975      2000      2025      2050
 1.0000    1.0000    1.0000    1.0000    USA
 2.0700    2.0700    1.7500    1.5000    CANADA&EUR
 1.0000    1.0000    1.0000    1.0000    JANZ
 1.0200    1.0000    1.0000    1.0000    EUSSR
 1.0000    1.0000    1.0000    1.0000    ACENP
 1.0000    1.0000    1.0000    1.0000    MIDEAST
 1.0000    1.0000    1.0000    1.0000    AFR
```

The following is a list of all input values that were changed from the IEA Base Case. All values not listed for the cases are the same as the values in the IEA Base Case (left side of page).

There are eleven MIT/IEA cases:

A, B, C, D, E, F, H, J, K, L, M.

General references for some letters used in the variables:

I = fuel (primary, refinable)
L = region (1-9)
T = period
J = secondary fuel
M = time period
K = sector of energy consumption

Regions:

1 USA = United States
2 CAN/WE = Canada, Western Europe, and Turkey
3 JANZ = Japan, Australia, New Zealand
4 EUSSR = Soviet Union and Centrally Planned Europe
5 ACENP = Centrally Planned Asia
6 MIDEAST = Middle East
7 AFR = Africa
8 LA = Latin America
9 SEAsia = Noncommunist South, East, and Southeast Asia

```
  1.0800    1.0400    1.0000    1.0000    LA
  1.0800    1.0400    1.0000    1.0000    S&E ASIA


TXJLM -- ENERGY TAXES ON FINAL CONSUMPTION BY FUEL, REGION AND PERIOD

   OIL --  TXJLM
  1975      2000      2025      2050
  1.0000    1.0000    1.0000    1.0000    USA
  1.0000    1.0000    1.0000    1.0000    CANADA&EUR
  1.0000    1.0000    1.0000    1.0000    JANZ
  1.0000    1.0000    1.0000    1.0000    EUSSR
  1.0000    1.0000    1.0000    1.0000    ACENP
  1.0000    1.0000    1.0000    1.0000    MIDEAST
  1.0000    1.0000    1.0000    1.0000    AFR
  1.0000    1.0000    1.0000    1.0000    LA
  1.0000    1.0000    1.0000    1.0000    S&E ASIA

   GAS -- TXJLM
  1975      2000      2025      2050
  1.0000    1.0000    1.0000    1.0000    USA
  1.0000    1.0000    1.0000    1.0000    CANADA&EUR
  1.0000    1.0000    1.0000    1.0000    JANZ
  1.0000    1.0000    1.0000    1.0000    EUSSR
  1.0000    1.0000    1.0000    1.0000    ACENP
  1.0000    1.0000    1.0000    1.0000    MIDEAST
  1.0000    1.0000    1.0000    1.0000    AFR
  1.0000    1.0000    1.0000    1.0000    LA
  1.0000    1.0000    1.0000    1.0000    S&E ASIA

   COAL -- TXJLM
  1975      2000      2025      2050
  1.0000    1.0000    1.0000    1.0000    USA
  1.0000    1.0000    1.0000    1.0000    CANADA&EUR
  1.0000    1.0000    1.0000    1.0000    JANZ
  1.0000    1.0000    1.0000    1.0000    EUSSR
  1.0000    1.0000    1.0000    1.0000    ACENP
  1.0000    1.0000    1.0000    1.0000    MIDEAST
  1.0000    1.0000    1.0000    1.0000    AFR
  1.0000    1.0000    1.0000    1.0000    LA
  1.0000    1.0000    1.0000    1.0000    S&E ASIA

   ELECTRICITY -- TXJLM
  1975      2000      2025      2050
  1.0000    1.0000    1.0000    1.0000    USA
  1.0000    1.0000    1.0000    1.0000    CANADA&EUR
  1.0000    1.0000    1.0000    1.0000    JANZ
  1.0000    1.0000    1.0000    1.0000    EUSSR
  1.0000    1.0000    1.0000    1.0000    ACENP
  1.0000    1.0000    1.0000    1.0000    MIDEAST
  1.0000    1.0000    1.0000    1.0000    AFR
  1.0000    1.0000    1.0000    1.0000    LA
  1.0000    1.0000    1.0000    1.0000    S&E ASIA


 1975 ACTUAL POPULATION (ZL, THOUSANDS) AND BASE GNP (MIL 75 DOLS)

                             OECD REGIONS
     UNITED STATES            WEUR+CAN            OECD PACIFIC
  POPULATION    GNP    POPULATION    GNP    POPULATION     GNP
   213925.  1519890.    405025.  1817860.    127961.    586400.
```

TXJLM = 1.0   means no CO_2 tax.

NO CHANGES

```
        CENTRALLY PLANNED AND MIDDLE EAST REGIONS
        EUSSR                   ACENPL                  MIDEAST
    POPULATION    GNP   POPULATION     GNP   POPULATION     GNP
     394582.   966400.   910964.    323600.     81371.   138410.

                DEVELOPING COUNTRY REGIONS
        AFRICA                LATIN AMERICA     SOUTH & EAST ASIA
    POPULATION    GNP   POPULATION     GNP   POPULATION     GNP
     399370.   154690.   312631.    315490.   1129957.   233620.


 POPULATION (ZLM) AND BASE ECONOMIC ACTIVITY (GNP)
   (POPULATION AND GNP ARE READ IN AS AN INDEX, 1975=1.00)

                     OECD REGIONS
      UNITED STATES        WEUR+CAN          OECD PACIFIC
    POPULATION    GNP   POPULATION     GNP   POPULATION     GNP      YEAR
      1.0000    1.0000    1.0000    1.0000    1.0000    1.0000     1975
      1.1890    1.8770    1.1760    1.9780    1.2010    2.7010     2000
      1.3170    3.0210    1.3030    3.5340    1.2790    5.4320     2025
      1.3470    4.5050    1.3650    5.7090    1.3050    9.1210     2050

           CENTRALLY PLANNED AND MIDDLE EAST REGIONS
       EUSSR                 ACENPL                  MIDEAST
    POPULATION    GNP   POPULATION     GNP   POPULATION     GNP      YEAR
      1.0000    1.0000    1.0000    1.0000    1.0000    1.0000     1975
      1.1960    1.8150    1.3700    2.6650    1.8030    3.6490     2000
      1.3080    2.9430    1.6450    5.4680    2.4480    8.9590      2025
      1.3510    4.4420    1.7700   10.3350    2.8470   18.0440     2050

                 DEVELOPING COUNTRY REGIONS
       AFRICA          LATIN AMERICA         SOUTH & EAST ASIA
    POPULATION    GNP   POPULATION     GNP   POPULATION     GNP      YEAR
      1.0000    1.0000    1.0000    1.0000    1.0000    1.0000     1975
      1.7450    3.0690    1.7280    3.4750    1.6850    3.0790     2000
      2.3610    7.3270    2.2980    9.0050    2.2260    7.1690     2025
      2.7580   13.8060    2.6310   16.3950    2.5560   13.5020     2050


    REFINERY COEFFICIENTS (GIJ AND HIJ)
      "GIJ" IS A CONVERSION EFFICIENCY, THE RATIO OF JOULES OF PRIMARY
      ENERGY IN TO JOULES OF ENERGY PRODUCT OUT (EXCLUSIVE OF FUELS
      USED AS ENERGY BY THE REFINERY).  IT IS APPROXIMATED AS 1.
      "HIJ" IS A MARK-UP COST, ACCOUNTING FOR COST OF REFINING AND
      DISTRIBUTING ENERGY PRODUCTS.

        OIL                    GAS                    COAL
     GIJ       HIJ        GIJ       HIJ        GIJ       HIJ
      1.0000    1.4250    1.0000    0.3487    1.0000    0.2600


    ELECTRICITY GENERATION COEFFICIENTS (GUI, HUIL, AND RUI)
      "GUI" IS A GENERATION EFFICIENCY COEFFICIENT -- THE RATIO OF JOULES
      OF ENERGY IN TO JOULES OF ELECTRICITY OUT.  BY DEFINITION, GUI=1 FOR
      NUCLEAR, HYDRO, AND SOLAR.
      "HUIL" REFLECTS NONENERGY COSTS IN 1975 DOLLARS PER GJ.
      "RUI" IS A LOGIT SUBSTITUTION PARAMETER GOVERNING THE RESPONSE OF
      UTILITIES TO PRICE INCREASES FOR A GIVEN TECHNOLOGY -- HYDRO ENTERS
      AS A FIXED AMOUNT.
```

NO CHANGES

OIL	GAS	FUEL COAL	NUCLEAR	SOLAR	HYDRO	PARAMETER
3.6580	3.6580	3.3250	1.0970	1.0970	1.0970	GUI
4.5330	4.5052	6.8660	1.7000	1.7000	1.7000	HUIL L=1
4.5330	4.5052	6.8660	1.7000	1.7000	1.7000	HUIL L=2
4.5330	4.5052	6.8660	1.7000	1.7000	1.7000	HUIL L=3
4.5330	4.5052	5.8630	1.7000	1.7000	1.7000	HUIL L=4
4.5330	4.5052	5.8630	1.7000	1.7000	1.7000	HUIL L=5
4.5330	4.5052	5.8630	1.7000	1.7000	1.7000	HUIL L=6
4.5330	4.5052	5.8630	1.7000	1.7000	1.7000	HUIL L=7
4.5330	4.5052	5.8630	1.7000	1.7000	1.7000	HUIL L=8
4.5330	4.5052	5.8630	1.7000	1.7000	1.7000	HUIL L=9
-3.0000	-3.0000	-3.0000	-3.0000	-3.0000		RUI

PAUIL — ELECTRICITY GENERATION COEFFICIENTS
(PAUIL IS A MULTIPLICATIVE FACTOR WHICH ADJUSTS THE REFINED FOSSILE FUEL PRICE TO ACCOUNT FOR DIFFERENT FUEL TYPE (E.G. RESIDUAL US GASOLINE) AND DISTRIBUTION COSTS.)

LIQUID	FUEL GAS	SOLID	REGION
0.4850	0.7330	1.0000	US
0.5747	0.6195	0.8293	WEUR+CAN
0.5243	0.9595	1.0000	OECD PAC
0.4000	1.0000	1.0000	EUSSR
0.4000	1.0000	1.0000	ACENP
1.0595	1.0000	1.0000	MIDEAST
0.4185	1.0000	1.0000	AFRICA
0.4013	1.0000	1.0000	L AMER
0.6059	1.0000	1.0000	S&E ASIA

BSUILM: ELECTRIC UTILITY FUEL SHARE WEIGHTS,
BY PERIOD, FUEL AND REGION

BSUILM - share of electricity generated by fuel I in period M in region L.
Maximum value = 1/5.

OIL	GAS	1975 COAL	NUCLEAR	SOLAR	REGION
0.0915	0.0274	0.2000	0.0346	0.0253	US
0.1680	0.0694	0.2000	0.0192	0.0172	WEUR+CAN
0.1937	0.2000	0.0458	0.0082	0.0056	OECD PAC
0.1157	0.0565	0.2000	0.0060	0.0060	EUSSR
0.0547	0.0074	0.2000	0.0013	0.0011	ACENP
0.2000	0.0408	0.0	0.0001	0.0	MIDEAST
0.1851	0.0128	0.2000	0.0011	0.0009	AFRICA
0.2000	0.0453	0.0319	0.0080	0.0061	L AMER
0.1158	0.0007	0.2000	0.0039	0.0036	S&E ASIA

BSUILM: YEAR 2000

OIL	GAS	COAL	NUCLEAR	SOLAR	REGION
0.0181	0.0288	0.2000	0.0702	0.0651	US
0.1403	0.0542	0.2000	0.0718	0.0458	WEUR+CAN
0.2000	0.0667	0.1178	0.0433	0.0347	OECD PAC
0.2000	0.1359	0.2000	0.0373	0.0370	EUSSR
0.1346	0.0082	0.2000	0.0161	0.0062	ACENP
0.2000	0.1102	0.0203	0.0045	0.0045	MIDEAST
0.2000	0.0276	0.2000	0.0148	0.0134	AFRICA
0.2000	0.1174	0.0951	0.0428	0.0376	L AMER
0.1600	0.0118	0.2000	0.0291	0.0280	S&E ASIA

CASES	BSUILM YEAR 2000 Solar	Region
A, B, C, D, E, F, H, J, L, M	0.0100	ACENP

```
BSUILM:   YEAR 2025

 OIL        GAS       COAL      NUCLEAR     SOLAR    REGION
0.0850    0.1274    0.2000     0.1754     0.2000   US
0.2000    0.2000    0.2000     0.2000     0.2000   WEUR+CAN
0.2000    0.2000    0.2000     0.2000     0.2000   OECD PAC
0.2000    0.2000    0.2000     0.2000     0.2000   EUSSR
0.2000    0.1000    0.2000     0.2000     0.0353   ACENP
0.2000    0.2000    0.1000     0.2000     0.2000   MIDEAST
0.2000    0.2000    0.2000     0.2000     0.2000   AFRICA
0.2000    0.2000    0.2000     0.2000     0.2000   L AMER
0.2000    0.2000    0.2000     0.2000     0.2000   S&E ASIA


BSUILM:   YEAR 2050

 OIL        GAS       COAL      NUCLEAR     SOLAR    REGION
0.1275    0.2000    0.2000     0.2000     0.2000   US
0.2000    0.2000    0.2000     0.2000     0.2000   WEUR+CAN
0.2000    0.2000    0.2000     0.2000     0.2000   OECD PAC
0.2000    0.2000    0.2000     0.2000     0.2000   EUSSR
0.2000    0.2000    0.2000     0.2000     0.2000   ACENP
0.2000    0.2000    0.1000     0.2000     0.2000   MIDEAST
0.2000    0.2000    0.2000     0.2000     0.2000   AFR
0.2000    0.2000    0.2000     0.2000     0.2000   L AMER
0.2000    0.2000    0.2000     0.2000     0.2000   S&E ASIA

TECHNOLOGICAL CHANGE (TJKLM)
  TECHNOLOGICAL CHANGE IS READ IN AS AN INDEX WITH 1975=1.  AN
  INCREASING VALUE OVER TIME IMPLIES ENERGY SAVINGS PER UNIT OUTPUT.

                    OECD REGIONS

       UNITED STATES -- RESIDENTIAL/COMMERCIAL
 LIQUIDS    GASES     SOLIDS     ELEC      YEAR
1.0000     1.0000    1.0000    1.0000     1975
1.0000     1.0000    1.0000    1.0000     2000
1.0000     1.0000    1.0000    1.0000     2025
1.0000     1.0000    1.0000    1.0000     2050

       UNITED STATES -- INDUSTRIAL
 LIQUIDS    GASES     SOLIDS     ELEC      YEAR
1.0000     1.0000    1.0000    1.0000     1975
1.2500     1.2500    1.2500    1.2500     2000
1.5000     1.5000    1.5000    1.5000     2025
1.7500     1.7500    1.7500    1.7500     2050
```

0.01 per year

```
       UNITED STATES -- TRANSPORTATION
 LIQUIDS    GASES     SOLIDS     ELEC      YEAR
1.0000     1.0000    1.0000    1.0000     1975
1.0000     1.0000    1.0000    1.0000     2000
1.0000     1.0000    1.0000    1.0000     2025
1.0000     1.0000    1.0000    1.0000     2050


       WEUR+CAN -- RESIDENTIAL/COMMERCIAL
 LIQUIDS    GASES     SOLIDS     ELEC      YEAR
1.0000     1.0000    1.0000    1.0000     1975
1.0000     1.0000    1.0000    1.0000     2000
1.0000     1.0000    1.0000    1.0000     2025
1.0000     1.0000    1.0000    1.0000     2050
```

CASES	BSUILM YEAR 2025	
	Solar	Region
A, C, B, D, E, F, H, J, L, M	0.2000	ACENP

TJKLM - increase in efficiencies for end-use of energy J, in sector K, region L, period M.

CASES	OCED REGIONS
A, B, C, D, E, F, H,	arithmetic progression per year in all OECD Regions for all secondary fuels J

Res/Com	Trans	Ind
0.01/yr	0.01/yr	0.01/yr

WEUR+CAN — INDUSTRIAL

LIQUIDS	GASES	SOLIDS	ELEC	YEAR
1.0000	1.0000	1.0000	1.0000	1975
1.2500	1.2500	1.2500	1.2500	2000
1.5000	1.5000	1.5000	1.5000	2025
1.7500	1.7500	1.7500	1.7500	2050

WEUR+CAN — TRANSPORTATION

LIQUIDS	GASES	SOLIDS	ELEC	YEAR
1.0000	1.0000	1.0000	1.0000	1975
1.0000	1.0000	1.0000	1.0000	2000
1.0000	1.0000	1.0000	1.0000	2025
1.0000	1.0000	1.0000	1.0000	2050

OECD PAC — RESIDENTIAL/COMMERCIAL

LIQUIDS	GASES	SOLIDS	ELEC	YEAR
1.0000	1.0000	1.0000	1.0000	1975
1.0000	1.0000	1.0000	1.0000	2000
1.0000	1.0000	1.0000	1.0000	2025
1.0000	1.0000	1.0000	1.0000	2050

OECD PAC — INDUSTRIAL

LIQUIDS	GASES	SOLIDS	ELEC	YEAR
1.0000	1.0000	1.0000	1.0000	1975
1.2500	1.2500	1.2500	1.2500	2000
1.5000	1.5000	1.5000	1.5000	2025
1.7500	1.7500	1.7500	1.7500	2050

OECD PAC — TRANSPORTATION

LIQUIDS	GASES	SOLIDS	ELEC	YEAR
1.0000	1.0000	1.0000	1.0000	1975
1.0000	1.0000	1.0000	1.0000	2000
1.0000	1.0000	1.0000	1.0000	2025
1.0000	1.0000	1.0000	1.0000	2050

NON-OECD REGIONS
(NON-OECD REGIONS ARE NOT DIFFERENTIATED BY SECTOR)

EUSSR

LIQUIDS	GASES	SOLIDS	ELEC	YEAR
1.0000	1.0000	1.0000	1.0000	1975
1.1000	1.1000	1.1000	1.1000	2000
1.2000	1.2000	1.2000	1.2000	2025
1.3000	1.3000	1.3000	1.3000	2050

ACENP

LIQUIDS	GASES	SOLIDS	ELEC	YEAR
1.0000	1.0000	1.0000	1.0000	1975
1.1000	1.1000	1.1000	1.1000	2000
1.2000	1.2000	1.2000	1.2000	2025
1.3000	1.3000	1.3000	1.3000	2050

MIDEAST

LIQUIDS	GASES	SOLIDS	ELEC	YEAR
1.0000	1.0000	1.0000	1.0000	1975
1.1000	1.1000	1.1000	1.1000	2000
1.2000	1.2000	1.2000	1.2000	2025
1.3000	1.3000	1.3000	1.3000	2050

TJKLM continued

CASES

J, L, M — geometric progression (/yr) in all OECD Regions for all secondary fuels J

Res/Com	Ind	Trans
0.01 /yr	0.01 /yr	0.01 /yr

K — geometric progression (%/yr) in all OECD Regions for all secondary fuels J

Res/Com	Ind	Trans
0.0	0.01 /yr	0.0

NON-OECD REGIONS

A, C, B, D, E
F, H
} arithmetic progression per year in all Non-OECD Regions for all secondary fuels J

0.04/yr

J, L, M — geometric progression (/yr) in all Non-OECD Regions for all secondary fuels J

0.01 /yr

K — geometric progression (/yr) in all Non-OECD Regions for all secondary fuels J

0.004 /yr

```
                                     AFR
LIQUIDS        GASES       SOLIDS        ELEC          YEAR
1.0000        1.0000       1.0000       1.0000         1975
1.1000        1.1000       1.1000       1.1000         2000
1.2000        1.2000       1.2000       1.2000         2025
1.3000        1.3000       1.3000       1.3000         2050

                                     LA
LIQUIDS        GASES       SOLIDS        ELEC          YEAR
1.0000        1.0000       1.0000       1.0000         1975
1.1000        1.1000       1.1000       1.1000         2000
1.2000        1.2000       1.2000       1.2000         2025
1.3000        1.3000       1.3000       1.3000         2050

                                   SEASIA
LIQUIDS        GASES       SOLIDS        ELEC          YEAR
1.0000        1.0000       1.0000       1.0000         1975
1.1000        1.1000       1.1000       1.1000         2000
1.2000        1.2000       1.2000       1.2000         2025
1.3000        1.3000       1.3000       1.3000         2050
```

```
PARAMETER VALUES FOR RESOURCE CONSTRAINED SUPPLY TECHNOLOGIES
  EXHAUSTABLE, RESOURCE CONSTRAINED TECHNOLOGIES
    PARAMETERS ARE THOSE OF LOGISTICS FUNCTION -- "AIL" IS THE AMOUNT
    OF CUMULATIVE PRODUCTION OF CONVENTIONAL FUEL I IN REGION L TO
    THE BASE PERIOD.  "BIL" DETERMINES THE SHAPE OF THE FUNCTION AND
    "RESIL" IS THE TOTAL RESOURCE IN EXAJOULES.

                 OIL                                 GAS
  AIL           BIL       RESIL       AIL          BIL       RESIL       REGION
634.5850      0.0524 1605.5310    514.1000      0.0524 1582.5000    US
 54.5690      0.0520  988.0960     76.0960      0.0520 1087.7050    WEUR+CAN
  5.2300      0.1200   34.5110      0.0980      0.1200  158.2500    OECD PAC
303.8180      0.0600 2047.4570    148.9270      0.0600 2557.6680    EUSSR
 37.4550      0.0700  680.1270      5.2670      0.0700  403.0100    ACENP
482.6890      0.1000 3854.0520     55.7290      0.0700 2088.7840    MIDEAST
160.1910      0.0600 1687.0500     18.2840      0.0600  796.5250    AFR
258.0050      0.0600 1449.9560     66.5840      0.0600  502.0250    LA
 52.1550      0.0943  368.1190     12.2550      0.0943  374.6250    SEASIA
```

```
EXOGENOUS MIDEAST SUPPLIES OF OIL AND GAS (UNITS=EXAJOULES -- J*10**18)

  1975        2000        2025        2050        FUEL
 42.5000     37.0000     37.0000     37.0000       OIL
 10.5500     10.5500     15.0000     30.0000       GAS
```

```
 GAS FLARING
   "FLRL1" IS THE FLARING RATE IN 1975, "FLRL2" IS THE ULTIMATE
   FLARING RATE, AND "FLRL3" IS THE NUMBER OF YEARS TO REACH "FLRL2."
   THE MODEL EXPONENTIALLY INTERPOLATES BETWEEN THE RATES.

    FLRL1       FLRL2       FLRL3    REGION
    0.0550      0.0500     10.0000   US
    0.0700      0.0500     10.0000   WEUR+CAN
    0.0050      0.0100     10.0000   JANZ
    0.0490      0.0500     10.0000   EUSSR
    0.1070      0.0500     10.0000   ACENP
    0.7270      0.0500     50.0000   MIDEAST
    0.7360      0.0500     50.0000   AFR
    0.5230      0.0500     28.0000   LA
    0.3490      0.0500     15.0000   SEASIA
```

conventional oil and gas.

RESIL - the resource of conventional fuel I in region L after the year 1975 (EJ)

	Region	Oil	Gas = 1/2 (Base Case)
	USA	1106	791
	WE/CAN	513	544
	JANZ	20	79
A, C, F, H J, L, M	EUSSR	1502	1279
	ACENP	353	202
	ME	2135	1044
	AFR	702	398
	LA	702	451
	SEA	207	187
	GLOBAL	7240	4976

*In the MIT/IEA Cases BIL is specified as the year of peak production of conventional fuel I. The values in the IEA Base Case for the USA are equal to 1983.12 for oil and 1989.98 for gas.

	BIL	
	Oil	Gas
A, C, E, F H, J, L, M	1960.1	1960.0

Exogeneous Mid-East Supplies

CASES		2000	2025	2050
A, C, E, F, H, L, M	Oil	35.0	30.0	30.0
	Gas	10.6	10.0	10.0
J	Oil	37.0	0	0
	Gas	10.6	15.0	30.0

Flared gas is considered to have a portion reinject and a portion burned.

CASES	REGION	FLRL2	FLRL3
A, B, C, D, E, F, H, J, L, M	ME	same as IEA Base Case	30
	AFR		30
	LA		20

The portion burned is defined as SBURNLT on page 13.

RENEWABLE RESOURCE CONSTRAINED TECHNOLOGIES

PARAMETERS INCLUDE LOGISTICS FUNCTION PARAMETERS, COST, AND SHARE DATA. "HYDRO1L" ORIENTS THE PRODUCTION PATH IN TIME; "HYDRO2L" DETERMINES ITS SHAPE; "HYDRO3L" IS THE RESOURCE AMOUNT IN EJ; "HYDRO4L" IS PRODUCTION PRICE IN 1975 DOLLARS PER GJ; AND "HYDRO5L" IS THE ELECTRICITY SHARE OF HYDRO.

HYDRO1L	HYDRO2L	HYDRO3L	HYDRO4L	HYDRO5L	REGION
0.4204	0.0651	1.8300	4.0300	0.1530	US
0.3861	0.0720	3.5100	4.0300	0.3427	WEUR+CAN
0.2416	0.0688	0.7700	4.0300	0.2100	JANZ
-1.9979	0.0931	4.9700	4.0300	0.1159	EUSSR
-3.2069	0.0903	5.7600	4.0300	0.3467	ACENP
-3.6418	0.1549	0.6100	4.0300	0.0969	MIDEAST
-3.9701	0.0997	7.3100	4.0300	0.2872	AFR
-2.5238	0.0970	6.4800	4.0300	0.5624	LA
-2.7723	0.1006	4.1700	4.0300	0.2693	SEASIA

PARAMETER VALUES FOR BACKSTOP SUPPLY TECHNOLOGIES

UNCONVENTIONAL OIL, UNCONVENTIONAL GAS, COAL, NUCLEAR, AND SOLAR ARE DESCRIBED SIMILARLY. EACH TECHNOLOGY HAS 9 DATA ELEMENTS WHICH MUST BE READ IN FOR EACH REGION. THESE ARE: "CIL1" -- THE BASE YEAR BREAKTHROUGH PRICE; "CIL2" -- THE ULTIMATE BREAKTHOUGH PRICE; AND "CIL3" -- THE NUMBER OF YEARS TO REACH "CIL2". "RIL" -- SUPPLY PRICE ELASTICITY AT OIL AND BASE QUANTITY; "BESILM" -- BASE QUANTITY IN EACH PERIOD; "DILSET" -- REFERENCE PRICE AT BASE QUANTITY, EXPRESSED AS A RATIO TO CIL. NOTE PRICES ARE 1975$/GJ.

UNCONVENTIONAL OIL; I=1,L=1,2,...,9

CIL1	CIL2	CIL3	RIL	REGION
13.3100	3.8500	35.0000	1.1400	US
19.7000	5.7000	35.0000	1.1400	WEUR+CAN
13.3100	3.8500	35.0000	1.1400	JANZ
13.3100	3.8500	35.0000	1.1400	EUSSR
13.3100	3.8500	35.0000	1.1400	ACENP
13.3100	3.8500	35.0000	1.1400	MIDEAST
13.3100	3.8500	35.0000	1.1400	AFR
13.3100	3.8500	35.0000	1.1400	LA
13.3100	3.8500	35.0000	1.1400	SEASIA

UNCONVENTIONAL OIL; BESILM VALUES IN EJ

YEAR					REGION
1975	2000	2025	2050	DILSET	
1.0000	4.4700	25.7200	79.3100	1.3500	US
1.0000	3.0400	17.4900	47.5500	2.0000	WEUR+CAN
1.0000	1.1600	6.6800	18.1500	1.3500	OECD PAC
1.0000	3.1500	18.1300	49.2800	1.3500	EUSSR
1.0000	0.2200	2.0000	24.3600	1.3500	ACENP
1.0000	0.1100	0.3800	1.3400	1.3500	MIDEAST
1.0000	0.1100	1.0000	12.1800	1.3500	AFR
1.0000	1.6800	9.7500	39.4500	1.3500	LA
1.0000	0.1100	1.0000	12.1800	1.3500	SEASIA

include syfuels from coal or biomass.

Note that CILT x DILSET = reference price at BESILM

CIL is the price below which no production occurs

Oil CIL2 for all regions

A, C, E, F H, L, M	6.00
K	3.70
J	7.00

Oil BESILM

	2000	2025	2050	Region
A, C, E, F, H, J	10.75	32.00	85.74	US
	8.43	22.88	52.44	WE/CAN
	1.35	6.87	18.34	OECD PAC
	19.12	34.10	63.25	EUSSR
	4.42	6.20	28.56	ACENP
	7.32	7.59	8.55	ME
	22.12	23.01	34.19	AFR
	7.65	15.92	45.42	LA
	2.16	3.05	14.23	SEA
K	3.57	15.8	41.2	US
	2.57	11.4	26.6	WE/CAN
	1.13	5.0	11.8	OECD PAC
	2.65	11.7	27.5	EUSSR
	0.28	1.8	15.1	ACENP
	0.15	0.4	1.3	ME
	0.15	1.0	8.4	AFR
	1.55	7.1	72.7	LA
	0.15	1.0	8.4	SEA

	All Periods	Region
L	10.75	US
	8.43	WE/CAN
	1.35	OECD PAC
	19.12	EUSSR
	4.42	ACENP
	7.32	ME
	22.12	AFR
	7.65	LA
	2.16	SEA

M Oil BESILM is 1.0 for all periods, all regions

CIL1	CIL2	CIL3	RIL	REGION
3.7000	3.7000	1.0000	0.4700	US
3.7000	3.7000	1.0000	0.4700	WEUR+CAN
3.7000	3.7000	1.0000	0.4700	OECD PAC
3.7000	3.7000	1.0000	0.4700	EUSSR
3.7000	3.7000	1.0000	0.4700	ACENP
3.7000	3.7000	1.0000	0.4700	MIDEAST
3.7000	3.7000	1.0000	0.4700	AFR
3.7000	3.7000	1.0000	0.4700	LA
3.7000	3.7000	1.0000	0.4700	SEASIA

UNCONVENTIONAL GAS: BESILM VALUES IN EJ

YEAR 1975	2000	2025	2050	DILSET	REGION
15.0000	15.0000	15.0000	15.0000	1.7973	US
7.7000	7.7000	7.7000	7.7000	1.7973	WEUR+CAN
0.0	1.1000	1.1000	1.1000	1.7973	OECD PAC
22.3000	22.3000	22.3000	22.3000	1.7973	EUSSR
2.8500	2.8500	2.8500	2.8500	1.7973	ACENP
17.2000	17.2000	17.2000	17.2000	1.7973	MIDEAST
5.6000	5.6000	5.6000	5.6000	1.7973	AFR.
6.4000	6.4000	6.4000	6.4000	1.7973	LA
2.6000	2.6000	2.6000	2.6000	1.7973	SEASIA

COAL: CIL1, CIL2, CIL3, RIL: L=1,....,9

CIL1	CIL2	CIL3	RIL	REGION
0.2600	0.2600	1.0000	0.2000	US
0.2600	0.2600	1.0000	0.2000	WEUR+CAN
0.2600	0.2600	1.0000	0.2000	OECD PAC
0.2600	0.2600	1.0000	0.2000	EUSSR
0.2600	0.2600	1.0000	0.2000	ACENP
0.2600	0.2600	1.0000	0.2000	MIDEAST
0.2600	0.2600	1.0000	0.2000	AFR
0.2600	0.2600	1.0000	0.2000	LA
0.2600	0.2600	1.0000	0.2000	SEASIA

COAL: BESILM VALUES IN EJ

YEAR 1975	2000	2025	2050	DILSET	REGION
17.1790	32.6350	61.9960	117.7740	1.9700	US
9.6020	15.7530	25.8450	42.4010	6.8100	WEUR+CAN
2.6670	8.9910	27.0220	61.0090	3.2700	JANZ
25.7730	31.0610	53.2630	81.2380	2.0000	EUSSR
15.0070	32.0140	79.6950	169.9710	1.9700	ACENP
0.0290	0.2000	1.6500	4.5000	3.2700	MIDEAST
2.1840	11.1850	27.4550	70.6610	3.2700	AFR
0.3440	4.0350	29.8170	89.6930	3.5400	LA
2.6800	8.4910	38.8130	95.6190	3.5400	SEASIA

A, C, E, F
H, J, L, M } CIL2 = 4.50
CIL3 = 40   All Regions

Gas BESILM

Case	Region	EJ in all periods
A	US	26.0
	WE/CAN	15.0
	OECD PAC	2.0
	EUSSR	40.0
	ACENP	6.0
	ME	41.0
	AFR	11.0
	LA	12.0
	SEA	5.0

COAL

A   CIL3 = 25.0 yrs

B, C, E, F,
H, J, M } CIL2 = 1.1
CIL3 = 25 yrs   DILSET for WE/CAN = 5.0

L   CIL2 = 1.1, CIL3 = 75.0

Coal BESILM

Cases	Region	2000	2025	2050
B, C, E, F, H, J, L	US	25.00	35.00	50.00
	WE/CAN	14.00	20.00	25.00
	JANZ	6.00	10.00	20.00
	EUSSR	30.00	40.00	50.00
	ACENP	30.00	40.00	50.00
	ME	0.10	0.50	1.00
	AFR	8.00	18.00	35.00
	LA	5.00	5.00	30.00
	SEA	10.00	10.00	30.00
K	US	32.0	51.1	88.2
	WE/CAN	14.6	22.3	33.9
	JANZ	7.5	19.1	38.2
	EUSSR	30.2	47.8	68.4
	ACENP	28.6	62.0	99.0
	ME	.15	6.9	2.1
	AFR	8.75	18.8	41.9
	LA	2.8	15.3	38.9
	SEA	7.1	25.9	55.9
M	US	25.00	17.00	10.00
	WE/CAN	14.00	10.00	5.00
	JANZ	6.00	3.00	1.50
	EUSSR	30.00	25.00	12.50
	ACENP	30.00	15.00	7.50
	ME	0.10	0.10	0.10
	AFR	8.00	2.00	1.00
	LA	5.00	1.00	0.50
	SEA	10.00	3.00	1.50

```
   NUCLEAR AND SOLAR COSTS:  CIL1, CIL2, CIL3; L=1,...,9

            NUCLEAR                                   SOLAR
 CIL1        CIL2         CIL3        CIL1        CIL2         CIL3        REGION
 6.83        6.83         1.00       200.60      17.10        50.00        US
 6.83        6.83         1.00       402.40      18.00        50.00        WEUR+CAN
 6.83        6.83         1.00       281.60      15.48        50.00        OECD PAC
 6.83        6.83         1.00       402.40      21.78        50.00        EUSSR
25.80        6.83        30.00       321.40      19.80        50.00        ACENP
 7.36        6.83        70.00       128.60      17.15        50.00        MIDEAST
25.80        6.83        30.00       144.00      19.20        50.00        AFR
 7.36        6.83        30.00       321.40      19.08        50.00        LA
 7.36        6.83        30.00       200.60      19.80        50.00        SEASIA


SYNFUEL PARAMETERS
  (PARAMETERS INCLUDE A CONVERSION EFFICIENCY (GCI), AND UN
  COSTS (HCILT) AND AN ELASTICITY CONTROL PARAMETER (RCI).
  HCILT1 IS THE INITIAL VALUE, HCILT2 THE FINAL VALUE,
  AND HCILT3 THE NUMBER OF YEARS TO REACH THE FINAL VALUE.
  THE MODEL EXPONENTIALLY INTERPOLATES FOR INTERMEDIATE
  YEARS)
         SYNCRUDE                                  SYNGAS
 HCILT1      HCILT2       HCILT3      HCILT1      HCILT2       HCILT3      REGION
100.00        4.55        25.00      100.00        3.30        25.00       US
100.00        4.55        25.00      100.00        3.30        25.00       WEUR+CAN
100.00        4.55        25.00      100.00        3.30        25.00       OECD PAC
100.00        4.55        25.00      100.00        3.30        25.00       EUSSR
100.00        4.55        50.00      100.00        3.30        50.00       ACENP
100.00        4.55       100.00      100.00        3.30       100.00       MIDEAST
 12.56        4.55        25.00      100.00        3.30        25.00       AFRICA
 12.54        4.55        25.00      100.00        3.30        25.00       L AMER
100.00        4.55        50.00      100.00        3.30        50.00       SCE ASIA

  SYNCRUDE GCI =     2.13            SYNGAS GCI =     1.50
  SYNCRUDE RCI =   -6.00             SYNGAS RCI =   -6.00


                  ENERGY SERVICE INPUT-OUTPUT COEFFICIENTS

                              TABLE 1.
                  ENERGY TRANSFORMATION BY SECTOR
                              (GJK, GJ)

   OIL         GAS         COAL      ELECTRIC SECTOR     VARIABLE
 1.6700      1.5400      2.5000      0.8600   RES/CON    GJK,J=1,NJ  K=1
 1.9200      1.9000      2.0000      1.0500   INDUSTRY   GJK,J=1,NJ  K=2
 3.0000      3.0000      3.3300      1.0500   TRANSPORT  GJK,J=1,NJ  K=3
 2.0000      1.7000      2.0500      0.9500   AGGREGATE  GJ, J=1,NJ

                              TABLE 2.
                 NON-ENERGY I-O COEFFICIENTS BY SECTOR
                              (HJK, HJ)

   OIL         GAS        COAL      ELECTRIC    SECTOR     VARIABLE
 4.9800      3.2400      2.8700      3.4100    RES/CON    HJK,J=1,NJ  K=1
 0.4100      0.3200      0.8000      1.1600    INDUSTRY   HJK,J=1,NJ  K=2
98.8800    200.0000    200.0000    153.1700    TRANSPORT  HJK,J=1,NJ  K=3
 2.1000      2.0300      1.1800      1.1500    AGGREGATE  HJ, J=1,NJ
```

NUCLEAR - All Regions

Cases	CIL 2	CIL 3
A, C, F	9.0	1.0
H	100	50
J	14.85	50

SOLAR - All Regions

Cases	CIL 2	CIL 3
D, E, H, J, L, M	9.50	35
F	20	35

SYNCRUDE - All Regions

Cases	HCILT2	HCILT3
A, B, C, D, E, F, H, J, L, M	6.00	35

SYNGAS

Cases	HCILT2	HCILT3
A, B, C, D, E, F, H, J, L, M	4.50	40

All cases: GCI = 1.50

```
            BY FUEL BY SECTOR BY REGION
 SJKLP (UNITS=UNDIMENTIONED) AND BSKL (UNITS=EXAJOULES)

OIL       GAS       COAL      ELECTRIC    BSKL      SECTOR      REGION
0.1850    0.6830    0.0110    0.3790    15.2377    RES/COM     USA
0.0910    0.3450    0.1290    0.1450     9.7881    INDUSTRY    USA
1.3690    0.0       0.0       0.0010     6.6411    TRANSPORT   USA
0.3590    0.1220    0.1120    0.3720    11.1476    RES/COM     WEUR+CAN
0.2600    0.0650    0.1310    0.2120     9.4047    INDUSTRY    WEUR+CAN
1.9620    0.0       0.0030    0.0280     3.3974    TRANSPORT   WEUR+CAN
0.4430    0.0880    0.2070    0.4620     2.0876    RES/COM     OECD PAC
0.2240    0.0320    0.2670    0.2630     3.9391    INDUSTRY    OECD PAC
2.6720    0.0       0.0010    0.0500     0.8941    TRANSPORT   OECD PAC
0.2730    0.1940    0.3360    0.1970    26.3832    AGGREGATE   USSR
0.1560    0.0050    0.7640    0.0740     9.1210    AGGREGATE   CHINA
0.6870    0.2120    0.0090    0.0930     1.8153    AGGREGATE   MIDEAST
0.4370    0.0090    0.3400    0.2140     2.2834    AGGREGATE   AFRICA
0.6350    0.1480    0.0440    0.1740     5.0414    AGGREGATE   L AMER
0.5160    0.0680    0.1720    0.2440     4.2498    AGGREGATE   S&E ASIA
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          BSJKLM -- LOGIT FUNCTION SCALE PARAMETERS
                (UNITS BSJKLM=UNDIMENSIONED)
                        YEAR = 1975
 OIL        GAS        COAL      ELECTRIC   SECTOR     REGION
0.3585     0.0548     0.0008     0.5858    RES/COM    USA
0.1871     0.0124     0.0047     0.7958    INDUSTRY   USA
0.7030     0.0        0.0004     0.2966    TRANSPORT  USA
0.5492     0.0814     0.0118     0.3577    RES/COM    WEUR+CAN
0.3184     0.0831     0.0122     0.5863    INDUSTRY   WEUR+CAN
0.0736     0.0        0.5008     0.4256    TRANSPORT  WEUR+CAN
0.4533     0.0622     0.0058     0.4787    RES/COM    OECD PAC
0.1948     0.0420     0.0091     0.7541    INDUSTRY   OECD PAC
0.0299     0.0        0.5779     0.3922    TRANSPORT  OECD PAC
0.4795     0.0380     0.0339     0.4486    AGGREGATE  USSR
0.5764     0.0018     0.1465     0.2753    AGGREGATE  CHINA
0.6032     0.0451     0.0025     0.3492    AGGREGATE  MIDEAST
0.7670     0.0004     0.0213     0.2113    AGGREGATE  AFRICA
0.7910     0.0186     0.0054     0.1850    AGGREGATE  L AMER
0.5508     0.0089     0.0260     0.4143    AGGREGATE  S&E ASIA
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          BSJKLM -- LOGIT FUNCTION SCALE PARAMETERS
                (UNITS BSJKLM=UNDIMENSIONED)
                        YEAR = 2000
 OIL        GAS        COAL      ELECTRIC   SECTOR     REGION
0.2600     0.0548     0.0008     0.5858    RES/COM    USA
0.1871     0.0207     0.0047     0.7958    INDUSTRY   USA
0.7030     0.0        0.0004     0.2966    TRANSPORT  USA
0.5492     0.0814     0.0118     0.3577    RES/COM    WEUR+CAN
0.3184     0.0831     0.0122     0.5863    INDUSTRY   WEUR+CAN
0.0736     0.0        0.5008     0.4256    TRANSPORT  WEUR+CAN
0.4533     0.0622     0.0058     0.4787    RES/COM    OECD PAC
0.1948     0.0420     0.0091     0.7541    INDUSTRY   OECD PAC
0.0299     0.0        0.5779     0.3922    TRANSPORT  OECD PAC
0.4795     0.0790     0.0339     0.4486    AGGREGATE  USSR
0.5200     0.0200     0.1039     0.2753    AGGREGATE  CHINA
0.6032     0.0451     0.0025     0.3492    AGGREGATE  MIDEAST
0.6700     0.0287     0.0213     0.2800    AGGREGATE  AFRICA
0.6001     0.0423     0.0054     0.2117    AGGREGATE  L AMER
0.6500     0.0187     0.0260     0.4400    AGGREGATE  S&E ASIA
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NO CHANGES

```
            BSJKLM -- LOGIT FUNCTION SCALE PARAMETERS
                  (UNITS BSJKLM=UNDIMENSIONED)
                          YEAR = 2025
   OIL        GAS         COAL      ELECTRIC   SECTOR     REGION
 0.2600     0.0548      0.0008      0.5858   RES/COM    USA
 0.1871     0.0207      0.0047      0.7958    INDUSTRY  USA
 0.7030     0.0         0.0004      0.2966    TRANSPORT USA
 0.5492     0.0814      0.0118      0.3577   RES/COM    WEUR+CAN
 0.3184     0.0831      0.0122      0.5863    INDUSTRY  WEUR+CAN
 0.0736     0.0         0.5008      0.4256    TRANSPORT WEUR+CAN
 0.4533     0.0622      0.0058      0.4787   RES/COM    OECD PAC
 0.1948     0.0420      0.0091      0.7541    INDUSTRY  OECD PAC
 0.0299     0.0         0.5779      0.3922    TRANSPORT OECD PAC
 0.4795     0.1125      0.0198      0.4486   AGGREGATE USSR
 0.5764     0.0400      0.0706      0.2753   AGGREGATE CHINA
 0.6032     0.0451      0.0025      0.3492   AGGREGATE MIDEAST
 0.5800     0.0487      0.0213      0.3400   AGGREGATE AFRICA
 0.6001     0.0423      0.0054      0.2383   AGGREGATE L AMER
 0.4500     0.0273      0.0260      0.4500   AGGREGATE S&E ASIA
```

```
            BSJKLM -- LOGIT FUNCTION SCALE PARAMETERS
                  (UNITS BSJKLM=UNDIMENSIONED)
                          YEAR = 2050
   OIL        GAS         COAL      ELECTRIC   SECTOR     REGION
 0.2600     0.0548      0.0008      0.5858   RES/COM    USA
 0.1871     0.0207      0.0047      0.7958   INDUSTRY   USA
 0.7030     0.0         0.0004      0.2966   TRANSPORT  USA
 0.5492     0.0814      0.0118      0.3577   RES/COM    WEUR+CAN
 0.3184     0.0831      0.0122      0.5863   INDUSTRY   WEUR+CAN
 0.0736     0.0         0.5008      0.4256   TRANSPORT  WEUR+CAN
 0.4533     0.0622      0.0058      0.4787   RES/COM    OECD PAC
 0.1948     0.0420      0.0091      0.7541   INDUSTRY   OECD PAC
 0.0299     0.0         0.5779      0.3922   TRANSPORT  OECD PAC
 0.4795     0.1425      0.0128      0.4486   AGGREGATE USSR
 0.4323     0.0800      0.0347      0.2753   AGGREGATE CHINA
 0.6032     0.0451      0.0025      0.3492   AGGREGATE MIDEAST
 0.4800     0.0787      0.0213      0.4000   AGGREGATE AFRICA
 0.6001     0.0423      0.0054      0.2650   AGGREGATE L AMER
 0.3900     0.0374      0.0260      0.4600   AGGREGATE S&E ASIA

PRICE ELASTICITY CONTROL PARAMETERS

   AGG          OIL         GAS        COAL       ELECTRIC  SECTOR
   RPKK                          RPJK
   -1.3000    -3.0000    -3.0000    -3.0000    -3.0000 RES/COM    RPKK,JK,K=1
   -0.9000    -3.0000    -3.0000    -3.0000    -3.0000 INDUSTRY   RPKK,JK,K=2
   -5.5000   -13.0000   -13.0000   -13.0000   -13.0000 TRANSPORT  RPKK,JK,K=3

   RPK                           RPJ
   -1.0000    -2.5000    -2.5000    -2.5000    -2.5000 AGGREGATE. RPK,RPJ
```

NO CHANGES

```
    INCOME ELASTICITY CONTROL PARAMETERS
AGG        OIL        GAS        COAL       ELECTRIC  SECTOR
RYKK                       RYJK
 1.0000    -0.1000    0.3000    -0.2000     0.1000 RES/COM    RYKK,JK,K=1
 0.0        0.0       0.1000    -0.3000     0.3000 INDUSTRY   RYKK,JK,K=2
 1.0000     0.0       0.0        0.0        0.0    TRANSPORT  RYKK,JK,K=3

RYK                        RYJ
 0.2500    -0.1000    0.1000    -0.2000     0.1000 AG(AC'S) RYK,J,NT=1
 0.4000                                            AG(LDC'S)RYK,J,NT=2

    ENERGY-GNP FEEDBACK ELASTICITY

-0.0500  RY
```

In all cases RYK (income elasticity for Regions 4-9) was changed to RYKLT. This change allows this elasticity to be applied to region L (L=1 is USSR, L=2 is LDC's) and T = 1 for ultimate elasticity and T = 3 for the number of years to T = 2. In all cases, this parameter equals zero at 75 years after 1975.

RYJ – general income substitution elasticity for fuel

RY – higher energy prices cause a depresstion of GNP

RY = -0.10 in all cases

```
 COI -- CARBON RELEASE BY SOURCE
 (IN TERAGRAMS OF CARBON PER EXAJOULE)

   OIL        GAS        COAL    COAL LIQ-  COAL GAS-  SHALE OIL
  BURNUP     BURNUP     BURNUP  UIFACTION  IFICATION  PRODUCTION   BIOMASS
  19.70      13.80      23.90     18.90      26.90      27.90        0.0
```

```
PROPORTION OF FLARED GAS BURNED (SBURNLT T=1 IS INITIAL
  (1975) SHARE, T=2 IS ULTIMATE SHARE, T=3 IS NUMBER OF YEARS
  TO SBURNL2.  PROPORTION OF BACKSTOP FUEL FROM CARBONATE ROCK
  (SHALET, T=1,2,3) HAS IDENTICAL INTERPRETATION.
SBURNL1  SBURNL2   SBURNL3    SHALE1    SHALE2    SHALE3    REGION
  0.13      0.13      1.00      0.01      0.59     70.00    US
  0.47      0.15     25.00      0.01      0.45     70.00    WEUR+CAN
  1.00      0.15     35.00      0.01      0.59     70.00    OECD PAC
  1.00      0.15     35.00      0.01      0.90     70.00    EUSSR
  1.00      0.15     35.00      0.01      0.25     70.00    ACENP
  0.90      0.15     35.00      0.01      0.25     70.00    MIDEAST
  0.90      0.15     35.00      0.01      0.25     70.00    AFRICA
  0.35      0.15     25.00      0.01      0.25     70.00    L AMER
  0.85      0.15     35.00      0.01      0.25     70.00    SCE ASIA
```

CASES	Region	SBURNL3
A, B, C, D, E	US	1.0
F, H, J, L, M	Others	15.0

```
FEEDSTOCK USES OF FOSSIL FUELS (SFEDIL) -- SHARE OF EACH
  FOSSIL FUEL USED AS A FEEDSTOCK.

  OIL        GAS        COAL      REGION
  0.0450     0.0290     0.0070    US
  0.0720     0.0290     0.0070    WEUR+CAN
  0.0920     0.0290     0.0070    OECD PAC
  0.0910     0.0290     0.0070    EUSSR
  0.0700     0.0290     0.0070    ACENP
  0.1410     0.0290     0.0070    MIDEAST
  0.0300     0.0290     0.0070    AFRICA
  0.0680     0.0290     0.0070    L AMER
  0.0820     0.0290     0.0070    SCE ASIA
```

```
BIOMASS COEFFICIENTS:  THE SUPPLY FUNCTION FOR BIOMASS
INCLUDES WASTE AND "ENERGY FARMS" AS SEPARATE TECHNOLOGIES.
THE CODED FUNCTIONS ARE REPRESENTED BY LINEAR SEGMENTS.
THE JPARAMETERS ARE CRITICAL POINTS FOR THE FUNCTION AND
REGIONAL RESOURCES.  BIOPSM ARE CRITICAL PRICE/SHARE
COMBINATIONS.  BIOLM ARE MAXIMUM RESOURCE AMOUNTS -- WASTE
IS DEPENDENT ON ECONOMIC ACTIVITY.  THE WASTE TOTAL IS
BASED ON 1975 ECONOMIC ACTIVITY (PRICE--1975 $/GJ, QUANTITY--EJ)

 WASTE (BIOPSM)  ENERGY FARMS (BIOPSM)
 PRICE      SHARE      PRICE     SHARE
0.4000     0.1000     0.0       0.0
1.6000     0.3000     2.1000    0.0
4.6000     0.8000     2.6000    0.2000
5.6000     0.8000     4.6000    0.8000

WASTE    ENERGY FARMS
(BIOLM)    (BIOLM)        REGION
   5.48      82.29        US
   7.95       0.0         WEUR+CAN
   2.71      13.19        OECD PAC
   8.73      98.43        EUSSR
   7.04       0.0         ACENP
   1.00       0.0         MIDEAST
   5.71     173.44        AFRICA
   7.81     225.45        L AMER
  10.40       0.0         SEE ASIA
```

BIOMASS

	Waste		Energy Farms	
	Price	Share	Price	Share
A, C, E, F, H, J, L, M	0.0	1.0	0.0	0.0
	0.0	1.0	3.0	0.5
	0.0	1.0	5.0	1.0
	0.0	1.0	5.0	1.0

BIOLM

Wasted	Energy Farms
2.89	10.0
4.20	5.0
1.43	0.0
4.61	10.0
3.72	0.0
0.52	0.0
3.02	20.0
4.15	20.0
5.50	20.0
30.0	85.0

APPENDIX C

THE ELEVEN MIT/IEA ENERGY SCENARIOS, INPUTS

<u>Note</u>: Pages are numbered consecutively at the top of each page; originally assigned case numbers are retained at the bottom, to aid recognition.

Case A Inputs

RYJK - Non OECD income elasticity.
Region 4 (SU/EE) = 1.00
Regions 5-9 (LDC's) = 1.40

RY - Feedback elasticity of energy prices on GNP.
RY = -0.10

GCI - Input-output coefficient of coal into primary equivalent.
GCI = 1.50

TJKLM - Technological change parameter for end-use of energy.

Arithmetic progression

OECD Regions			Non-OECD Regions
Res/Com	Ind	Tran	
0.01	0.01	0.01	0.004

BSUILM - Share of electricity generated by fuel I in period M, region L

For solar in Region 5 (ACENP) in year 2000 = 0.0100
For solar in Region 5 (ACENP) in year 2025 = 0.2000

RESIL - Total resource of conventional fuels in region L after 1975 (EJ)

Region	Oil	Gas
USA	1106	791
WE/CAN	513	544
JANZ	20	79
SU/EE	1502	1279
ACENP	353	202
ME	2135	1044
AFR	702	398
LA	702	451
SEA	207	187
GLOBAL	7240	4976

BIL - Year of peak production of conventional fuel in region L.

	Oil	Gas
Region 1 (USA)	1960.1	1960.0

EASTIM - Exogenous supplies of conventional oil and gas in the Middle East.

	2000	2025	2050
Oil	35.0	30.0	30.0
Gas	10.6	10.0	10.0

FLRL3 - The number of years to reach the ultimate flaring rate FLRL2. Note that flared gas consists of two portions: reinjected and burned.

Region	FLRL3
ME	30
AFR	30
LA	20

SBURNL3 - The number of years to reach the ultimate fraction of flared gas which is burned.

Region	SBURNL3
USA	1.0
Others	15.0

CIL2 - The ultimate breakthrough price of fuel I in region L.

CIL3 - The number of years to reach CIL2.

The following values are for all regions.

	CIL2	CIL3	
Unconventional Oil	6.00	35	(CIL3=Base Case)
Unconventional Gas	4.50	40	
Coal	0.26	25	(CIL2=Base Case)
Nuclear	9.00	1.0	

BESILM - Base quantity of unconstrained fuel I in region L, period M. (EJ)

Unconventional Oil

Region	2000	2025	2050
USA	10.75	32.00	85.74
WE/CAN	8.43	22.88	52.44
JANZ	1.35	6.87	18.34
SU/EE	19.12	34.10	65.25
ACENP	4.42	6.20	28.56
ME	7.32	7.59	8.55
AFR	22.12	23.01	34.19
LA	7.65	15.92	45.42
SEA	2.16	3.05	14.23

Unconventional Gas

Region	All Periods
USA	26.0
WE/CAN	15.0
JANZ	2.0
SU/EE	40.0
ACENP	6.0
ME	41.0
AFR	11.0
LA	12.0
SEA	5.0

HCILT2 - The ultimate conversion add-on cost for synfuels ($/GJ).
HCILT3 - The number of years to reach HCILT2.

Synoil in all regions:
HCILT2 = 6.00
HCILT3 = 35

Syngas in all regions:
HCILT2 = 4.50
HCILT3 = 40

BIOPSM - Biomass supply schedule parameters. Price/share combinations for waste and energy farms. (Price=$/GJ)

Waste		Energy Farms	
Price	Share	Price	Share
0.0	1.0	0.0	0.0
0.0	1.0	3.0	0.5
0.0	1.0	5.0	1.0
0.0	1.0	5.0	1.0

BIOLM - Maximum biomass resource available in region L.

Region	Waste	Energy Farms
USA	2.89	10.0
WE/CAN	4.20	5.0
JANZ	1.43	0.0
SU/EE	4.61	10.0
ACENP	3.72	0.0
ME	0.52	0.0
AFR	3.02	20.0
LA	4.15	20.0
SEA	5.50	20.0
GLOBAL	30.04	85.0

Case B Inputs

RYJK - Non OECD income elasticity.
Region 4 (SU/EE) = 1.00
Regions 5-9 (LDC's) = 1.40

RY - Feedback elasticity of energy prices on GNP.
RY = -0.10

GCI - Input-output coefficient of coal into primary equivalent.
GCI = 1.50

TJKLM - Technological change parameter for end-use of energy.

Arithmetic progression

OECD Regions			Non-OECD Regions
Res/Com	Ind	Tran	
0.01	0.01	0.01	0.004

BSUILM - Share of electricity generated by fuel I in period M, region L

For solar in Region 5 (ACENP) in year 2000 = 0.0100
For solar in Region 5 (ACENP) in year 2025 = 0.2000

FLRL3 - The number of years to reach the ultimate flaring rate FLRL2. Note that flared gas consists of two portions: reinjected and burned.

Region	FLRL3
ME	30
AFR	30
LA	20

SBURNL3 - The number of years to reach the ultimate fraction of flared gas which is burned.

Region	SBURNL3
USA	1.0
Others	15.0

CIL2 - The ultimate breakthrough price of fuel I in region L.

CIL3 - The number of years to reach CIL2.

The following values are for all regions.

	CIL2	CIL3
Coal	1.10	25

DILSET - Scale factor applied to the breakthrough price of unconstrained fossil fuels in each region.

DILSET for WE/CAN = 5.0 (Other regions remain as in the Base Case)

BESILM - Base quantity of unconstrained fuel I in region L, period M. (EJ)

Coal

Region	2000	2025	2050
USA	25.00	35.00	50.00
WE/CAN	14.00	20.00	25.00
JANZ	6.00	10.00	20.00
SU/EE	30.00	40.00	50.00
ACENP	30.00	40.00	50.00
ME	0.10	0.50	1.00
AFR	8.00	18.00	35.00
LA	5.00	5.00	30.00
SEA	10.00	10.00	30.00

HCILT2 - The ultimate conversion add-on cost for synfuels ($/GJ).

HCILT3 - The number of years to reach HCILT2.

Synoil in all regions:
HCILT2 = 6.00
HCILT3 = 35

Syngas in all regions:
HCILT2 = 4.50
HCILT3 = 40

BIOPSM - Biomass supply schedule parameters. Price/share combinations for waste and energy farms. (Price=$/GJ)

Waste		Energy Farms	
Price	Share	Price	Share
0.0	1.0	0.0	0.0
0.0	1.0	3.0	0.5
0.0	1.0	5.0	1.0
0.0	1.0	5.0	1.0

BIOLM - Maximum biomass resource available in region L.

Region	Waste	Energy Farms
USA	2.89	10.0
WE/CAN	4.20	5.0
JANZ	1.43	0.0
SU/EE	4.61	10.0
ACENP	3.72	0.0
ME	0.52	0.0
AFR	3.02	20.0
LA	4.15	20.0
SEA	5.50	20.0
GLOBAL	30.04	85.0

Case C Inputs

RYJK - Non OECD income elasticity.
Region 4 (SU/EE) = 1.00
Regions 5-9 (LDC's) = 1.40

RY - Feedback elasticity of energy prices on GNP.
RY = -0.10

GCI - Input-output coefficient of coal into primary equivalent.
GCI = 1.50

TJKLM - Technological change parameter for end-use of energy.

Arithmetic progression

OECD Regions			Non-OECD Regions
Res/Com	Ind	Tran	
0.01	0.01	0.01	0.004

BSUILM - Share of electricity generated by fuel I in period M, region L

For solar in Region 5 (ACENP) in year 2000 = 0.0100
For solar in Region 5 (ACENP) in year 2025 = 0.2000

RESIL - Total resource of conventional fuels in region L after 1975 (EJ)

Region	Oil	Gas
USA	1106	791
WE/CAN	513	544
JANZ	20	79
SU/EE	1502	1279
ACENP	353	202
ME	2135	1044
AFR	702	398
LA	702	451
SEA	207	187
GLOBAL	7240	4976

BIL - Year of peak production of conventional fuel in region L.

	Oil	Gas
Region 1 (USA)	1960.1	1960.0

EASTIM - Exogenous supplies of conventional oil and gas in the Middle East.

	2000	2025	2050
Oil	35.0	30.0	30.0
Gas	10.6	10.0	10.0

FLRL3 - The number of years to reach the ultimate flaring rate FLRL2. Note that flared gas consists of two portions: reinjected and burned.

Region	FLRL3
ME	30
AFR	30
LA	20

SBURNL3 - The number of years to reach the ultimate fraction of flared gas which is burned.

Region	SBURNL3
USA	1.0
Others	15.0

CIL2 - The ultimate breakthrough price of fuel I in region L.

CIL3 - The number of years to reach CIL2.

The following values are for all regions.

	CIL2	CIL3	
Unconventional Oil	6.00	35	(CIL3=Base Case)
Unconventional Gas	4.50	40	
Coal	1.10	25	
Nuclear	9.00	1.0	

DILSET - Scale factor applied to the breakthrough price of unconstrained fossil fuels in each region.

DILSET for WE/CAN = 5.0 (Other regions remain as in the Base Case)

BESILM - Base quantity of unconstrained fuel I in region L, period M. (EJ)

Unconventional Oil

Region	2000	2025	2050
USA	10.75	32.00	85.74
WE/CAN	8.43	22.88	52.44
JANZ	1.35	6.87	18.34
SU/EE	19.12	34.10	65.25
ACENP	4.42	6.20	28.56
ME	7.32	7.59	8.55
AFR	22.12	23.01	34.19
LA	7.65	15.92	45.42
SEA	2.16	3.05	14.23

Coal

Region	2000	2025	2050
USA	25.00	35.00	50.00
WE/CAN	14.00	20.00	25.00
JANZ	6.00	10.00	20.00
SU/EE	30.00	40.00	50.00
ACENP	30.00	40.00	50.00
ME	0.10	0.50	1.00
AFR	8.00	18.00	35.00
LA	5.00	5.00	30.00
SEA	10.00	10.00	30.00

HCILT2 - The ultimate conversion add-on cost for synfuels ($/GJ).
HCILT3 - The number of years to reach HCILT2.

Synoil in all regions:
HCILT2 = 6.00
HCILT3 = 35

Syngas in all regions:
HCILT2 = 4.50
HCILT3 = 40

BIOPSM - Biomass supply schedule parameters. Price/share combinations for waste and energy farms. (Price=$/GJ)

Waste		Energy Farms	
Price	Share	Price	Share
0.0	1.0	0.0	0.0
0.0	1.0	3.0	0.5
0.0	1.0	5.0	1.0
0.0	1.0	5.0	1.0

BIOLM - Maximum biomass resource available in region L.

Region	Waste	Energy Farms
USA	2.89	10.0
WE/CAN	4.20	5.0
JANZ	1.43	0.0
SU/EE	4.61	10.0
ACENP	3.72	0.0
ME	0.52	0.0
AFR	3.02	20.0
LA	4.15	20.0
SEA	5.50	20.0
GLOBAL	30.04	85.0

Case D Inputs

RYJK - Non OECD income elasticity.
Region 4 (SU/EE) = 1.00
Regions 5-9 (LDC's) = 1.40

RY - Feedback elasticity of energy prices on GNP.
RY = -0.10

GCI - Input-output coefficient of coal into primary equivalent.
GCI = 1.50

TJKLM - Technological change parameter for end-use of energy.

Arithmetic progression

OECD Regions			Non-OECD Regions
Res/Com	Ind	Tran	
0.01	0.01	0.01	0.004

BSUILM - Share of electricity generated by fuel I in period M, region L

For solar in Region 5 (ACENP) in year 2000 = 0.0100
For solar in Region 5 (ACENP) in year 2025 = 0.2000

FLRL3 - The number of years to reach the ultimate flaring rate FLRL2. Note that flared gas consists of two portions: reinjected and burned.

Region	FLRL3
ME	30
AFR	30
LA	20

SBURNL3 - The number of years to reach the ultimate fraction of flared gas which is burned.

Region	SBURNL3
USA	1.0
Others	15.0

CIL2 - The ultimate breakthrough price of fuel I in region L.

CIL3 - The number of years to reach CIL2.

The following values are for all regions.

	CIL2	CIL3
Solar	9.50	35

HCILT2 - The ultimate conversion add-on cost for synfuels ($/GJ).

HCILT3 - The number of years to reach HCILT2.

Synoil in all regions:
HCILT2 = 6.00
HCILT3 = 35

Syngas in all regions:
HCILT2 = 4.50
HCILT3 = 40

BIOPSM - Biomass supply schedule parameters. Price/share combinations for waste and energy farms. (Price=$/GJ)

Waste		Energy Farms	
Price	Share	Price	Share
0.0	1.0	0.0	0.0
0.0	1.0	3.0	0.5
0.0	1.0	5.0	1.0
0.0	1.0	5.0	1.0

BIOLM - Maximum biomass resource available in region L.

Region	Waste	Energy Farms
USA	2.89	10.0
WE/CAN	4.20	5.0
JANZ	1.43	0.0
SU/EE	4.61	10.0
ACENP	3.72	0.0
ME	0.52	0.0
AFR	3.02	20.0
LA	4.15	20.0
SEA	5.50	20.0
GLOBAL	30.04	85.0

Case E Inputs

RYJK - Non OECD income elasticity.
Region 4 (SU/EE) = 1.00
Regions 5-9 (LDC's) = 1.40

RY - Feedback elasticity of energy prices on GNP.
RY = -0.10

GCI - Input-output coefficient of coal into primary equivalent.
GCI = 1.50

TJKLM - Technological change parameter for end-use of energy.

Arithmetic progression

OECD Regions			Non-OECD Regions
Res/Com	Ind	Tran	
0.01	0.01	0.01	0.004

BSUILM - Share of electricity generated by fuel I in period M, region L

For solar in Region 5 (ACENP) in year 2000 = 0.0100
For solar in Region 5 (ACENP) in year 2025 = 0.2000

RESIL - Total resource of conventional fuels in region L after 1975 (EJ)

Region	Oil	Gas
USA	1106	791
WE/CAN	513	544
JANZ	20	79
SU/EE	1502	1279
ACENP	353	202
ME	2135	1044
AFR	702	398
LA	702	451
SEA	207	187
GLOBAL	7240	4976

BIL - Year of peak production of conventional fuel in region L.

	Oil	Gas
Region 1 (USA)	1960.1	1960.0

EASTIM - Exogenous supplies of conventional oil and gas in the Middle East.

	2000	2025	2050
Oil	35.0	30.0	30.0
Gas	10.6	10.0	10.0

FLRL3 - The number of years to reach the ultimate flaring rate FLRL2. Note that flared gas consists of two portions: reinjected and burned.

Region	FLRL3
ME	30
AFR	30
LA	20

SBURNL3 - The number of years to reach the ultimate fraction of flared gas which is burned.

Region	SBURNL3
USA	1.0
Others	15.0

CIL2 - The ultimate breakthrough price of fuel I in region L.

CIL3 - The number of years to reach CIL2.

The following values are for all regions.

	CIL2	CIL3	
Unconventional Oil	6.00	35	(CIL3=Base Case)
Unconventional Gas	4.50	40	
Coal	1.10	25	
Solar	9.50	35	

DILSET - Scale factor applied to the breakthrough price of unconstrained fossil fuels in each region.

DILSET for WE/CAN = 5.0 (Other regions remain as in the Base Case)

BESILM - Base quantity of unconstrained fuel I in region L, period M. (EJ)

Unconventional Oil

Region	2000	2025	2050
USA	10.75	32.00	85.74
WE/CAN	8.43	22.88	52.44
JANZ	1.35	6.87	18.34
SU/EE	19.12	34.10	65.25
ACENP	4.42	6.20	28.56
ME	7.32	7.59	8.55
AFR	22.12	23.01	34.19
LA	7.65	15.92	45.42
SEA	2.16	3.05	14.23

Coal

Region	2000	2025	2050
USA	25.00	35.00	50.00
WE/CAN	14.00	20.00	25.00
JANZ	6.00	10.00	20.00
SU/EE	30.00	40.00	50.00
ACENP	30.00	40.00	50.00
ME	0.10	0.50	1.00
AFR	8.00	18.00	35.00
LA	5.00	5.00	30.00
SEA	10.00	10.00	30.00

HCILT2 - The ultimate conversion add-on cost for synfuels ($/GJ).
HCILT3 - The number of years to reach HCILT2.

Synoil in all regions:
HCILT2 = 6.00
HCILT3 = 35

Syngas in all regions:
HCILT2 = 4.50
HCILT3 = 40

BIOPSM - Biomass supply schedule parameters. Price/share combinations for waste and energy farms. (Price=$/GJ)

Waste		Energy Farms	
Price	Share	Price	Share
0.0	1.0	0.0	0.0
0.0	1.0	3.0	0.5
0.0	1.0	5.0	1.0
0.0	1.0	5.0	1.0

BIOLM - Maximum biomass resource available in region L.

Region	Waste	Energy Farms
USA	2.89	10.0
WE/CAN	4.20	5.0
JANZ	1.43	0.0
SU/EE	4.61	10.0
ACENP	3.72	0.0
ME	0.52	0.0
AFR	3.02	20.0
LA	4.15	20.0
SEA	5.50	20.0
GLOBAL	30.04	85.0

Case F Inputs

RYJK - Non OECD income elasticity.
Region 4 (SU/EE) = 1.00
Regions 5-9 (LDC's) = 1.40

RY - Feedback elasticity of energy prices on GNP.
RY = -0.10

GCI - Input-output coefficient of coal into primary equivalent.
GCI = 1.50

TJKLM - Technological change parameter for end-use of energy.

Arithmetic progression

OECD Regions			Non-OECD Regions
Res/Com	Ind	Tran	
0.01	0.01	0.01	0.004

BSUILM - Share of electricity generated by fuel I in period M, region L

For solar in Region 5 (ACENP) in year 2000 = 0.0100
For solar in Region 5 (ACENP) in year 2025 = 0.2000

RESIL - Total resource of conventional fuels in region L after 1975 (EJ)

Region	Oil	Gas
USA	1106	791
WE/CAN	513	544
JANZ	20	79
SU/EE	1502	1279
ACENP	353	202
ME	2135	1044
AFR	702	398
LA	702	451
SEA	207	187
GLOBAL	7240	4976

BIL - Year of peak production of conventional fuel in region L.

	Oil	Gas
Region 1 (USA)	1960.1	1960.0

EASTIM - Exogenous supplies of conventional oil and gas in the Middle East.

	2000	2025	2050
Oil	35.0	30.0	30.0
Gas	10.6	10.0	10.0

FLRL3 - The number of years to reach the ultimate flaring rate FLRL2. Note that flared gas consists of two portions: reinjected and burned.

Region	FLRL3
ME	30
AFR	30
LA	20

SBURNL3 - The number of years to reach the ultimate fraction of flared gas which is burned.

Region	SBURNL3
USA	1.0
Others	15.0

CIL2 - The ultimate breakthrough price of fuel I in region L.

CIL3 - The number of years to reach CIL2.

The following values are for all regions.

	CIL2	CIL3	
Unconventional Oil	6.00	35	(CIL3=Base Case)
Unconventional Gas	4.50	40	
Coal	1.10	25	
Nuclear	9.00	1.0	
Solar	20.00	35	

DILSET - Scale factor applied to the breakthrough price of unconstrained fossil fuels in each region.

DILSET for WE/CAN = 5.0 (Other regions remain as in the Base Case)

BESILM - Base quantity of unconstrained fuel I in region L, period M. (EJ)

Unconventional Oil

Region	2000	2025	2050
USA	10.75	32.00	85.74
WE/CAN	8.43	22.88	52.44
JANZ	1.35	6.87	18.34
SU/EE	19.12	34.10	65.25
ACENP	4.42	6.20	28.56
ME	7.32	7.59	8.55
AFR	22.12	23.01	34.19
LA	7.65	15.92	45.42
SEA	2.16	3.05	14.23

Coal

Region	2000	2025	2050
USA	25.00	35.00	50.00
WE/CAN	14.00	20.00	25.00
JANZ	6.00	10.00	20.00
SU/EE	30.00	40.00	50.00
ACENP	30.00	40.00	50.00
ME	0.10	0.50	1.00
AFR	8.00	18.00	35.00
LA	5.00	5.00	30.00
SEA	10.00	10.00	30.00

HCILT2 - The ultimate conversion add-on cost for synfuels ($/GJ).
HCILT3 - The number of years to reach HCILT2.

Synoil in all regions:
HCILT2 = 6.00
HCILT3 = 35

Syngas in all regions:
HCILT2 = 4.50
HCILT3 = 40

BIOPSM - Biomass supply schedule parameters. Price/share combinations for waste and energy farms. (Price=$/GJ)

Waste		Energy Farms	
Price	Share	Price	Share
0.0	1.0	0.0	0.0
0.0	1.0	3.0	0.5
0.0	1.0	5.0	1.0
0.0	1.0	5.0	1.0

BIOLM - Maximum biomass resource available in region L.

Region	Waste	Energy Farms
USA	2.89	10.0
WE/CAN	4.20	5.0
JANZ	1.43	0.0
SU/EE	4.61	10.0
ACENP	3.72	0.0
ME	0.52	0.0
AFR	3.02	20.0
LA	4.15	20.0
SEA	5.50	20.0
GLOBAL	30.04	85.0

Case H Inputs

RYJK - Non OECD income elasticity.
Region 4 (SU/EE) = 1.00
Regions 5-9 (LDC's) = 1.40

RY - Feedback elasticity of energy prices on GNP.
RY = -0.10

GCI - Input-output coefficient of coal into primary equivalent.
GCI = 1.50

TJKLM - Technological change parameter for end-use of energy.

Arithmetic progression

OECD Regions			Non-OECD Regions
Res/Com	Ind	Tran	
0.01	0.01	0.01	0.004

BSUILM - Share of electricity generated by fuel I in period M, region L

For solar in Region 5 (ACENP) in year 2000 = 0.0100
For solar in Region 5 (ACENP) in year 2025 = 0.2000

RESIL - Total resource of conventional fuels in region L after 1975 (EJ)

Region	Oil	Gas
USA	1106	731
WE/CAN	513	544
JANZ	20	79
SU/EE	1502	1279
ACENP	353	202
ME	2135	1044
AFR	702	398
LA	702	451
SEA	207	187
GLOBAL	7240	4976

BIL - Year of peak production of conventional fuel in region L.

	Oil	Gas
Region 1 (USA)	1960.1	1960.0

EASTIM - Exogenous supplies of conventional oil and gas in the Middle East.

	2000	2025	2050
Oil	35.0	30.0	30.0
Gas	10.6	10.0	10.0

FLRL3 - The number of years to reach the ultimate flaring rate FLRL2. Note that flared gas consists of two portions: reinjected and burned.

Region	FLRL3
ME	30
AFR	30
LA	20

SBURNL3 - The number of years to reach the ultimate fraction of flared gas which is burned.

Region	SBURNL3
USA	1.0
Others	15.0

CIL2 - The ultimate breakthrough price of fuel I in region L.

CIL3 - The number of years to reach CIL2.

The following values are for all regions.

	CIL2	CIL3	
Unconventional Oil	6.00	35	(CIL3=Base Case)
Unconventional Gas	4.50	40	
Coal	1.10	25	
Nuclear	100.00	50	
Solar	9.50	35	

DILSET - Scale factor applied to the breakthrough price of unconstrained fossil fuels in each region.

DILSET for WE/CAN = 5.0 (Other regions remain as in the Base Case)

BESILM - Base quantity of unconstrained fuel I in region L, period M. (EJ)

Unconventional Oil

Region	2000	2025	2050
USA	10.75	32.00	85.74
WE/CAN	8.43	22.88	52.44
JANZ	1.35	6.87	18.34
SU/EE	19.12	34.10	65.25
ACENP	4.42	6.20	28.56
ME	7.32	7.59	8.55
AFR	22.12	23.01	34.19
LA	7.65	15.92	45.42
SEA	2.16	3.05	14.23

Coal

Region	2000	2025	2050
USA	25.00	35.00	50.00
WE/CAN	14.00	20.00	25.00
JANZ	6.00	10.00	20.00
SU/EE	30.00	40.00	50.00
ACENP	30.00	40.00	50.00
ME	0.10	0.50	1.00
AFR	8.00	18.00	35.00
LA	5.00	5.00	30.00
SEA	10.00	10.00	30.00

HCILT2 - The ultimate conversion add-on cost for synfuels ($/GJ).
HCILT3 - The number of years to reach HCILT2.

Synoil in all regions:
HCILT2 = 6.00
HCILT3 = 35

Syngas in all regions:
HCILT2 = 4.50
HCILT3 = 40

BIOPSM - Biomass supply schedule parameters. Price/share combinations for waste and energy farms. (Price=$/GJ)

Waste		Energy Farms	
Price	Share	Price	Share
0.0	1.0	0.0	0.0
0.0	1.0	3.0	0.5
0.0	1.0	5.0	1.0
0.0	1.0	5.0	1.0

BIOLM - Maximum biomass resource available in region L.

Region	Waste	Energy Farms
USA	2.89	10.0
WE/CAN	4.20	5.0
JANZ	1.43	0.0
SU/EE	4.61	10.0
ACENP	3.72	0.0
ME	0.52	0.0
AFR	3.02	20.0
LA	4.15	20.0
SEA	5.50	20.0
GLOBAL	30.04	85.0

Case J Inputs

RYJK - Non OECD income elasticity.
Region 4 (SU/EE) = 1.00
Regions 5-9 (LDC's) = 1.40

RY - Feedback elasticity of energy prices on GNP.
RY = -0.10

GCI - Input-output coefficient of coal into primary equivalent.
GCI = 1.50

TJKLM - Technological change parameter for end-use of energy.

Geometric progression

OECD Regions			Non-OECD Regions
Res/Com	Ind	Tran	
0.01	0.01	0.01	0.01

BSUILM - Share of electricity generated by fuel I in period M, region L

For solar in Region 5 (ACENP) in year 2000 = 0.0100
For solar in Region 5 (ACENP) in year 2025 = 0.2000

RESIL - Total resource of conventional fuels in region L after 1975 (EJ)

Region	Oil	Gas
USA	1106	791
WE/CAN	513	544
JANZ	20	79
SU/EE	1502	1279
ACENP	353	202
ME	2135	1044
AFR	702	398
LA	702	451
SEA	207	187
GLOBAL	7240	4976

BIL - Year of peak production of conventional fuel in region L.

	Oil	Gas
Region 1 (USA)	1960.1	1960.0

EASTIM - Exogenous supplies of conventional oil and gas in the Middle East.

	2000	2025	2050
Oil	37.0	0.0	0.0
Gas	10.6	10.0	10.0

FLRL3 - The number of years to reach the ultimate flaring rate FLRL2. Note that flared gas consists of two portions: reinjected and burned.

Region	FLRL3
ME	30
AFR	30
LA	20

SBURNL3 - The number of years to reach the ultimate fraction of flared gas which is burned.

Region	SBURNL3
USA	1.0
Others	15.0

CIL2 - The ultimate breakthrough price of fuel I in region L.

CIL3 - The number of years to reach CIL2.

The following values are for all regions.

	CIL2	CIL3	
Unconventional Oil	7.00	35	(CIL3=Base Case)
Unconventional Gas	4.50	40	
Coal	1.10	25	
Solar	9500	35	

DILSET - Scale factor applied to the breakthrough price of unconstrained fossil fuels in each region.

DILSET for WE/CAN = 5.0 (Other regions remain as in the Base Case)

BESILM - Base quantity of unconstrained fuel I in region L, period M. (EJ)

Unconventional Oil

Region	2000	2025	2050
USA	10.75	32.00	85.74
WE/CAN	8.43	22.88	52.44
JANZ	1.35	6.87	18.34
SU/EE	19.12	34.10	65.25
ACENP	4.42	6.20	28.56
ME	7.32	7.59	8.55
AFR	22.12	23.01	34.19
LA	7.65	15.92	45.42
SEA	2.16	3.05	14.23

Coal

Region	2000	2025	2050
USA	25.00	35.00	50.00
WE/CAN	14.00	20.00	25.00
JANZ	6.00	10.00	20.00
SU/EE	30.00	40.00	50.00
ACENP	30.00	40.00	50.00
ME	0.10	0.50	1.00
AFR	8.00	18.00	35.00
LA	5.00	5.00	30.00
SEA	10.00	10.00	30.00

HCILT2 - The ultimate conversion add-on cost for synfuels ($/GJ).
HCILT3 - The number of years to reach HCILT2.

Synoil in all regions:
HCILT2 = 6.00
HCILT3 = 35

Syngas in all regions:
HCILT2 = 4.50
HCILT3 = 40

BIOPSM - Biomass supply schedule parameters. Price/share combinations for waste and energy farms. (Price=$/GJ)

Waste		Energy Farms	
Price	Share	Price	Share
0.0	1.0	0.0	0.0
0.0	1.0	3.0	0.5
0.0	1.0	5.0	1.0
0.0	1.0	5.0	1.0

BIOLM - Maximum biomass resource available in region L.

Region	Waste	Energy Farms
USA	2.89	10.0
WE/CAN	4.20	5.0
JANZ	1.43	0.0
SU/EE	4.61	10.0
ACENP	3.72	0.0
ME	0.52	0.0
AFR	3.02	20.0
LA	4.15	20.0
SEA	5.50	20.0
GLOBAL	30.04	85.0

Case K Inputs

RYJK - Non OECD income elasticity.
Region 4 (SU/EE) = 1.00
Regions 5-9 (LDC's) = 1.40

RY - Feedback elasticity of energy prices on GNP.
RY = -0.10

GCI - Input-output coefficient of coal into primary equivalent.
GCI = 1.50

TJKLM - Technological change parameter for end-use of energy.

Geometric progression

OECD Regions			Non-OECD Regions
Res/Com	Ind	Tran	
0.0	0.01	0.0	0.004

CIL2 - The ultimate breakthrough price of fuel I in region L.
CIL3 - The number of years to reach CIL2.

The following values are for all regions.

	CIL2	CIL3
Nuclear	14.85	50

BESILM - Base quantity of unconstrained fuel I in region L, period M. (EJ)

Unconventional Oil

Region	2000	2025	2050
USA	3.57	15.8	41.2
WE/CAN	2.57	11.4	26.6
JANZ	1.13	5.0	11.8
SU/EE	2.65	11.7	27.5
ACENP	0.28	1.8	15.1
ME	0.15	0.4	1.3
AFR	0.15	1.0	8.4
LA	1.55	7.1	22.7
SEA	0.15	1.0	8.4

BESILM continued

Coal

Region	2000	2025	2050
USA	32.00	51.10	88.20
WE/CAN	14.60	22.30	33.90
JANZ	7.50	19.10	38.20
SU/EE	30.20	47.80	68.40
ACENP	28.60	62.00	94.00
ME	0.15	0.90	2.10
AFR	8.75	18.80	41.90
LA	2.80	15.30	38.90
SEA	7.10	25.90	55.90

Case L Inputs

RYJK - Non OECD income elasticity.
Region 4 (SU/EE) = 1.00
Regions 5-9 (LDC's) = 1.40

RY - Feedback elasticity of energy prices on GNP.
RY = -0.10

GCI - Input-output coefficient of coal into primary equivalent.
GCI = 1.50

TJKLM - Technological change parameter for end-use of energy.

Geometric progression

OECD Regions			Non-OECD Regions
Res/Com	Ind	Tran	
0.01	0.01	0.01	0.01

BSUILM - Share of electricity generated by fuel I in period M, region L

For solar in Region 5 (ACENP) in year 2000 = 0.0100
For solar in Region 5 (ACENP) in year 2025 = 0.2000

RESIL - Total resource of conventional fuels in region L after 1975 (EJ)

Region	Oil	Gas
USA	1106	791
WE/CAN	513	544
JANZ	20	79
SU/EE	1502	1279
ACENP	353	202
ME	2135	1044
AFR	702	398
LA	702	451
SEA	207	187
GLOBAL	7240	4976

BIL - Year of peak production of conventional fuel in region L.

	Oil	Gas
Region 1 (USA)	1960.1	1960.0

EASTIM - Exogenous supplies of conventional oil and gas in the Middle East.

	2000	2025	2050
Oil	35.0	30.0	30.0
Gas	10.6	10.0	10.0

FLRL3 - The number of years to reach the ultimate flaring rate FLRL2. Note that flared gas consists of two portions: reinjected and burned.

Region	FLRL3
ME	30
AFR	30
LA	20

SBURNL3 - The number of years to reach the ultimate fraction of flared gas which is burned.

Region	SBURNL3
USA	1.0
Others	15.0

CIL2 - The ultimate breakthrough price of fuel I in region L.

CIL3 - The number of years to reach CIL2.

The following values are for all regions.

	CIL2	CIL3	
Unconventional Oil	6.00	35	(CIL3=Base Case)
Unconventional Gas	4.50	40	
Coal	1.10	75	
Solar	9500	35	

DILSET - Scale factor applied to the breakthrough price of unconstrained fossil fuels in each region.

DILSET for WE/CAN = 5.0 (Other regions remain as in the Base Case)

BESILM - Base quantity of unconstrained fuel I in region L, period M. (EJ)

Unconventional Oil

Region	All periods
USA	10.75
WE/CAN	8.43
JANZ	1.35
SU/EE	19.12
ACENP	4.42
ME	7.32
AFR	22.12
LA	7.65
SEA	2.16

Coal

Region	2000	2025	2050
USA	25.00	35.00	50.00
WE/CAN	14.00	20.00	25.00
JANZ	6.00	10.00	20.00
SU/EE	30.00	40.00	50.00
ACENP	30.00	40.00	50.00
ME	0.10	0.50	1.00
AFR	8.00	18.00	35.00
LA	5.00	5.00	30.00
SEA	10.00	10.00	30.00

HCILT2 - The ultimate conversion add-on cost for synfuels ($/GJ).
HCILT3 - The number of years to reach HCILT2.

Synoil in all regions:
HCILT2 = 6.00
HCILT3 = 35

Syngas in all regions:
HCILT2 = 4.50
HCILT3 = 40

BIOPSM - Biomass supply schedule parameters. Price/share combinations for waste and energy farms. (Price=$/GJ)

Waste		Energy Farms	
Price	Share	Price	Share
0.0	1.0	0.0	0.0
0.0	1.0	3.0	0.5
0.0	1.0	5.0	1.0
0.0	1.0	5.0	1.0

BIOLM - Maximum biomass resource available in region L.

Region	Waste	Energy Farms
USA	2.89	10.0
WE/CAN	4.20	5.0
JANZ	1.43	0.0
SU/EE	4.61	10.0
ACENP	3.72	0.0
ME	0.52	0.0
AFR	3.02	20.0
LA	4.15	20.0
SEA	5.50	20.0
GLOBAL	30.04	85.0

Case M Inputs

RYJK - Non OECD income elasticity.
Region 4 (SU/EE) = 1.00
Regions 5-9 (LDC's) = 1.40

RY - Feedback elasticity of energy prices on GNP.
RY = -0.10

GCI - Input-output coefficient of coal into primary equivalent.
GCI = 1.50

TJKLM - Technological change parameter for end-use of energy.

Geometric progression

OECD Regions			Non-OECD Regions
Res/Com	Ind	Tran	
0.01	0.01	0.01	0.01

BSUILM - Share of electricity generated by fuel I in period M, region L

For solar in Region 5 (ACENP) in year 2000 = 0.0100
For solar in Region 5 (ACENP) in year 2025 = 0.2000

RESIL - Total resource of conventional fuels in region L after 1975 (EJ)

Region	Oil	Gas
USA	1106	791
WE/CAN	513	544
JANZ	20	79
SU/EE	1502	1279
ACENP	353	202
ME	2135	1044
AFR	702	398
LA	702	451
SEA	207	187
GLOBAL	7240	4976

BIL - Year of peak production of conventional fuel in region L.

	Oil	Gas
Region 1 (USA)	1960.1	1960.0

EASTIM - Exogenous supplies of conventional oil and gas in the Middle East.

	2000	2025	2050
Oil	37.0	0.0	0.0
Gas	10.6	10.0	10.0

FLRL3 - The number of years to reach the ultimate flaring rate FLRL2. Note that flared gas consists of two portions: reinjected and burned.

Region	FLRL3
ME	30
AFR	30
LA	20

SBURNL3 - The number of years to reach the ultimate fraction of flared gas which is burned.

Region	SBURNL3
USA	1.0
Others	15.0

CIL2 - The ultimate breakthrough price of fuel I in region L.

CIL3 - The number of years to reach CIL2.

The following values are for all regions.

	CIL2	CIL3	
Unconventional Oil	6.00	35	(CIL3=Base Case)
Unconventional Gas	4.50	40	
Coal	1.10	25	
Solar	9.50	35	

DILSET - Scale factor applied to the breakthrough price of unconstrained fossil fuels in each region.

DILSET for WE/CAN = 5.0 (Other regions remain as in the Base Case)

BESILM - Base quantity of unconstrained fuel I in region L, period M. (EJ)

Unconventional Oil

For all periods in all regions = 1.0

Coal

Region	2000	2025	2050
USA	25.00	17.00	10.00
WE/CAN	14.00	10.00	5.00
JANZ	6.00	3.00	1.50
SU/EE	30.00	25.00	12.50
ACENP	30.00	15.00	7.50
ME	0.10	0.10	0.10
AFR	8.00	2.00	1.00
LA	5.00	1.00	0.50
SEA	10.00	3.00	1.50

HCILT2 - The ultimate conversion add-on cost for synfuels ($/GJ).

HCILT3 - The number of years to reach HCILT2.

Synoil in all regions:

HCILT2 = 6.00
HCILT3 = 35

Syngas in all regions:

HCILT2 = 4.50
HCILT3 = 40

BIOPSM - Biomass supply schedule parameters. Price/share combinations for waste and energy farms. (Price=$/GJ)

Waste		Energy Farms	
Price	Share	Price	Share
0.0	1.0	0.0	0.0
0.0	1.0	3.0	0.5
0.0	1.0	5.0	1.0
0.0	1.0	5.0	1.0

BIOLM - Maximum biomass resource available in region L.

Region	Waste	Energy Farms
USA	2.89	10.0
WE/CAN	4.20	5.0
JANZ	1.43	0.0
SU/EE	4.61	10.0
ACENP	3.72	0.0
ME	0.52	0.0
AFR	3.02	20.0
LA	4.15	20.0
SEA	5.50	20.0
GLOBAL	30.04	85.0

APPENDIX D

GLOBAL PRIMARY ENERGY CONSUMPTIONS IN THE MIT/IEA SCENARIOS, AND SPECIFIED CARBON EMISSIONS IN SELECTED CASES. DATA FROM COLOMBO AND BERNARDINI, LOVINS, AND IIASA SHOWN FOR COMPARISON.

GLOBAL PRIMARY ENERGY CONSUMPTION (EJ/yr = Q/yr = 0.031 TW)
AND AVERAGE ANNUAL RATES (EJ/yr per year)
BY ENERGY SOURCE FOR CASES: A, B, C

Source	Year	CASE A					
	1975	Rate Between	2000	Rate Between	2025	Rate Between	2050
Oil	122.6	-1.82	77.1	-0.01	76.9	-0.02	76.3
Gas	48.3	-0.07	46.5	0.20	51.6	-0.35	42.8
Coal	72.3	4.19	177.1	3.76	271.1	4.92	394.1
Synfuel	0.0	0.22	5.5	3.15	84.3	4.59	199.1
Nuclear	3.8	0.63	19.5	1.50	57.1	1.54	95.6
Solar	0.0	0.00	.1	0.38	9.6	0.22	15.1
Hydro	16.0	2.25	56.3	1.39	91.1	1.08	118.2
Total	263.0	5.40	382.1	10.38	641.7	11.98	941.2

Source	Year	CASE B					
	1975	Rate Between	2000	Rate Between	2025	Rate Between	2050
Oil	122.6	1.24	153.6	0.72	171.5	2.84	242.5
Gas	48.3	1.46	84.9	1.09	112.1	0.10	114.5
Coal	72.3	1.02	97.8	1.25	129.1	2.07	180.8
Synfuel	0.0	0.00	.1	0.21	5.3	0.40	15.2
Nuclear	3.8	1.27	35.6	3.80	130.7	4.22	236.1
Solar	0.0	0.00	.1	0.43	10.9	0.30	18.5
Hydro	16.0	2.31	57.7	1.42	93.3	1.10	120.9
Total	253.0	7.31	429.8	8.92	652.9	11.02	928.5

Source	Year	CASE C					
	1975	Rate Between	2000	Rate Between	2025	Rate Between	2050
Oil	122.6	-1.41	87.3	0.56	101.3	1.65	142.5
Gas	48.3	-0.13	45.1	0.27	51.8	0.82	72.3
Coal	72.3	2.14	125.9	0.77	145.2	2.16	199.2
Synfuel	0.0	0.10	2.6	1.67	44.3	1.16	73.4
Nuclear	3.8	0.99	28.6	2.63	94.4	2.56	158.5
Solar	0.0	0.00	.1	0.63	15.8	0.36	24.9
Hydro	16.0	2.27	56.7	1.43	92.4	1.10	119.8
Total	263.0	3.97	346.3	7.96	545.2	9.82	790.6

GLOBAL PRIMARY ENERGY CONSUMPTION (EJ/yr = Q/yr = 0.031 TW)
AND AVERAGE ANNUAL RATES (EJ/yr per year)
BY ENERGY SOURCE FOR CASES: D,E,F

Source	Year	CASE D					
	1975	Rate Between	2000	Rate Between	2025	Rate Between	2050
Oil	122.6	1.24	153.6	-0.46	142.2	2.00	192.2
Gas	48.3	1.42	83.9	1.00	108.9	-0.84	87.9
Coal	72.3	3.15	151.1	4.02	251.6	5.05	377.9
Synfuel	0.0	0.00	.1	0.66	16.6	1.65	57.9
Nuclear	3.8	0.88	25.8	1.87	72.5	2.41	132.7
Solar	0.0	0.03	.7	1.28	32.7	1.01	57.9
Hydro	16.0	2.29	57.3	1.36	91.4	1.10	118.9
Total	263.0	9.02	472.5	9.74	715.9	12.38	1025.4

Source	Year	CASE E					
	1975	Rate Between	2000	Rate Between	2025	Rate Between	2050
Oil	122.6	-1.52	84.7	0.07	86.5	1.29	118.7
Gas	48.3	-0.15	44.5	0.26	51.1	0.51	63.9
Coal	72.3	2.00	122.3	0.25	128.5	1.62	168.9
Synfuel	0.0	0.13	3.3	1.44	39.2	1.00	64.1
Nuclear	3.8	1.78	48.2	3.28	130.1	3.46	216.7
Solar	0.0	0.05	1.2	2.29	58.4	1.44	94.5
Hydro	16.0	2.27	56.7	1.96	105.6	0.56	119.5
Total	263.0	4.56	360.9	9.54	599.4	9.88	846.3

Source	Year	CASE F					
	1975	Rate Between	2000	Rate Between	2025	Rate Between	2050
Oil	122.6	-1.42	87.2	0.58	101.7	1.66	143.2
Gas	48.3	-0.13	45.1	0.27	51.9	0.83	72.6
Coal	72.3	2.14	125.7	0.81	145.9	2.17	200.2
Synfuel	0.0	0.10	2.6	1.67	44.3	1.17	73.6
Nuclear	3.8	0.98	28.3	2.74	96.8	2.60	161.9
Solar	0.0	0.01	.3	0.46	11.7	0.29	18.9
Hydro	16.0	2.27	56.7	1.43	92.4	1.10	119.8
Total	263.0	3.96	345.9	7.95	544.7	9.82	790.2

GLOBAL PRIMARY ENERGY CONSUMPTION (EJ/yr = Q/yr = 0.031 TW)
AND AVERAGE ANNUAL RATES (EJ/yr per year)
BY ENERGY SOURCE FOR CASES: H, J, K

CASE H

Source	Year 1975	Rate Between	2000	Rate Between	2025	Rate Between	2050
Oil	122.6	-1.33	89.3	0.63	105.1	1.76	149.2
Gas	48.3	-0.11	45.5	0.26	51.9	0.89	74.2
Coal	72.3	2.47	134.1	0.62	149.5	2.34	208.1
Synfuel	0.0	0.12	3.1	1.67	44.9	1.17	74.1
Nuclear	3.8	-0.08	1.9	-0.07	.2	0.00	.2
Solar	0.0	0.07	1.8	3.92	99.7	2.55	163.4
Hydro	16.0	2.27	56.7	1.44	92.6	1.09	119.9
Total	263.0	3.42	332.4	8.46	543.9	9.81	789.1

CASE J

Source	Year 1975	Rate Between	2000	Rate Between	2025	Rate Between	2050
Oil	122.6	-1.74	79.1	-1.18	49.5	-0.82	29.1
Gas	48.3	-0.18	43.7	0.38	53.3	0.20	58.3
Coal	72.3	1.49	109.5	-0.31	101.7	0.42	112.1
Synfuel	0.0	0.09	2.2	1.62	42.8	1.54	81.4
Nuclear	3.8	1.61	44.1	2.01	94.3	1.44	130.4
Solar	0.0	0.04	1.1	1.66	42.6	0.57	56.8
Hydro	16.0	2.26	56.6	1.36	90.7	0.40	100.8
Total	263.0	3.57	336.3	5.54	474.9	3.76	568.9

CASE K

Source	Year 1975	Rate Between	2000	Rate Between	2025	Rate Between	2050
Oil	122.6	1.24	153.6	-2.52	90.6	-1.79	45.8
Gas	48.3	1.36	82.2	1.26	113.6	0.22	119.2
Coal	72.3	3.01	147.6	1.87	194.3	2.30	251.8
Synfuel	0.0	0.25	6.3	4.14	109.8	7.14	288.4
Nuclear	3.8	0.62	19.3	0.97	43.5	0.18	47.9
Solar	0.0	0.00	.1	0.57	14.3	0.60	29.3
Hydro	16.0	2.29	57.2	1.36	91.3	0.41	101.5
Total	263.0	8.77	466.3	7.64	657.4	9.06	883.9

GLOBAL PRIMARY ENERGY CONSUMPTION (EJ/yr = W/yr = 0.031 TW)
AND AVERAGE ANNUAL RATES (EJ/yr/yr)
BY ENERGY SOURCE FOR CASES: A, B, C

Source	Year	CASE L					
	1975	Average EJ/yr/yr Between	2000	Average EJ/yr/yr Between	2025	Average EJ/yr/yr Between	2050
Oil	122.6	-1.82	77.1	-0.22	71.6	0.01	71.8
Gas	48.3	-0.24	42.3	0.26	48.8	-0.19	44.1
Coal	72.3	3.08	149.2	-0.42	138.8	-0.76	119.8
Synfuel	0.0	0.12	3.1	1.41	38.4	0.71	56.2
Nuclear	3.8	1.18	33.4	2.03	84.2	2.08	136.1
Solar	0.0	0.04	.9	1.49	38.1	0.85	59.3
Hydro	16.0	2.26	56.4	1.36	90.4	0.44	101.3
Total	263.0	4.62	362.4	5.92	510.3	3.13	588.6

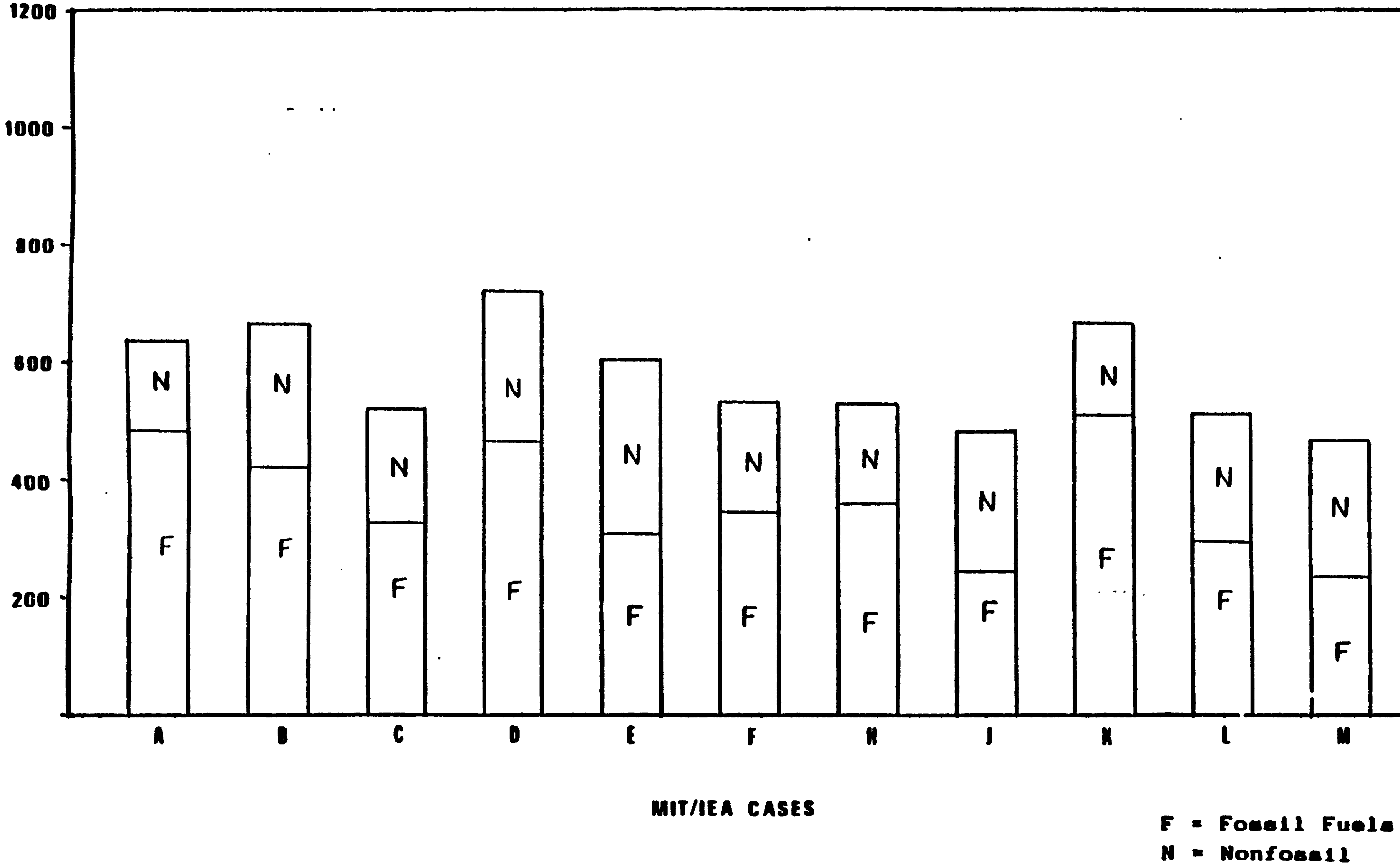
Source	Year	CASE M					
	1975	Average EJ/yr/yr Between	2000	Average EJ/yr/yr Between	2025	Average EJ/yr/yr Betwee	2050
Oil	122.6	-1.82	77.2	-0.28	70.3	-0.39	60.6
Gas	48.3	-0.18	43.7	0.26	50.3	0.20	55.4
Coal	72.3	1.49	109.5	-0.94	85.9	-0.86	64.3
Synfuel	0.0	0.09	2.3	0.84	23.3	0.18	27.7
Nuclear	3.8	1.61	44.1	2.33	102.4	1.91	150.1
Solar	0.0	0.04	1.1	1.80	46.2	0.77	65.5
Hydro	16.0	2.27	56.7	1.38	91.2	0.44	102.1
Total	263.0	3.50	334.6	5.40	469.6	2.24	525.7

GLOBAL PRIMARY ENERGY CONSUMPTION (EJ/yr = Q/yr = 0.031 TW)
AND AVERAGE ANNUAL RATES (EJ/yr per year)
BY ENERGY SOURCE FOR COLOMBO & BERNADINI AND LOVINS, ET.AL.

Source	Year	COLOMBO & BERNADINI			
		Rate		Rate	
	1975	Between	2000	Between	2030
Oil	122.6	0.55	136.3	-0.72	114.6
Gas	48.3	0.97	72.6	0.23	79.4
Coal	72.3	1.60	112.3	1.16	147.2
Synfuel	0.0	0.00	0.0	0.00	0.0
Nuclear	3.8	1.32	36.8	2.73	118.7
Solar	0.0	0.10	2.6	0.13	6.4
Hydro	16.0	0.31	23.7	0.32	33.3
Other	0.0	0.20	5.1	0.21	11.5
Total	263.0	5.06	389.4	4.06	511.1

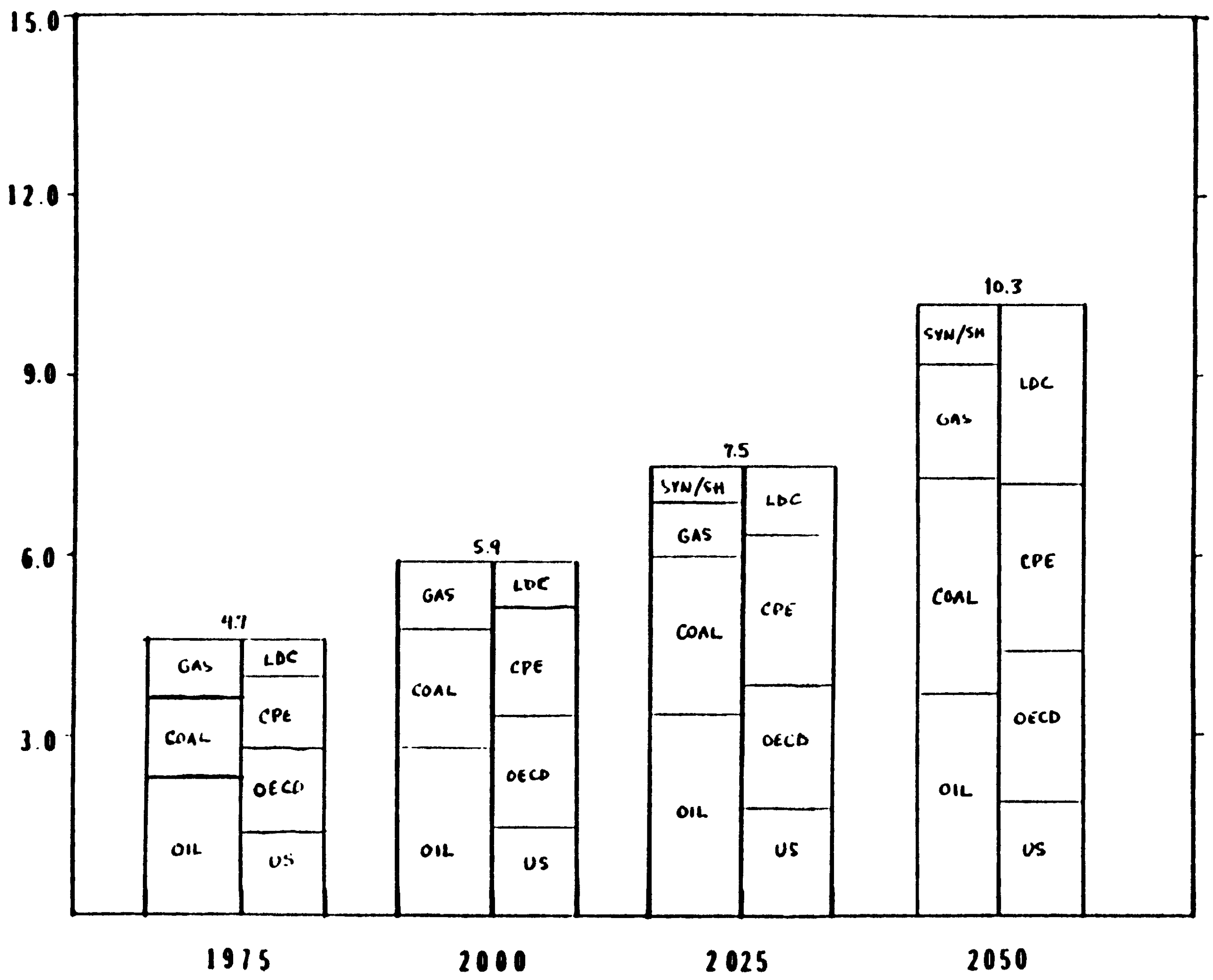
Source	Year	LOVINS, ET AL..			
		Rate		Rate	
	1975	Between	2000	Between	2030
Oil	122.6	-2.64	56.6	-1.63	7.7
Gas	48.3	0.00	48.3	-1.25	10.8
Coal	72.3	-0.63	56.5	-1.48	12.2
Synfuel	0.0	0.00	0.0	0.00	0.0
Nuclear	3.8	-0.15	0.0	0.00	0.0
Solar	0.0	1.44	36.1	1.14	70.2
Hydro	16.0	0.18	20.5	0.52	36.1
Other	0.0	0.34	8.5	0.73	30.3
Total	263.0	-1.46	226.5	-1.97	167.3

GLOBAL PRIMARY ENERGY CONSUMPTION (EJ per YEAR) in year 2025



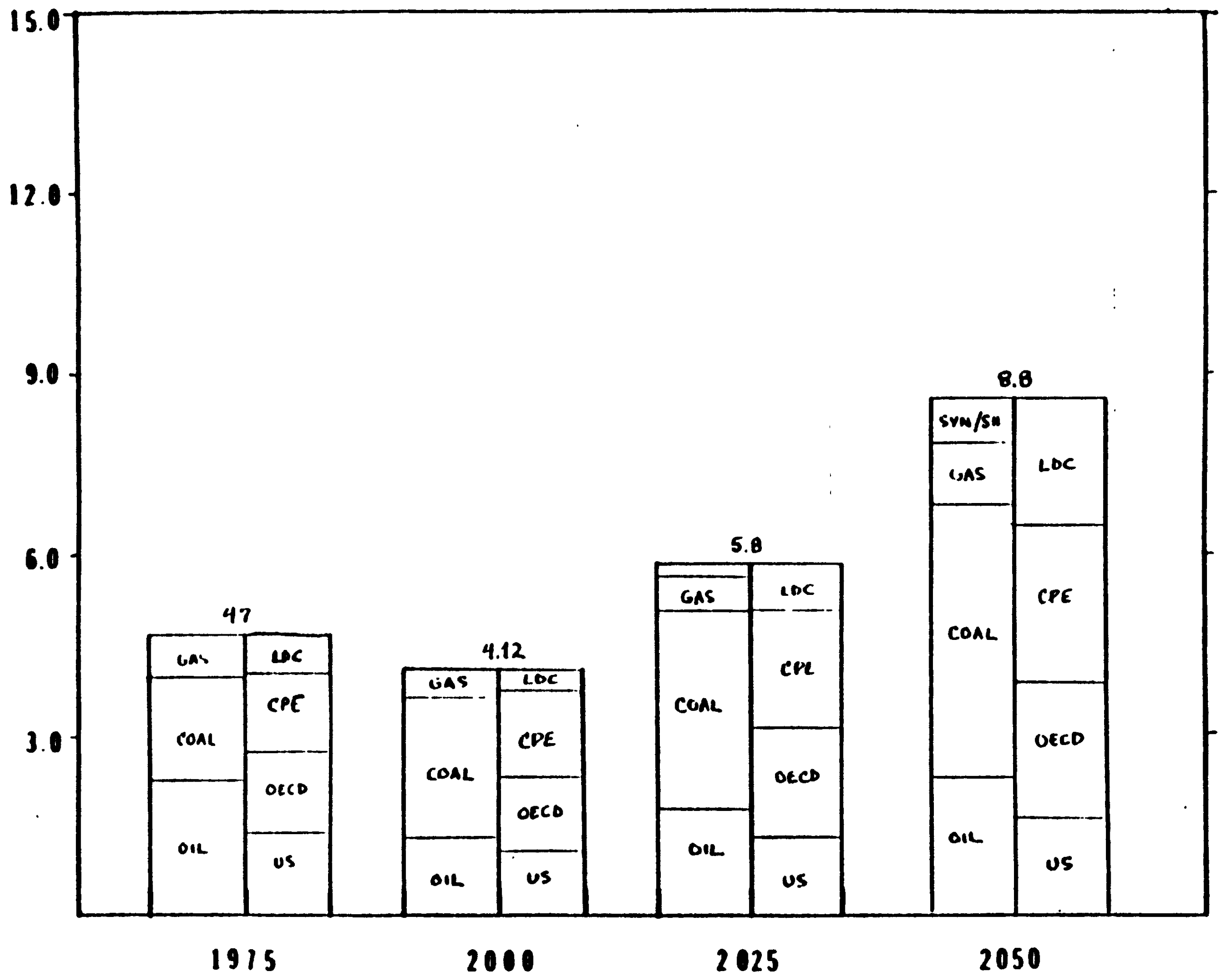
CASE B

GLOBAL CARBON EMISSIONS (10^9 mtons)



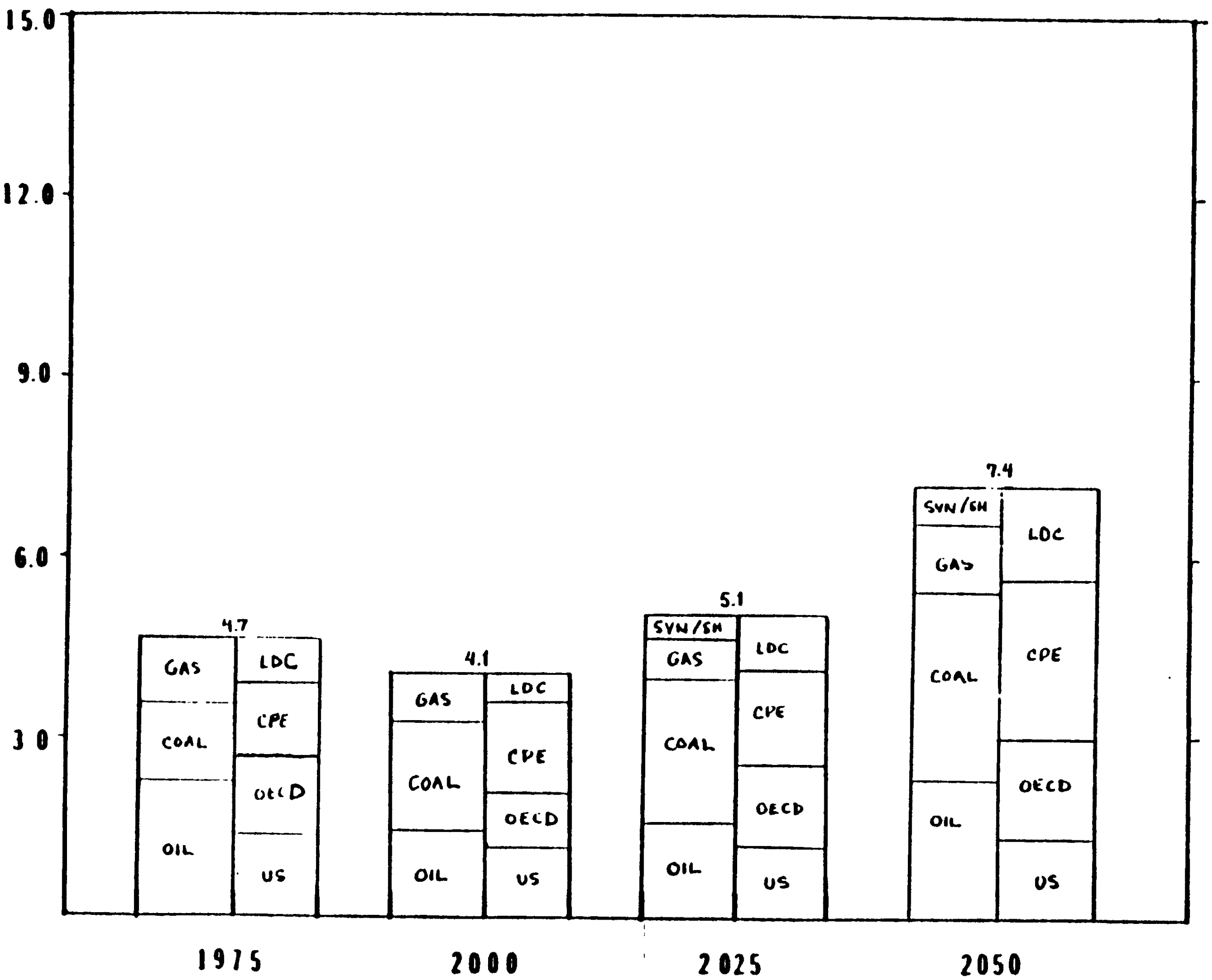
CASE C

GLOBAL CARBON EMISSIONS (10^9 mtons)



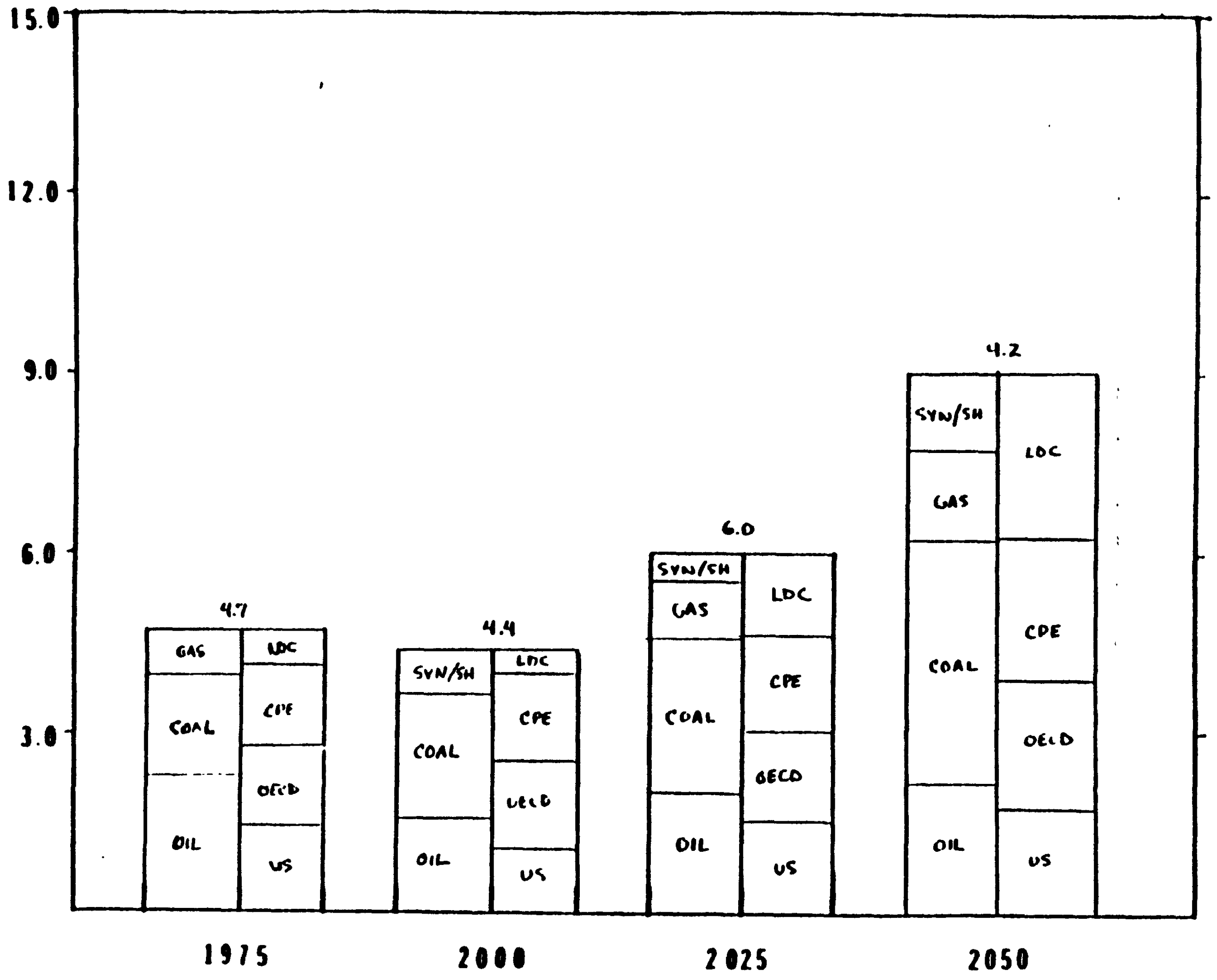
CASE E

GLOBAL CARBON EMISSIONS (10^9 mtons)



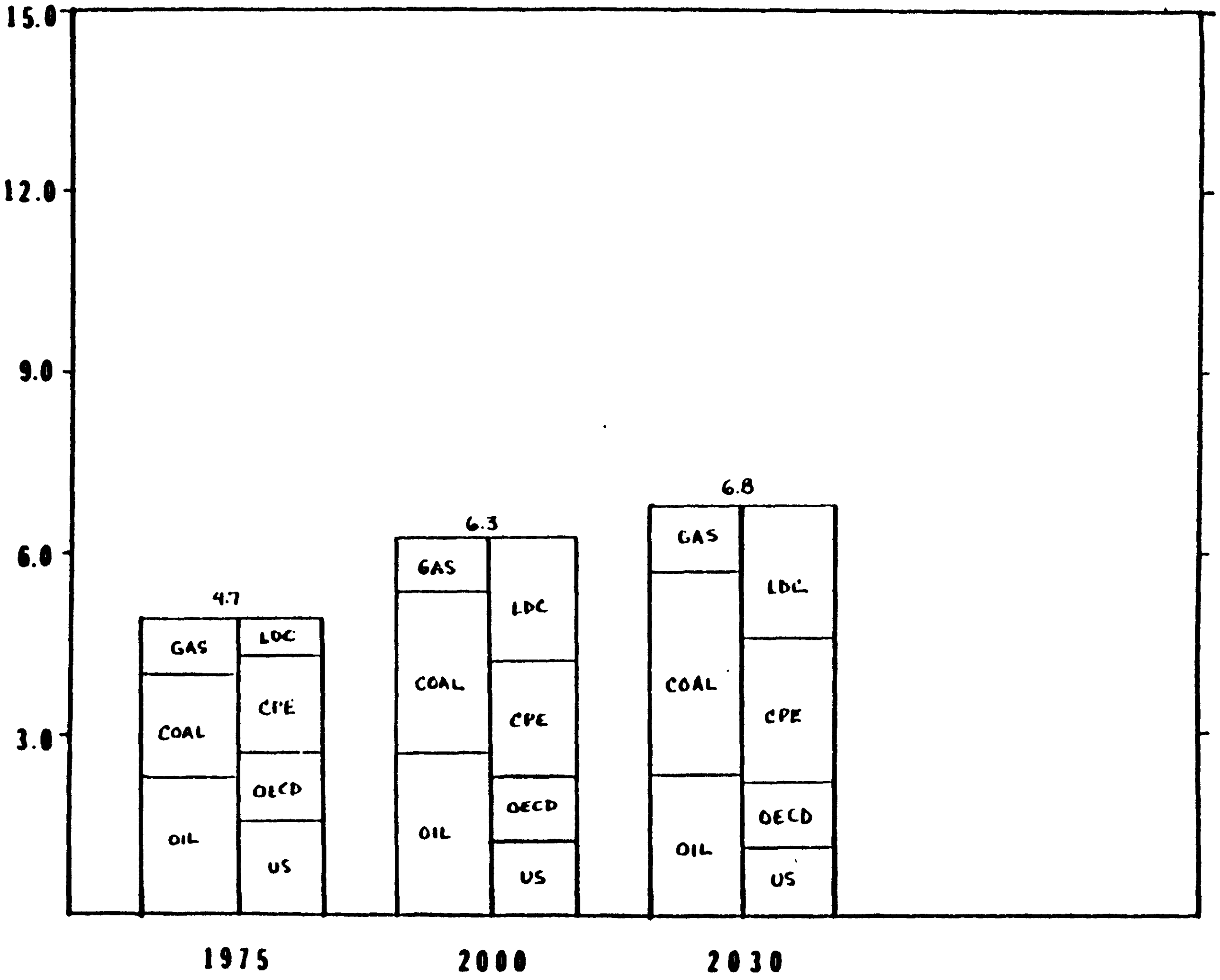
CASE H

GLOBAL CARBON EMISSIONS (10^9 mtons)



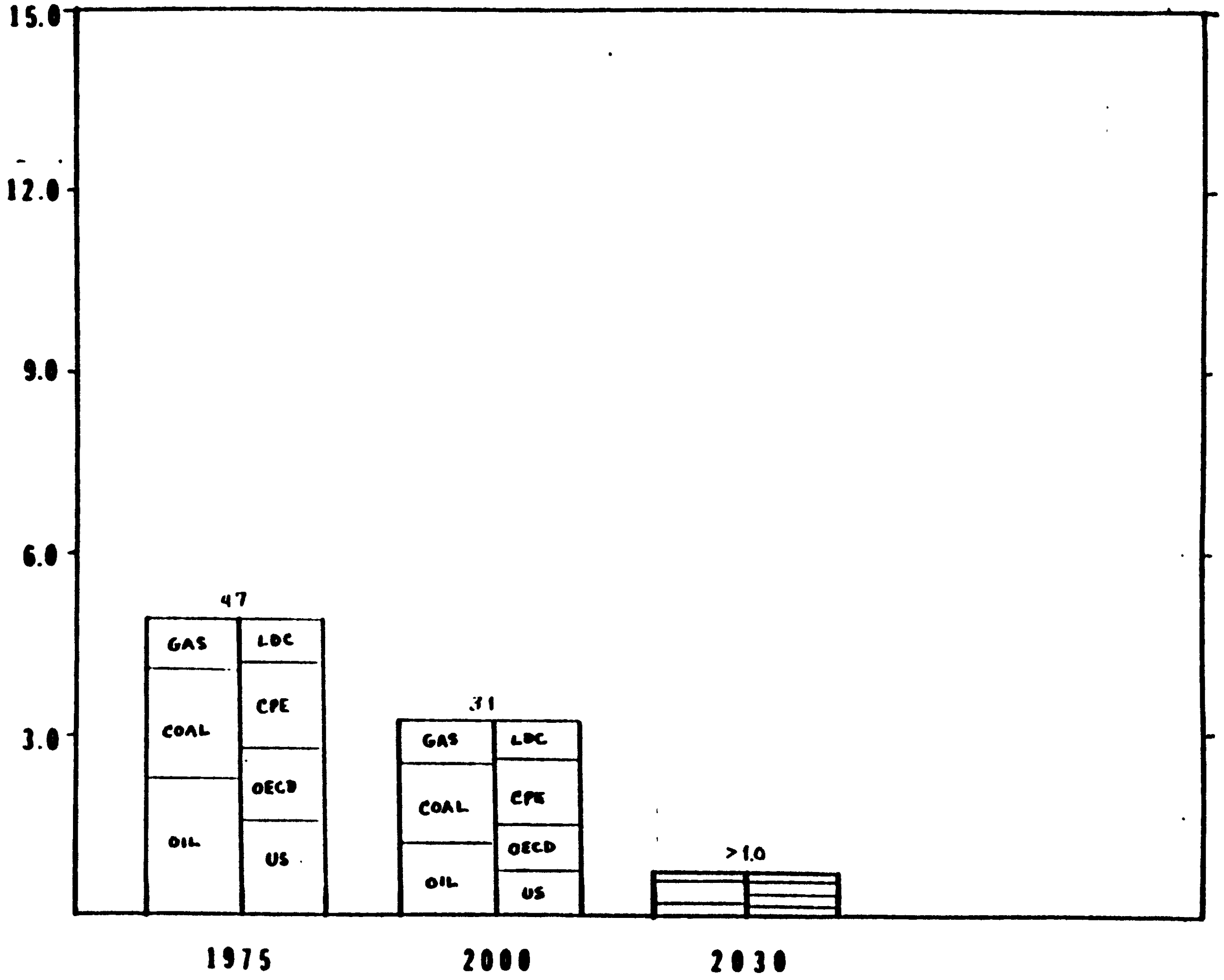
COLOMBO & BERNADINI

GLOBAL CARBON EMISSIONS (10^9 mtons)



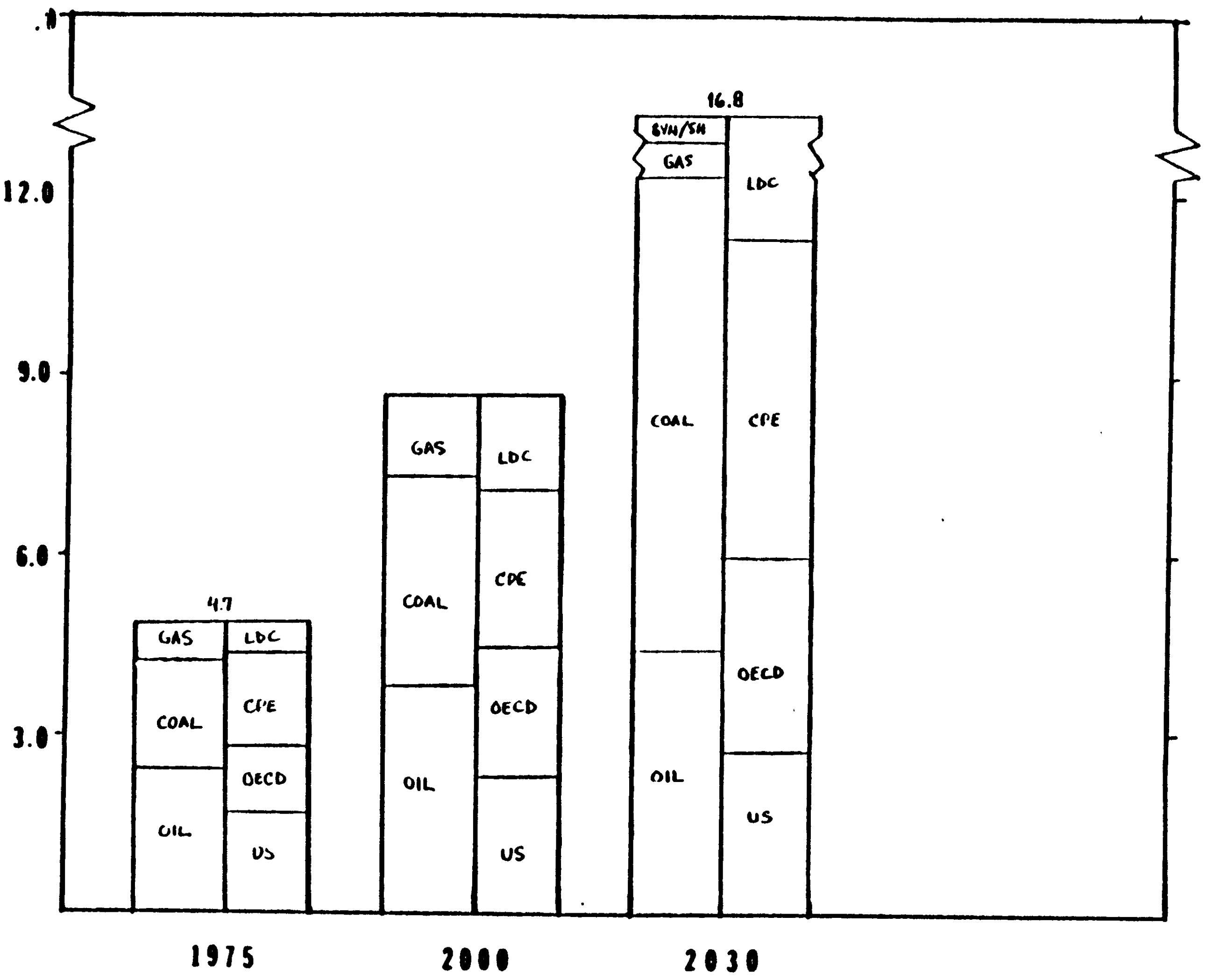
LOVINS, et al.

GLOBAL CARBON EMISSIONS (10^9 mtons)



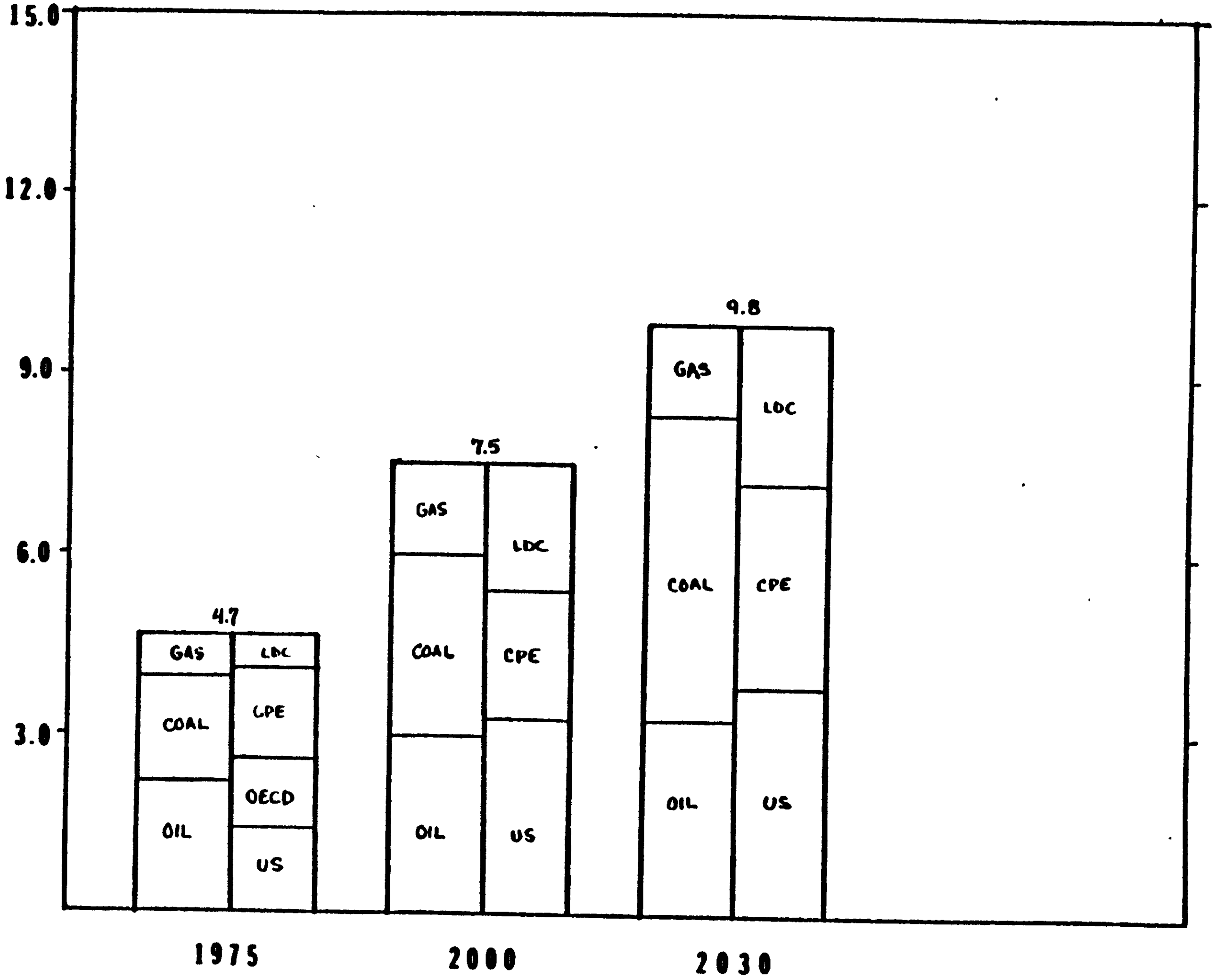
IIASA HIGH

GLOBAL CARBON EMISSIONS (10^9 mtons)



IIASA LOW

GLOBAL CARBON EMISSIONS (10^9 mtons)



APPENDIX E

MATERIAL REQUIREMENTS FOR ENERGY TECHNOLOGIES AND FOR THE MIT/IEA SCENARIOS

Summary Table 7.1 of the main text was the result of a literature search and, in part, an industry survey. The data obtained from the research is contained in Tables E.1 through E.5. The sources cited in the tables are listed at the end of this Appendix.

One source cited in all the tables is John Holdren, co-author of Environmental Aspects of Renewable Energy Sources[1]. Holdren, along with co-authors Gregory Morris and Irving Mintzer, has compiled a table of materials used for construction of energy facilities. Their table contains an extensive list of references verifying the range of values given. From examination of the table, it can be seen that the ranges of materials needed for nonrenewable technologies are much smaller than those for renewables. This is due to the fact that the nonrenewable technologies are well established, thus the values given are more accurate, whereas many of the values given for technologies such as solar and wind are estimations. As mentioned by Mintzer[2], many of the values given (most likely the upper bounds of the ranges) are for plausible system designs, but not necessarily efficient designs. Thus tables D.2 - D.5 are a compilation of data obtained from additional research to more accurately determine material requirements for solar photovoltaics, LWR-fission, wind energy conversion, and hydroelectric technologies.

Although the values chosen for Table 7.1 were selected from within the ranges specified in Tables E.1 - E.5, emphasis was placed on the source of the data. For example, in Table E.2 many of the values taken from Holdren are estimates whereas the information from ARCO Solar are actual working values. Similarly in Table E.3, data from Windtech, Energy Sciences, and Hamilton Standard are actual working values. Furthermore, the information obtained from DOE was developed and verified by technical specialists in the Technology Assessment Division, Office of Environmental Assessments, who conducted a survey of the respective industry.

Another aspect considered was larger energy facilities tend to be less material intensive. Thus while attempting to be conservative and select higher values of material requirements, we were influenced by the idea of large central utilities for solar photovoltaics and large wind farms. But the notions of small nuclear power plants (about 200 $MW_{(e)}$) and small-head hydro influenced us towards higher values.

Table E.1 Material Requirements from Holdren[1]
(10^6 metric tons per EJ/yr)

Energy System	Steel	Concrete[a]	Nonferrous[b]
Coal Electric[c]	1.1-2.0	4.5-6.6	0.03
Synfuels[d]	0.4-0.8	*	0-60.0
Biomass[e]	0.2-8.1	1.5-20.1	*

*Data not available

[a] Concrete is a mixture of sand, gravel, water, and cement. Cement is approximately 20% of the total mass.

[b] Nonferrous refers mainly to aluminum and copper.

[c] The data are for 900 to 1000 MW(e). Load factor is 0.7.

[d] From coal only. Range covers five types of gasification and liquefaction plants.

[e] For fluid fuel. Range covers four types of biomass conversion plants and facility sizes from 10^3 to 10^6 GJ per year plant. Larger individual facilities require fewer materials per unit energy produced.

Table E.2 Solar Photovoltaic Material Requirements
(10^6 metric tons per EJ/yr)

Source	Steel[a]	Concrete[b]	Nonferrous[c]	Glass	Silicon
Holdren	0-36.0	4.2-480.0	0-54.0	2.4-14.1	*
MITRE 1980	13-21.0	*	2.5-3.5	12.0-17.0	*
Kreider	*	4.5	59.0[d]	5.3	*
Sandia	*	210.0	*	*	*
GE 1977	*	400.0	422.0	18.2	<0.1
ARCO Solar[e]	*	210.0	*	*	1.8

*Data not available.

[a] Steel and aluminum are substitutable as construction materials.

[b] Concrete is a mixture of sand, gravel, water, and cement. Cement is approximately 20% of the total mass.

[c] Nonferrous refers mainly to aluminum and copper.

[d] This value refers to aluminum only.

[e] Data refers to the 1 MW plant installed February 1983, in Hesperia, California.

Table E.3 LWR-fission Material Requirements
(10^6 metric tons per EJ/yr)

Source	Steel	Concrete[a]	Nonferrous[b]
Holdren[c]	1.2-1.8	7.5-12.0	0.01
DOE 1980	3.3	23.3	0.13
MITRE 1980	2.0	3.0-8.0	*
Kreider	2.4	13.4	*
DOE 1980[d]	0.7-0.9	1.0-1.4	0.02-0.03

*Data not available.

[a] Concrete is a mixture of sand, gravel, water, and cement. Cement is approximately 20% of the total mass.

[b] Nonferrous refers mainly to aluminum and copper.

[c] Unit size for LWR's is 1000 MW(e). Load factor is 0.7.

[d] These values are total material requirements for the following uranium processes: mining, milling, conversion, enrichment, and fabrication.

Table E.4 Wind Energy Conversion Material Requirements
(10^6 metric tons per EJ/yr)

Source	Steel	Concrete[a]	Nonferrous[b]
Holdren[c]	3.6-25.0	5.7-33.0	0.2-0.9
DOE 1980	5.3-17.0	20.8-52.8	0.1-0.2[d]
MITRE 1980	3.0-5.0	30.0-35.0	1.5
Windtech[e]	*	80.0-100.0	*
Energy Sciences[f]	2.4	41.7	*
Hamilton Standard[g]	7.4	34.0	*

*Data not available.

[a] Concrete is a mixture of sand, gravel, water, and cement. Cement is approximately 20% of the total mass.

[b] Nonferrous refers mainly to aluminum and copper.

[c] Low figure for windmill of 4 MW(e) rated capacity, operating with load factor of 0.34. Higher figures cover a range of unit sizes from 5 kw(e) to 4 MW(e) and a range of capacity factors.

[d] These values refer to copper only.

[e] These values are for a 70 kw wind turbine.

[f] These values are for an 85 kw wind turbine.

[g] These values are for a 4000 kw wind turbine.

Table E.5 Hydroelectric Material Requirements
(10^6 metric tons per EJ/yr)

Source	Steel	Concrete[a]	Nonferrous[b]
Holdren[c]	1.4-3.6	21.9-330.0	0-0.02
DOE 1980	4.0	43.0	0.2

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[a] Concrete is a mixture of sand, gravel, water, and cement. Cement is approximately 20% of the total mass.

[b] Nonferrous refers mainly to aluminum and copper.

[c] Low values for a single 200 MW(e) dam.

AVERAGE ANNUAL MATERIAL REQUIREMENTS FROM 2000 to 2025 +

(Thousands of metric tons per year)

I I A S A   L O W

Source	steel	concrete	nonferrous	glass	silicon
Coal	0	0	0	0	0
Synfuel	2034	‡	102	-	-
Nuclear	10350	62100	518	-	-
Solar	4400	46200	6600	2640	396
Hydro	2345	40200	134	-	-
Total	19129	148500	7353	2640	396

I I A S A   H I G H

Source	steel	concrete	nonferrous	glass	silicon
Coal	810	2970	16	-	-
Synfuel	4182	‡	209	-	-
Nuclear	16925	101550	846	-	-
Solar	8400	88200	12600	5040	756
Hydro	2345	40200	134	-	-
Total	32662	232920	13806	5040	756

+ Values don't include requirements for replacement plants.
‡ Data not available.
- Relatively insignificant.

AVERAGE ANNUAL MATERIAL REQUIREMENTS FROM 2000 to 2025 +

(Thousands of metric tons per year)

COLOMBO & BERNADINI

Source	steel	concrete	nonferrous	glass	silicon
Coal	1740	6380	35	-	-
Synfuel	0	0	0	0	0
Nuclear	6825	40950	341	-	-
Solar	2600	27300	3900	1560	234
Hydro	1120	19290	64	-	-
Total	12285	93830	4340	1560	234

LOVINS, ET AL.

Source	steel	concrete	nonferrous	glass	silicon
Coal	0	0	0	0	0
Synfuel	0	0	0	0	0
Nuclear	0	0	0	0	0
Solar	22800	239400	34200	13680	2852
Hydro	1820	31200	184	-	-
Total	24620	270600	34384	13680	2852

+ Values do not include requirements for replacement plants.
- Relatively insignificant.

AVERAGE ANNUAL MATERIAL REQUIREMENTS FROM 2000 to 2025 +

(Thousands of metric tons per year)

CASE A

Source	steel	concrete	nonferrous	glass	silicon
Coal	5640	29680	113	-	-
Synfuel	1890	*	95	-	-
Nuclear	3750	22500	188	-	-
Solar	7600	79800	11400	4560	684
Hydro	4865	83400	278	-	-
Total	23745	296380	12073	4560	684

CASE B

Source	steel	concrete	nonferrous	glass	silicon
Coal	1875	6875	38	-	-
Synfuel	126	*	6	-	-
Nuclear	9500	57000	475	-	-
Solar	8600	90300	12900	5160	774
Hydro	4970	85200	284	-	-
Total	25071	239375	13703	5160	774

CASE C

Source	steel	concrete	nonferrous	glass	silicon
Coal	1155	4235	23	-	-
Synfuel	1002	*	50	-	-
Nuclear	6575	39450	329	-	-
Solar	12600	132300	18900	7560	1134
Hydro	5005	85800	286	-	-
Total	26337	261785	19588	7560	1134

+ Values do not include requirements for replacement plants.
* Data not available
- Relatively insignificant

AVERAGE ANNUAL MATERIAL REQUIREMENTS FROM 2000 to 2025 +

(Thousands of metric tons per year)

C A S E D

Source	steel	concrete	nonferrous	glass	silicon
Coal	6830	22110	121	-	-
Synfuel	396	‡	20	-	-
Nuclear	4675	28050	234	-	-
Solar	25600	268800	38400	15360	2304
Hydro	4760	81600	272	-	-
Total	41461	400560	39046	15360	2304

C A S E E

Source	steel	concrete	nonferrous	glass	silicon
Coal	375	1375	8	-	-
Synfuel	864	‡	43	-	-
Nuclear	8200	49200	410	-	-
Solar	45800	480900	68700	27480	4122
Hydro	6860	117600	392	-	-
Total	62099	649075	69553	27480	4122

C A S E F

Source	steel	concrete	nonferrous	glass	silicon
Coal	1215	4455	24	-	-
Synfuel	1002	‡	50	-	-
Nuclear	6850	41100	343	-	-
Solar	9200	96600	13800	5520	828
Hydro	5005	85800	286	-	-
Total	23272	227955	14503	5520	828

+ Values do not include requirements for replacement plants.

‡ Data not available.

\- Relatively insignificant.

AVERAGE ANNUAL MATERIAL REQUIREMENTS FROM 2000 to 2025 +

(Thousands of metric tons per year)

CASE H

Source	steel	concrete	nonferrous	glass	silicon
Coal	930	3410	19	-	-
Synfuel	1002	#	50	-	-
Nuclear	0	0	0	0	0
Solar	78400	823200	117600	47040	7056
Hydro	5040	86400	288	-	-
Total	85372	913010	117957	47040	7056

CASE J

Source	steel	concrete	nonferrous	glass	silicon
Coal	465	1785	9	-	-
Synfuel	972	#	49	-	-
Nuclear	5025	33150	251	-	-
Solar	33200	348600	49800	19920	2988
Hydro	4760	81600	272	-	-
Total	44422	462855	50381	19920	2988

CASE K

Source	steel	concrete	nonferrous	glass	silicon
Coal	2805	10285	56	-	-
Synfuel	2484	#	124	-	-
Nuclear	2425	14550	121	-	-
Solar	11400	119700	17100	6840	1026
Hydro	4760	81600	272	-	-
Total	23874	226135	17674	6840	1026

+ Values do not include requirements for replacement plants.
# Data not available.
- Relatively insignificant.

AVERAGE ANNUAL MATERIAL REQUIREMENTS FROM 2000 to 2025 +

(Thousands of metric tons per year)

C A S E L

Source	steel	concrete	nonferrous	glass	silicon
Coal	0	0	0	-	-
Synfuel	846	*	42	-	-
Nuclear	5075	30450	254	-	-
Solar	29800	312900	44700	17880	2682
Hydro	4760	81600	272	-	-
Total	40481	424950	45268	17880	2682

C A S E M

Source	steel	concrete	nonferrous	glass	silicon
Coal	0	0	0	-	-
Synfuel	504	*	25	-	-
Nuclear	5825	34950	291	-	-
Solar	36000	378000	54000	21600	3240
Hydro	4830	82800	276	-	-
Total	47159	495750	54592	21600	3240

APPENDIX E REFERENCES

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APPENDIX F

A TRANSBOUNDARY POLLUTION RECIPROCAL ACCESS ACT, REFERRED TO IN CHAPTER 8.4

ATTACHMENT

UNIFORM TRANSBOUNDARY POLLUTION RECIPROCAL ACCESS ACT

Drafted, Approved and Recommended for Enactment
by the

NATIONAL CONFERENCE OF COMMISSIONERS
ON UNIFORM STATE LAWS

and

UNIFORM LAW CONFERENCE OF CANADA

NATIONAL CONFERENCE OF COMMISSIONERS
ON UNIFORM STATE LAWS
ANNUAL CONFERENCE
MONTEREY, CALIFORNIA, JULY 30 - AUGUST 6, 1982

UNIFORM LAW CONFERENCE OF CANADA
ANNUAL CONFERENCE
MONTEBELLO, QUEBEC, AUGUST 19 - 28, 1982

Uniform Law
Commissioners

WITH PREFATORY NOTE AND COMMENTS

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UNIFORM TRANSBOUNDARY POLLUTION RECIPROCAL ACCESS ACT

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NATIONAL CONFERENCE OF COMMISSIONERS
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and
UNIFORM LAW CONFERENCE OF CANADA

Prefatory Note

In 1979, the Canadian Bar Association and the American Bar Association each adopted a report prepared by a joint committee of the two Associations on "The Settlement of International Disputes Between Canada and the United States of America." One of the areas on which the report focussed was the equalization of rights and remedies of citizens in Canada and the U.S.A. affected by pollution emanating from the other jurisdiction. The Committee drafted enacting legislation on this topic, in treaty form, basing its draft upon the Organization for Economic Co-operation and Development's Recommendation for the Implementation of A Regime of Equal Right of Access and Non-Discrimination in Relation to Transfrontier Pollution.

The ABA-CBA Committee's Report suggested that a liaison group ought to be established between the National Conference of Commissioners on Uniform State Laws and the Uniform Law Conference of Canada, the two organizations in their respective countries dedicated to the promotion of uniformity of law. The group was to have a mandate covering review, co-ordination and drafting of legislation on topics of mutual interest. The liaison committee was established in 1979 and has held five meetings in Canada and the U.S. to discuss the drafting of a Transboundary Pollution Reciprocal Access Act.

Pollution is no respecter of artificial lines on maps. Damage can occur in one jurisdiction from pollution produced in another jurisdiction. Reported caselaw reveals many examples of this phenomenon. A discharge of waste into a river in one jurisdiction can damage property in states downstream: see for example Missouri v. Illinois, 26 S.Ct. 268, 200 U.S. 496, 50 L.Ed.2d 572 (1906). Smoke can blow from one adjoining city to another: see for example Michie et al. v. Great Lakes Steel Division, National Steel Corporation, 495 F.2d 213 (6th Circ.), certiorari denied 95 S.Ct. 310, 419 U.S. 997, 42 L.Ed.2d 270. Metal smelters can generate pollutants that can travel into other jurisdictions: see for example The Trail Smelter Arbitration, 3 U.N.R.I.A.A. 1905 (1941) or Ducktown Sulphur, Copper and Iron Company v. Barnes et al., 60 S.W. 593 (Tenn.1900). At times, pollution from a number of jurisdictions may contribute to the damage: see for example Ohio v. Wyandotte Chemicals Corp. et al., 91 S.Ct. 1005, 401 U.S. 493, 28 L.Ed.2d 256 (1971). Pollution crossing boundaries may take a variety of forms ranging from simple escapes between adjacent land to immensely difficult problems, such as acid rain and nuclear emissions whose very complexity renders them as intractable to coherent policy or legislative treatment as they are to definitive scientific analysis and explanation.

It is a generally recognized rule of law in the Anglo-American tradition that actions for damages for trespass, nuisance, or negligent injury in respect to lands located in another state are local actions and may be brought only in the state where the land is situated. This rule has been criticized, but most courts still follow it. Its significance is that unless the alleged tortfeasor can be "found" in the state where the injury took place, an action for damages is for all intents and purposes precluded.

When only states of the United States are involved, the increasing number of state long-arm statutes may reduce the significance of this rule because valid in personam jurisdiction over the defendant can be obtained under a long-arm statute and judgment rendered, and that judgment is entitled to full faith and credit within the United States. But even if a long-arm statute is involved, two suits may be necessary—the first to obtain the judgment and a second in another state to enforce the judgment. Furthermore, whether equitable relief will be granted by the second state, is open to question.

If there is no long-arm statute, or it is not as extensive as it might be, and the prospective defendant is not "found" within the jurisdiction where the injury occurred, then the plaintiff, for all practical purposes, is without a forum. The problem can become acute in an international setting. Suppose that on the northern shore of Lake Ontario there is a manufacturing plant that regularly emits highly toxic materials into the air and these are carried by the prevailing winds across Lake Ontario and into the State of New York. A fish hatchery there is severely damaged. Assuming that a person in New York, who is damaged can establish causation, can he bring suit?

The Canadian courts will probably not entertain the action because of the rule in British South Africa Co. v. Companhia de Mozambique, [1893] AC 602 (H.L.). The New York state courts could entertain the action, but would they be able to acquire personal jurisdiction over the Canadian defendant in order to permit the action to proceed? Under the New York State long-arm statute, N.Y.C.P.L.R. § 302, perhaps it could; and perhaps New York would reduce the claim to a money judgment. But no Canadian court would be bound by the doctrine of full faith and credit, and the chances are great that a judgment of a United States court reached upon a long-arm statute would not be honored by a Canadian court.

In British South Africa Company v. Companhia de Mozambique, the House of Lords decided that only the courts of a jurisdiction where an immovable is situated can adjudicate upon its title. An English court thus had no jurisdiction to try a damage action for trespass to land situated abroad. Courts in Canada have extended this rule to an extreme. Dealing with an action in New Brunswick for damages to Quebec land caused by the negligent blocking of an interprovincial river, Chief Justice Baxter of New Brunswick stated:

> ". . . whether title to land comes into question or not appears to be immaterial. The moment it appears that the controversy relates to land in a foreign country our jurisdiction is excluded:"

Albert v. Fraser Companies Ltd., [1937] 1 D.L.R. 39, 45, 11 M.P.R. 209, 216 [N.B.C.A.]. Applying this rule to transboundary pollution, it would prevent an American citizen from suing in Canadian courts for damage caused by a Canadian polluter, if the controversy relates in any way to land in the United States. The same obstacle for Canadians is created in the United States by the "local action rule," established in Livingston v. Jefferson, 15 Fed.Cas. 660 (No. 8411) (Cir. Ct.D.Va.1811).

This Act is designed to eliminate this particular problem with respect to pollution. While conceptually the Act could be extended to deal with all unintentional tort actions affecting property, the Committee's mandate, and indeed the earlier work of the Joint ABA/CBA Committee and the OECD, was limited to interjurisdictional pollution problems and the difficulties which the local action rule presented in preventing non-resident litigants getting inside the courthouse door. Whether the pollution originated in Ontario or Ohio, a New Yorker injured in New York thereby, would be entitled to go into a Canadian court or an Ohio court and maintain an action for damages for injury to New York land. In other words, this proposed statute abrogates the rules in Livingston v. Jefferson and British South Africa Co. v. Companhia de Mozambique, which many believe to be anachronisms in any event.

While the joint committee of the ABA/CBA had recommended that the local action rule should be changed by way of bilateral treaty, the joint uniform law committee took a different position. Because of the difficulty of achieving such a treaty and the desirability of providing local rather than federal solutions to problems, the Committee decided at an early stage that changing the rules could be done more effectively and expeditiously through the enactment of uniform state and provincial laws than through a treaty.

The basic thrust of reform is to change the local action rules and provide equal access for the victims of transfrontier pollution to the courts of the jurisdiction where the contaminant originated. As Stephen McCaffrey puts it "the mere existence of a political boundary line should prevent neither the 'upstream' state from considering the transfrontier effects of an activity, nor the 'downstream' state from having an input into the decision-making process concerning the permissibility of that activity. Nor should the boundary line constitute an impediment to victims of transfrontier pollution seeking redress in the same country": Stephen McCaffrey, "Transboundary Pollution Injuries: Jurisdictional Consideration in Private Litigation Between Canada and the United States" (1973), 3 Cal. W.Int.L.J. 191.

The proposed statute also provides that in the event suit is brought in the province or state where the alleged pollution actually originated, the local law of that state (as distinguished from its whole law including conflict of laws rule) applies. This means that an alleged polluter sued in the state where the alleged pollution originated is governed by the substantive laws of that jurisdiction. Insofar as the courts of that state are concerned, he has one standard to meet, and he has the opportunity to defend the action on the basis of the substantive and procedural rules with which he is most familiar. Everyone would prefer to be sued in the courts of his own jurisdiction.

Of course, if service of process is achieved in the state where the pollution actually caused harm, then that state would be free, within constitutional restraints, to apply either its own law or the law of the state where the alleged pollution originated. That situation is not changed by this Act. Although total uniformity and predictability are not established, an injured party will know when choosing a particular court what law will be applied. The Act is designed to fill a procedural gap, and is not intended to alter substantive laws or standards, or change the ground rules under which individuals, corporations, or governments conduct their affairs.

UNIFORM TRANSBOUNDARY POLLUTION RECIPROCAL ACCESS ACT

Sec.
1. Definitions.
2. Forum.
3. Right to Relief.
4. Applicable Law.
5. Equality of Rights.
6. Right Additional to Other Rights.
7. [Alternative for the U.S.A.] Waiver of Sovereign Immunity.

Sec.
7(a). [Alternative for Canada] Act Binds Crown.
7(b). [For Canada only] Regulations.
8. Uniformity of Application and Construction.
9. Title.
10. Time of Taking Effect.

§ 1. Definitions

As used in this [Act]:

(1) "Reciprocating jurisdiction" means a state of the United States of America, the District of Columbia, the Commonwealth of Puerto Rico, a territory or possession of the United States of America, or a province or territory of Canada, which has enacted this [Act] or provides substantially equivalent access to its courts and administrative agencies.

(2) "Person" means an individual person, corporation, business trust, estate, trust, partnership, association, joint venture, government in its private or public capacity, governmental subdivision or agency, or any other legal entity.

Comment

The definition of "jurisdiction" performs a number of functions. It enables the Act to be applied in interstate and inter-provincial pollution actions, in addition to actions involving pollution spanning the U.S./Canada International boundary. The Act does not apply to U.S./Mexico transboundary pollution or to pollution from any other nation.

The reciprocal aspect of the Act is achieved by Section 1(1) providing that both the "polluting" and "polluted" jurisdictions must have "enacted this Act" or "provide substantially equivalent access to the courts and administrative agencies." The requirement of reciprocity applies to access only. This threshold test is applied by the courts in the U.S. on a case by case basis, it being regarded as a question of fact whether a particular jurisdiction is a reciprocating jurisdiction. In Canada, by contrast, it is usual for reciprocity to be formally recognized through provincial governments designating by regulation lists of reciprocating states, where they are satisfied that reciprocity exists. Section 7(b) is designed to permit this procedure to be followed. For jurisdictions, such as Minnesota by judicial decision and New York by statute, that already provide access to their courts for non-resident pollution victims by abandoning the rule of Livingston v. Jefferson, the words "provide substantially equivalent access" ensure that these jurisdictions will be recognized as reciprocating jurisdictions without the need to enact formally the Act. Finally, it should be noted that Section 1(1) concludes with the words "access to the courts and administrative agencies," a specific reference to the fact that it is contemplated that the Act will also apply to proceedings before tribunals.

The definition of "person" derives from standard wording used in many uniform acts adopted by the National Conference of Commissioners on Uniform State Laws. It is designed to include all natural and legal persons within the ambit of the Act. In addition, if the Attorney General, or another public official of the state or province where the injury occurred, is able to bring an action with respect to environmental injury, then the Attorney General of another state harmed by the "originating state's" pollution should also be able to bring an action in the "originating state."

§ 2. Forum

An action or other proceeding for injury or threatened injury to property or person in a reciprocating jurisdiction caused by pollution originating, or that may originate, in this jurisdiction may be brought in this jurisdiction.

Comment

Together with Section 3, this section forms the main operative provision of the statute. Section 2 provides access to the courts in one jurisdiction for pollution victims in another jurisdiction. A question may arise whether the pollution originated in a particular jurisdiction, and this is a question of fact which the courts must decide. It should be noted that the statute is not restricted in its scope to civil trials; it also extends to other proceedings before tribunals concerning environmental injury or threatened injury.

As used in this Act, "injury" includes wrongful death and "property" includes both real and personal property.

It has been suggested that enactment of this proposed statute would cause a rush of litigants from out of state to the state where the alleged pollution originated or where it may originate. So far as is known states with very extensive long-arm statutes have not experienced this rush of litigation, and this suggests that it would not happen if a new, and less convenient forum was made available to them.

§ 3. Right to Relief

A person who suffers, or is threatened with, injury to his person or property in a reciprocating jurisdiction caused by pollution originating, or that may originate, in this jurisdiction has the same rights to relief with respect to the injury or threatened injury, and may enforce those rights this jurisdiction as if the injury or threatened injury occurred in this jurisdiction.

Comment

This section equates the rights of an extra-jurisdictional pollution victim to those of a victim who is a resident of the jurisdiction. It is designed to ensure that the actual or potential victim of transfrontier pollution will have a remedy in the courts of the jurisdiction where the pollution originated, if a victim residing in that jurisdiction would have had a remedy for injury or threatened injury in the case of pollution caused locally. Whether or not particular pollution did originate in a jurisdiction is a question of fact for the court to decide.

§ 4. Applicable Law

The law to be applied in an action or other proceeding brought pursuant to this [Act], including what constitutes "pollution", is the law of this jurisdiction excluding choice of law rules.

Comment

This section provides that the law of this jurisdiction will apply in actions brought under the Act. In the United States this includes federal, state and local law where applicable. The applicable law is defined to exclude choice of law rules so as to avoid the whole problem of *renvoi*. While the Committee initially considered drafting a definition of "pollution" for inclusion in this Act, it was decided that it would be exceptionally difficult to draft such a definition without it degenerating into an unmanageable "shopping list" and difficult to harmonize such a list in practice with the definitions provided in the substantive law of a particular jurisdiction. Jurisdictions differ markedly in their treatment of matters such as smells, radiation, vibration, and visual pollution. To avoid difficulties in interpretation, it was decided that what constitutes pollution would be decided by reference to the law of an enacting jurisdiction: such a definition might encompass both statutory definitions as well as any applicable judicial decisions under the common law. It is contemplated that it would include but not be limited to discharges and emissions into land, air or water.

§ 5. Equality of Rights

This [Act] does not accord a person injured or threatened with injury in another jurisdiction any rights superior to those that the person would have if injured or threatened with injury in this jurisdiction.

Comment

See Comment following Section 6.

§ 6. Right Additional to Other Rights

The right provided in this Act is in addition to and not in derogation of any other rights.

Comment

These two sections clarify that the Act is designed to put non-residents on the same footing as residents with respect to access to courts and tribunals in claims involving transboundary pollution. The rights of non-residents under this Act will be no higher than those of residents, and they must accept any procedural or substantive limitations that may happen to exist under the applicable law of the originating jurisdiction. Section 6 ensures that the right of access provided by the Act is supplementary and is not intended in any way to diminish existing rights under the laws of this jurisdiction, which may be enforced independently of this Act.

ALTERNATIVE FOR THE U.S.A.

[§ 7. Walver of Sovereign Immunity

The defense of sovereignty immunity is applicable in any action or other proceeding brought pursuant to this [Act] only to the extent that it would apply to a person injured or threatened with injury in this jurisdiction.]

Comment

See Comment following Section 7(b).

ALTERNATIVE FOR CANADA

[§ 7(a). Act Binds Crown

This [Act] binds the Crown in right of (Province or Territory) only to the extent that the Crown would be bound if the person were injured or threatened with injury in this jurisdiction.]

Comment

See Comment following Section 7(b).

SECTION 7(b) FOR CANADA ONLY

[§ 7(b). Regulations

The Lieutenant Governor in Council may, where he is satisfied that a jurisdiction is a reciprocating jurisdiction, make a declaratory order, to that effect, and upon the making of such order, the jurisdiction is a reciprocating jurisdiction for the purposes of this [Act].]

Comment

The two alternative drafts, the one applicable in Canada, and the other in the United States, are provided to deal with the question of sovereign or crown immunity, and to ensure that extra-jurisdictional actions will be treated under the doctrines in the same way as actions brought by residents.

Section 7(b) establishes a procedure for Canadian provinces and territories to develop and maintain an authoritative list of reciprocating jurisdictions. In developing such a list, regard might be had to the lists of enacting jurisdictions contained in the Annual Handbook of the National Conference of Commissioners on Uniform State Laws.

§ 8. Uniformity of Application and Construction

This [Act] shall be applied and construed to carry out its general purpose to make uniform the law with respect to the subject of this [Act] among jurisdictions enacting it.

§ 9. Title

This [Act] may be cited as the Uniform Transboundary Pollution Reciprocal Access Act.

§ 10. Time of Taking Effect

This [Act] takes effect on ———.

Comment

[To be included in the Canadian version only.

Sections 8, 9 and 10 are formal sections which, under Rule 22 of the Drafting Rules for Writing Uniform or Model Acts of the National Conference of Commissioners on Uniform State Laws, must close every Uniform Act.]