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Comparing Energy Technology Alternatives from an Environmental Perspective

February 1981

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U.S. Department of Energy
Office of the Assistant Secretary for Environment
Office of Environmental Assessments

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Comparing Energy Technology Alternatives from an Environmental Perspective

February 1981

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Foreword

This paper is an attempt to put into perspective some of the debates that surround the question of choosing energy technology priorities primarily on the basis of environmental impact. Putting aside the reasonableness of making any choice in the public sector on the basis of a single component, this paper addresses the question of whether such an undertaking is technically possible. As such, no attempt is made to suggest an energy policy or strategy. Further, this paper is not meant to be an official position of the Department of Energy or the Office of Environment, but is presented as a research piece to improve the quality of our analyses.

Although there are several authors listed, not every one of us agreed with every statement; some clearly did not. However, all were contributors. The responsibility for the present form, therefore, must rest with the senior author.

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Emerging Issues Series

The Department of Energy stands in an interesting position vis-a-vis regulatory requirements. Like the Departments of Agriculture and Transportation, DOE is designed to respond to very specific issues that are narrowly defined to a single industry. As such, the impacts of policies and regulations of other agencies and departments, regardless of how segmented they may be, all come together to impact on industry and can be addressed as such. Because of this, the regulated industry sometimes has a better understanding of the overall effect of an agency's regulatory policies than the agency itself.

To the combined and often unanticipated impact of regulations issued and updated over time in an irregular pattern can be added the impact analyses fostered by the interaction of potentially competing goals of, for example, domestic energy self-sufficiency and environmental protection. Because regulators often have to be concerned with a large number of interest groups their regulations will affect, more indepth analyses can be expected to be put forth, in the normal course of events, from specific groups that are impacted by the regulations.

Furthermore, regulators are often constrained by legislation, legal precedent, and convention from looking at new ways of addressing old problems or recognizing problems they cause; for example, in other media, regulations must also deal with sources outside the imagination of those who drafted the original legislation or regulations, e.g., the long-range transport of air pollutants across state boundaries, which are not and cannot be controlled by the state-based regulatory strategies.

To those who are regulated, these impacts, both real and potential, are usually very clear because they have to meet these future requirements and they probably have to begin today to factor them into engineering plans. For some energy technologies, a decade or more is normal to move from planning to production state. The public sector and farsighted groups in the private sector generate numerous assessments of these emerging regulations and their impacts. Most times, because of their specialized nature and because they are designed for a particular audience, the information may never reach such communities as research, academia, or even policymakers and their staffs. This series is an attempt to capture and package several such issues in a fashion useful to a wide audience. We hope these papers can act as an early warning for some groups and serve to stimulate discussion of the issues among others, both to gauge the importance of these problems and to begin to frame strategies to address them.

Peter W. House
Director
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Comparing Energy Technology Alternatives from an Environmental Perspective

Executive Summary

What are the safest methods for producing and using energy? This question is frequently asked when national energy policy is debated. If the answer were known, it would be possible to encourage the safe technologies and to avoid the dangerous ones, thereby minimizing potential damage to human well-being and to ecosystem integrity.

*Comparative analysis has
long been advocated*

*We feel it is not really
possible yet*

A number of individuals and organizations advocate the use of comparative, formal analysis to determine which are the safest methods for producing and using energy. Indeed, some have suggested that the findings of such analyses should be the basis upon which final decisions are made about whether to actually deploy energy technologies. Some of those who support formal comparative analysis are in a position to shape the policy debate on energy and environment. This paper presents an opposing viewpoint, arguing that for technical reasons, analysis can provide no definitive or rationally credible answers to the question of overall safety. Analysis has not and cannot determine the sum total of damage to human welfare and ecological communities from energy technologies. Analysis has produced estimates of particular types of damage; however, it is impossible to make such estimates comparable and commensurate across different classes of technologies and environmental effects. As a result of the deficiencies, comparative analysis cannot form the basis of a credible, viable energy policy.

*A method for improving
decisions is presented*

Yet, without formal comparative analysis, how can health, safety, and the natural environment be protected? This paper proposes a method for improving the Nation's approach to this problem. The proposal essentially is that health and the environment should be considered as constraints on the deployment of energy technologies, constraints that are embodied in Government regulations.

Health and the environment are the constraints

Whichever technologies can function within these constraints should then compete among themselves. This competition should be based on market factors like cost and efficiency and on political factors like national security and the questions of equity.

The Failures of Comparative Analysis

Rational individuals might try to undertake a quantitative analysis of the comparative effects of energy technologies on health, safety, and the environment. In so doing, they would bring with them certain standards of validity and reliability. Both the models and data used in analysis should meet appropriate standards.

Studies based on comparative environmental analysis do not meet minimum standards

Some literature describes actual studies that report environmental impacts of energy technologies. Other literature describes conceptual methodologies for performing such an analytical task. We have carefully reviewed representative samples of both types of literature. Neither the actual studies nor the theoretical methods meet our minimum standards. If these standards were met, policymakers could trust the analytical findings. They could use them as the principal basis for tradeoffs between energy production and environmental protection. However, they cannot.

Six analytical flaws have been found

The following list indicates why the papers we reviewed did not meet the applied standards of validity and reliability. Not all the studies had every flaw, but every study had several of them. The cumulative impact of the flaws of each study or method rendered it useless as a source of clear guidance for setting policy. Such efforts simply cannot tell us which technologies to support in order to minimize environmental insults.

The deficiencies fall into the following categories: incompleteness, incommensurability, uncertainty, ignorance, subjectivity, and bias.

1. Incompleteness

The study failed to consider the complete range of agents that could cause damages; the complete range of media through which agents could act; the complete range of targets to damage, both human and nonhuman; and the complete range of effects and outcomes of exposure to agents. The study also failed to consider the complete range of technological alternatives, technological subsystems, fuel cycle stages, and siting possibilities.

2. Incommensurability

The study failed to establish a meaningful common base for comparing very different environmental impacts on either the same or on different targets. Each major energy technology has such unique environmental, health, and safety impacts that comprehensive intertechnology comparisons are very difficult. For example, how can respiratory distress in miners be compared with the disturbance of fragile ecosystems? How many dollars is a human life worth?

3. Uncertainty

The study failed to consider or deal adequately with uncertainty. Important uncertainties concern our understanding of the present energy situation; our understanding of present ecosystems; our understanding of how pollutants damage the human organism; future social preferences and energy goals; future environmental, health, and safety objectives and standards; future energy supply and demand; and future advances in the performance of energy technologies. Large ranges of two or more values were often multiplied together, thus compounding the level of uncertainties in the analysis.

4. Ignorance

The study contained postulated health and environmental impacts that were based on speculative, unproved relationships.

For example, health effects from low-level, long-term exposure of humans to an agent were estimated from the effects of shorter term, higher level doses to animals. Evidence was employed from epidemiological studies that did not have the sensitivity to disentangle the effects caused by a relevant agent and effects caused by other factors, e.g., smoking and diet. Long-term effects or slow-acting agents were omitted from analysis.

Many impacts considered were synthetically derived quantities. Individual items of data were rarely available in an appropriate form. Considerable manipulation, e.g., disaggregation, averaging, and normalization, was needed in order to use the information in the analysis. Data from work that was originally undertaken for totally different purposes were combined.

5. Subjectivity

There was excessive reliance on arbitrary, subjective judgments to determine how highly certain environmental

impacts were valued. Measures of relative importance were assigned on the basis of attitudes, beliefs, and opinions of a small number of people.

6. Bias

Errors were made in assembling, selecting, or presenting data and in choosing surrogate data sets. Often the result of this was that the bias of an author was inappropriately supported. The study also failed to make all key assumptions explicit.

Where Do We Go From Here?

Without formal comparative analysis, how can health, safety, and the natural environment be protected? This paper briefly presents a technique for partially dealing with this problem. It is based upon work that has been done by the Office of Environment in the Department of Energy. Energy technologies being developed by the Department to meet the objectives of the National Energy Plan must satisfy a set of "specifications" or requirements imposed by standards mandated under environmental legislation. In this way, national environmental policies place boundary conditions on the implementation of national energy policy. Environmental acceptability and safeguards for public health and safety are therefore designed into the technology before it is introduced into the market place. To provide a check on this development, Office of Environment scientists prepare Environmental Readiness Documents for each technology at critical decision points considering both existing and projected environmental standards.

The documents themselves do not contain direct intertechnology comparisons, but provide information to be used in such comparisons. In each document, estimated probabilities (on a scale of 0.1–0.9) are provided for three outcomes: (1) the probability that further research and development will result in an adverse finding as to the ability of the technology to meet existing and projected environmental standards; (2) the probability that such an adverse finding would result in significant delays in development and deployment of the technology; and (3) the probability of increased energy cost as a result of incorporating necessary environmental control technology. A recently completed summary of Environmental Readiness Documents that used such estimated probabilities as a mechanism for comparing 24 technologies shown in Figure 3 is discussed in Part IV of this paper.

Comparing Energy Technology Alternatives from an Environmental Perspective

I. Introduction

Formulating Policy on Complex Issues

Complex issues make decisions on energy and the environment difficult

Formulating a national energy policy involves considering a highly complex and much-debated set of issues, most of them politically charged. The complexity stems from many factors ranging from defining the nature of the energy crises, if indeed there are crises, to disagreement on ways to rectify the situation. The recent Iranian cutback on oil exports and resultant gasoline shortages have highlighted once more the domestic oil shortage issue. The Three Mile Island Nuclear Incident, [1] as well as the debates concerning the effect of the Clean Air Act Amendments of 1977 [2] on the potential for increased use of coal, illustrate the difficulties encountered when technological alternatives to the widespread use of oil are considered. To determine how to examine such alternatives and how to establish priorities established for development and deployment of new energy systems, this paper addresses a small portion of the overall energy policy debate, namely, the "cost" of energy in health and environmental terms. These complex tradeoffs should be made in a defensible, analytical manner. Regardless of the methods and information that are available, tradeoffs are constantly being made. As a result, the public seems to be calling daily for more specificity in our Nation's energy future.

This paper addresses the "cost" of energy in environmental terms

Tradeoffs between energy and the environment are being made constantly

Congress made tradeoffs in the National Energy Act

For example, throughout the process of Administration proposal and congressional debate on the National Energy Act of 1978 (NEA) [3], decisions were made that included simultaneous consideration of national energy, economic, and environmental goals. To formulate an acceptable bill, Congress implicitly and explicitly made decisions that incorporated tradeoffs among various energy initiatives, technologies, and pricing strategies. They formulated energy supply and demand goals, discussed the reliability of

major sources of energy supplies, and selected energy forms (liquid, gas, solid) that would be appropriate for the U.S. economy. They projected the comparative costs of different sources of energy over time, as well as the costs of controlling pollution from energy development and use, and the impact and opportunity costs of a potential energy shortfall on producers and consumers. They decided equity issues associated with availability of energy to consumers and projected impacts on distribution of disposable income. In the assessments of various energy technologies, Congress reviewed public health and safety considerations, along with the impacts of energy-related pollution (current, future, and cumulative) on the environment.

*Not all tradeoffs were
based on analysis*

As complex and laborious as the passage of the National Energy Act of 1978 was, it could have been worse if all decisions had been required to be explicit and analytically defensible. Consider the resources required to quantify every tradeoff so that the results of each decision could be weighed in terms of its impact on every other decision. Although such a requirement might seem impractical to experienced politicians and policy analysts, suggestions of this nature are quite common when concerned people, including planning theorists and researchers, postulate measuring environmental and economic risks of alternative energy strategies.

*The nature of the "real"
issues is often in dispute*

Reviewing the metamorphosis of the first National Energy Plan (NEP I) [4] proposed in 1977 into the National Energy Act of 1978 (NEA) demonstrates the complexity of the decisionmaking process when establishing a national policy is involved. When the first National Energy Plan was developed, many individuals disagreed about what the "real" energy issues were and how they should be resolved. Was the primary issue the physical energy supply, or was it strictly a question of supply economics, or was it national security? Or, rather, was it some combination of these issues? Should the United States continue to import oil, thereby reducing pressure for massive increases in domestic energy production? Should we switch from traditional exhaustible sources of oil and gas to inexhaustible sources of energy such as solar and nuclear technologies? Should we increase our use of our most abundant energy resource, coal? What planning should be done for near-, mid-, and long-term sources of energy?

When the NEA was debated in Congress, the "real" issues seemed to be all of those mentioned, with no special emphasis given to any single energy technology. General objectives were to reduce U.S. dependence on oil and gas, especially when imported; to delay extensive reliance on nuclear sources of energy until questions of safety and of

disposal of nuclear wastes could be resolved; to develop a solar industry for the long term; and to use coal and its derivatives extensively in the near- and mid-terms. All of these energy supply strategies were supplemented by the national goal of fostering conservation in all energy-using sectors.

*Environmental concerns
have been expressed about
many technologies*

The rationale for this strategy in the first National Energy Act was a result of several basic factors in our culture, economic systems, and quality of life. One such factor was the environmental acceptability of each energy supply technology recommended for adoption, both in itself and vis-a-vis the others. A variety of concerns were expressed about several technological solutions. For example, some interests were anxious about the nuclear option with respect to radioactive waste management problems and nuclear proliferation issues. Coal was considered by some to be an environmentally troublesome energy source, but stringent environmental standards, provisions of the Clean Air Act, and other environmental laws and regulations were thought to be sufficient to protect environmental quality. Nearly everyone believes that solar energy systems are environmentally benign, and emphasizing such sources would relieve heavy use of coal and nuclear systems, and their associated environmental impacts.

*NEP I emphasized the
increased use of coal*

NEP I recommended converting as many industrial and utility facilities as possible from oil and gas to coal. These conversions were to be accomplished in an environmentally acceptable manner, since continued improvement in environmental quality was essential.

NEP I indicates that

Coal will meet the greatest portion of increased U.S. energy needs. A comprehensive coal research and development program is a high priority. The program should focus on meeting environmental requirements more effectively and economically and should seek to expand the substitution of coal for natural gas and petroleum products.

In the short term, most coal will continue to be burned directly. Hence, the highest immediate priority is the development of more effective, economical methods to meet air pollution control standards.

Except for nuclear waste disposal, the plan included little mention of specific environmental impacts from nuclear technologies. On the other hand, solar and renewable sources of energy were cited as a long-term goal. NEP I

The environmentally sound production and use of energy was advocated

emphasized "small, dispersed, and environmentally sound production and use of energy, particularly renewable energy."

The President's environmental program for 1977 reiterated the need to enforce strict environmental protection standards while trying to formulate a rational energy strategy.

Through NEP I, the President supported use of the "best available control" technologies in all new facilities and, in particular, "strict controls on coal-burning plants to ensure that they meet air quality standards."

NEP I further states that

The transition to renewable energy resources, particularly solar energy, must be made. But it will take time. Meanwhile, we should satisfy our energy needs from existing sources, both fossil and nuclear, in a safe and environmentally acceptable way.

NEP I goes on to discuss the environmental problems with the primary transitional fossil fuel that the Nation has available: coal. Studies were to be done, standards were to be set, and protection of the environment was to be guaranteed. But the message was clear; coal was the favored fuel source in the near and mid-term future, and control technologies were to be developed that would mitigate unacceptable environmental side effects. Nuclear energy was admitted to have great potential, but was to be deemphasized until waste management and proliferation fears were adequately addressed. The use of solar energy, assumed to have a relatively benign environmental impact, was to be encouraged in the commercial sector.

Comparison of Environmental Impacts

Environmental constraints can limit the use of an energy technology

Penetration of the market by one energy technology might be limited by stringent environmental constraints, depending upon the pollutant or medium so constrained. For example, a total coal strategy could result in more air pollution than a total nuclear strategy; while a total nuclear strategy could result in more incidents of exposure to ionizing radiation than a total solar energy strategy, and so on.

There are many problems in comparing the environmental impacts of energy technologies

Each major energy technology tends to have such unique environmental, health, and safety impacts that comprehensive intertechnology comparisons are difficult, if not impractical. The problem of comparing environmental impacts of energy technologies is compounded by the lack of

information concerning the health effects of energy-related pollutants. Present day concerns about nuclear energy systems, for example, center around radioactive waste management, public safety, and the effects of low-level radiation. For coal-based systems, only a few of the many known pollutants have been definitively and quantitatively linked to health effects. Even when health standards exist, as for total suspended particulates, problems may remain. For example, current analyses indicate that the fine particulates, which are not specifically regulated and for which pollution controls are less effective, may prove to be a serious health hazard.

It is very difficult to demonstrate analytically the environmental superiority of one technology over another

Recently, environmental regulations are often considered to be one of the most significant barriers to energy development, while, conversely, energy development is thought to have the potential for producing significant damage to the health and safety of humans and to ecosystems. Therefore, it might be argued that any policy that produces energy at the least risk to the environment would be, per se, preferable. We do not intend to further muddy this swirling stream of controversy by espousing yet another opinion; instead we suggest that the very attempt analytically to demonstrate the superiority of one technology over another, given the state of our knowledge, may actually exacerbate the choice problem. Not that trained analysts should not provide insights to the debate, but within the limited information available and the lack of a commonly accepted calculus, even the more sophisticated techniques become unreliable and the guidance they suggest potentially misleading.

We review studies of energy/environmental tradeoffs in Section II

To demonstrate this assertion, in Section II we have reviewed a number of studies purporting to measure energy/environmental tradeoffs. Not all known studies comparing the energy technologies or suggesting the role of environmental considerations in policymaking have been reviewed. The studies discussed are a sampling of the better known efforts and provide a representative picture of recent attempts in comparing impacts of energy technologies.

No study is definitive. We can identify six common flaws

In general, none of the studies is a universally acceptable assessment of the environmental impacts of the various energy systems. The fact that each energy system tends to have a unique set of impacts makes their comparison difficult. Presently, there is no well-developed, widely accepted calculus for handling this complex problem. But there are other reasons for questioning the findings of these studies:

- Failure of analysts to consider one or more of the factors that are crucial in formulating public policy, e.g., security of energy supply or market readiness

- Lack of sufficient empirical data to substantiate the models employed; e.g., there are insufficient supporting data for realistic implementation of cost-benefit techniques
- Poor integration of national goals, such as energy independence or security, into the quantitative objective functions required to implement most of the decision models
- Failure of analysts to consider distributional problems
- Failure of most assessments to be totally objective—either through personal bias or variation in the quality of the data used
- Failure to account for the effects of environmental regulations generally or as specifically applied in particular situations.

A Process for Tradeoff Analyses

*A model for judging
environmental assessments
is presented*

The process shown in Figure 1 will order our thinking for judging the completeness of the environmental assessments. A complete analysis should take into consideration all of the items presented in the Figure 1. The process begins with an agreed-upon scenario that estimates the amount of energy required by the specific technology at locations in the Nation. The agreed-upon mix of technologies would then be analyzed over the total fuel cycle (including secondary impacts induced by construction) and for those impacts unique to each geographical location. The site-specific impacts are used to derive average coefficients for environmental impacts that are regionally sensitive.

Ideally, environmental impacts include consideration of such factors as habitat conservation and other ecological effects, as well as accidents and human morbidity and mortality effects due to illness. Finally, the raw impact data will be used to derive damage estimates, the benefit of avoiding the damage, and intertechnology risk estimates.

*There are limits to energy
tradeoff studies*

Unquestionably, the use of quantification in the process portrayed in Figure 1 is difficult and is not likely to be achieved in the near future for the reasons noted in the critiques of comparative studies that were given earlier. Our level of understanding as a society of the significant energy-related environmental impacts that might occur is

Figure 1. "Ideal" taxonomy of energy-environment issues

rather primitive. Even in areas where we have better understanding, there is still a great deal of debate over the interpretation of data. In many analyses, the energy technologies themselves are highly aggregated, are not differentiated by process, are not collocated geographically, and may be skipped altogether. Often the only environmental effects that are studied in depth involve health and occupational impacts, while little attention is given to ecological effects.

Because the total environmental picture is not usually considered, most energy tradeoff studies seem weak and somewhat biased. The methods employed in these studies do not represent all of the possible methods for comparing alternative energy technologies. Conceptually, several more exist.

The taxonomy presented is made up of two major portions. The left side asks where the pollution is taking place, when it is apt to occur (and what else is occurring at the same time and place), and how much is being generated. To accomplish this, questions of energy demand (and conservation) are addressed by geographical locations and by stages of the fuel cycle. Thus at any particular time and place one knows the full supply and demand picture for energy-pollution-related changes against a backdrop of complete system environmental growth or change.

The second portion of the figure represents the translation of environmental coefficients into total impact values. The coefficients are specific for location, time, sector, and stage of the fuel cycle.

Clearly, these requirements for a full assessment of any single technology make the study very complex and time consuming. It would indeed be difficult to do several such studies for each fuel or technology type, however desirable it might seem.

*Theoretical approaches
outstrip the ability to
actually perform
assessments*

As our investigation of the methodologies illustrates, there is no lack of guidance about how to carry out assessments allowing an objective tradeoff of energy, environment, and economics. Investigation of the actual studies makes it clear that the theoretical structure outstrips the capability of carrying out the actual assessments. In fact, in this area of environmental tradeoffs when health and safety risks are the principal impact variables, lack of confidence in the data means that the adage, "little information is better than none at all," is replaced by "a little knowledge is a dangerous thing."

*There are problems with
health-related statistics*

To be more specific, the high levels of uncertainty in health-related statistics add a dimension of confusion to pollution or safety information that only confuses the decisionmaker. For example, a recent study done by Brookhaven National Laboratory as part of the National Coal Utilization Assessment (NCUA) translated air emissions data calculated on the basis of industrial and utility combustion into long- and short-range transport of pollutants. These data were then used to compute the expected health effects of the study scenario, using a 60 percent confidence region in order to deal with the range of possible error in the estimates of health damage. In 1985, between 7,600 and 122,000 excess deaths were forecast, and in 1990, between 8,600 and 140,000 compared to a range of 7,500–120,000 in 1975. Ignoring the confusing nature of the term “excess deaths,” the significant fact is that when the confidence limit is extended to 95 percent (two standard deviations) in 1985, the number of excess deaths is estimated to be from 0 to 250,000. [5] These numbers, even assuming that one can give some credence to them at face value, provide a range so great that it is unclear what a decisionmaker should do. Such data are so primitive that it is questionable whether they can truly be considered “information.” Surely the steps of the calculation from pollution emitted, to population-at-risk, to estimates of mortality cannot add to the caliber of the decision, if the data deteriorate as rapidly as experience suggests.

*The proper function of the
analyst is not normative in
nature*

We assume that the studies that attempt to trade off energy, economics, and environment ought not to be normative in nature. Although it is right and proper for an analyst to continually strive to introduce the best analytical process that can be brought to bear on an issue, it is not the place of an analyst to prejudge the outcome of an analysis by proselytizing a specific technology at the expense of others. Although this may seem extreme, the situation often gets out of hand when proponents of a technique condemn a decision process in favor of their own pet theory or technique, regardless of the practicality of actually carrying out the assessment. Normative analysis that sets out to teach the policymakers how they “should” make decisions comes dangerously close to the prejudgment flaw. In short, this paper considers the proper function of the analyst to be to facilitate the decision process by making available the best information that can be brought to bear in a timely fashion, as objectively as possible.

Again, no refutation is intended concerning the value of analysis per se. However, the line is drawn in this paper at several points:

*Data should not be
speculative*

- Data should be presented only if the analyst is fairly certain of its causality, value, sign, etc. Highly speculative relationships, values, and the like, or ones that are known to be very incomplete have no place in a policy analysis, although they may be useful in a broader research or assessment piece.

*Emotional issues should be
treated with care*

- At the very least, a taxonomy of effects and impacts may be all that can be presented in a tradeoff analysis, and, in areas where the emotional impact quotient is high because of the nature of the subject matter, great care must be exercised to exclude pejorative findings—regardless of how well documented they are.

*Limited data should not
be over-interpreted by
sophisticated techniques*

- In the situation where an analyst is stretching hard to find enough information to say something meaningful about a tradeoff, it is inappropriate to suggest sophisticated techniques that rely on a richness of data and that enable stochastic and distributive measures to be applied to the findings.

*How can the tradeoffs be
addressed?*

Given the complexity of formulating a national energy policy, the variety of variables that should be examined, the lack of data on environmental impacts, the uncertainties in the existing data, and the many public interests, how then does one address the issue of environmental tradeoffs between energy alternatives? This issue is explored in the remainder of this paper, focusing on three general questions:

- How have complex tradeoff analyses been carried out in the past?
- What methodologies are currently available for performing such tradeoff analyses?
- How can tradeoffs of energy and environmental issues be improved?

*Section II reviews actual
tradeoff studies*

Section II reviews the current literature. These reviews are, of necessity, brief and will only give the reader a general idea of what is in the whole piece. Further, only a partial critique is done of the study in terms of such factors as data consistency, accuracy, and utility. Whenever possible, the analyses will be related back to the ideal structure presented earlier in this section.

*Section III reviews metho-
dological approaches*

Section III will take us from the actual attempts presented in Section II, to a more generalized discussion of the various techniques and conceptualizations proposed to handle

trading off such variables as energy, economics, and environment. Again, a critique is given of each technique, primarily from the perspective of its utility today in real-world policy issues. We intend no judgments as to their utility as useful approaches for some energy analyses.

*Section IV presents a way
of dealing with energy and
environmental tradeoffs*

Section IV summarizes the principal limitations of current analyses and methods. It suggests a way to handle the problems of comparing energy technology alternatives for decisions on a national energy policy that must be defined in the next few years.

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II. Studies Comparing Energy Technologies Impacts

Examining Tradeoffs

*Assumptions used in
analysis are
often questioned*

Nothing is attacked so vigorously by special interests and professional analysts as the set of assumptions on which a controversial major decision or finding is based. [6, 7] A careful analysis, reexamination, or even a new long-term original effort often results in conclusions that are counter to the original prognosis. This results in a certain fame or notoriety for the analyst who reveals the new conclusions. Certainly situations of this sort took place as a result of the first National Energy Plan and its implementation through the National Energy Act.

*Several cross-technology
studies have been published*

In the environmental area, a variety of studies and analyses have been published in which authors have addressed such concerns as public safety and nuclear power development, the management of radioactive wastes, the effects of exposure to low levels of nuclear radiation, and the mining and transportation of coal. There are frequent questions about how environmentally benign solar energy technologies are. Coal, oil, and gas production, distribution, and use have been subjected to increasing scrutiny concerning their related health and safety impacts on man and certain ecosystems. Such studies are being carried out, not only by researchers interested in testing earlier premises, but also by proponents and opponents of specific energy technologies who see the comparison of environmental impacts of one vis-a-vis another as a way to foster their own preferences. Such cross-technology studies are the focus of this section.

Some authors attempt to apply a common measure to compare technologies

A number of studies published during the past few years purport to show the environmental acceptability of one energy technology in relation to the others. Because the studies are themselves unique in the sense that they are not clear examples of particular methodologies, it is difficult, if not impossible, to categorize them. Most of the authors search for a common unit or attribute that allows them to compare technologies. For several studies, this consists of estimates of morbidity and mortality related to units of energy production. Generally, the individual authors admit that their data are sparse. However, depending upon relative data availability and ingenuity, they do go on to "quantify" the risks associated with different stages of each energy technology fuel cycle. Estimates are then made of "costs" and impacts of energy production. In contrast, a more useful study would be one that estimates the total "cost" of an energy technology cycle on our ecological systems and human health for all subtechnologies and all phases of the fuel cycle. No study reviewed herein comes close to this ideal.

Nuclear Power—Compared to What?

The impacts of nuclear power, coal use, and emerging technologies are compared

In an article in *American Scientist* in 1976, Rose, Walsh, and Leskovjan [8] compared the impacts of nuclear power to coal use and emerging energy technologies. The focus of the article is on the decisions that will affect electric power generation in the year 2000. The article was written with the assumption that petroleum and natural gas will be depleted by that time. As the authors see it, the basic energy supply will have to be chosen from nuclear fission (including the breeder), central station fusion, bulk solar power, and coal combustion.

Health impacts are described

This study addressed the health impacts of several different technologies and included a terse description of the technologies themselves. The authors concluded that, after maximizing efforts to conserve energy and to use it more efficiently, the choice for replacement of power plants before the year 2000 must be between coal and nuclear power. They stated that, in a stable society, nuclear power is generally superior to coal unless plutonium is as hazardous as its most severe critics claim; emissions from coal are very strictly controlled; and the current reactor safety studies misstate the risks by some very large factors. The authors suggest that the proper use of coal is as a chemical feedstock rather than as a basic power source. They base their conclusion on the fact that over a billion dollars has been spent on reducing and eliminating nuclear hazards. Nothing approaching this amount has been spent on coal, thus suggesting a gap in knowledge.

Flaws include: questionable data and lack of information

Critique. This study makes an informed attempt to compare energy technologies and to delineate the data gaps concerning related health effects, particularly for the coal technologies. However, in some cases, the work is outdated; it uses questionable data from old studies such as the EPA CHESS (1970–1971) [9] and the NRC Rasmussen (1975) [10] studies. Further, the authors have so qualified their analysis that they have essentially claimed that the validity of their data base and their findings is a function of the knowledge available about each of the alternative technologies. In short, their conclusions are only as valid as the available research results, which does not come as a surprise. Clearly one major problem with comparative assessments of energy technologies is a serious lack of effects and safety research results, especially for the nonnuclear technologies.

Several types of effects are ignored

In terms of our “ideal,” the study only partially addresses the demand, technology, and conservation areas, ignores ecological impacts and risk assessment, and, as noted above, treats human impacts with inadequate data.

Health Evaluation of Energy-Generating Sources [11]

This study compares human health effects of major energy fuel cycles

The goal of this study, published in 1978, was to compare the effects of coal, nuclear power, and other major energy-generating fuel cycles on human health. The methodology employed characterized each stage in a fuel cycle through a series of effects modules, each depicting environmental stress. The modules are related by vectors that define the series of effects or components of the fuel cycle on an ecosystem. Each effects diagram provides a means of predicting the impact throughout the ecosystem of various stresses produced by fuel cycles. The major components of the coal and nuclear fuel cycles are: resource extraction processing, fuel transportation, fuel storage, power generation, reprocessing, and waste management.

Mortality and morbidity

The authors estimate the total number of deaths and injuries from the two major fuel cycles, coal and nuclear. The estimated values are given per 1,000 MWe units of energy output per year. Table 1 contains estimates combined from several sources. Table 2 categorizes the data in terms of mortality and morbidity for the coal, oil, natural gas, and nuclear fuel cycles. These estimates show that a coal-fired power plant may cause 40 to 285 more total deaths per year than a nuclear plant, 2 to 3 more than oil, and 26 to 1,120 more than the natural gas cycle. In an attempt to place these estimates in perspective, the study relates them to similar total impacts from production in the

Table 1. Estimates of Health Effects of Coal and Nuclear Fuel Cycles

Procedure	Occupational Deaths*	Occupational Injuries and Disease*	Nonoccupational Deaths
Coal Fuel			
Extraction			
Accidents.....	0.45-1.24	22.0-80.0.....	
Disease.....	0.00-4.8	0.6-48.0.....	
Transport			
Accidents.....	0.055-1.9	0.33-23.0	0.56-1.3
Processing			
Accidents.....	0.02-0.05	2.6-3.1	1.0-10.0
Air Pollution			0.067-295.0
Total**	0.054-8.0	26.0-156.0	1.62-306.0
Nuclear Fuel			
Extraction			
Accidents.....	0.005-0.2	1.8-10.0.....	
Disease.....	0.002-0.1		
Transport			
Accidents.....	0.002-0.005	0.14-0.45.....	
Processing			
Accidents.....	0.003-0.2	0.6-1.5	
Disease.....	0.13-0.33		
Power Generation			
Accidents.....	1.01	1.3	0.01-0.16
Disease.....	0.00-0.1		
Total**	0.035-0.945	3.7-13.0	0.01-0.16

*Per 1,000 megawatt electric units per year.

**Some totals do not add up because of rounding.

Source: "Health Evaluation of Energy-Generating Sources," *Journal of the American Medical Association*, Volume 240, No. 20, November 10, 1978, pp. 2193-2195.**Table 2. Comparison of Health Effects of Alternative Fuel Cycles***

Effect	Coal	Oil	Natural Gas	Nuclear
Occupational Deaths.....	0.54-8.0	0.14-1.3	0.06-0.28	0.035-0.945
Nonoccupational Deaths	1.62-306.0	1.0-100.0.....		0.01-0.16
Total Deaths	2.16-314.0	1.1-101.0	0.06-0.28	0.045-1.1
Occupational Impairments.	26.0-156.0	12.0-94.0	4.0-24.0	4.0-13.0

*For electric power production per 1,000 megawatt electric units.

Source: "Health Evaluation of Energy-Generating Sources," *Journal of the American Medical Association*, Volume 240, No. 20, November 10, 1978, pp. 2193-2195.

United States in 1975. The large number of coal-related deaths or accidents still stand out. In addition to the figure estimated from emissions-related research, the authors suggest the number could be even larger.

One problem is inadequate data

The study goes on to state that available data are inadequate for other energy sources such as solar, geothermal, and hydropower. The authors state:

In comparisons between coal and nuclear fuel cycles, a greater uncertainty in the estimates occurs in the former because data are sparse and equivocal whereas radiation measurement can be made fairly precisely down to low levels.

The authors mention several difficulties with their statistics; problems relating the data obtained in the different health-related studies to each other; difficulties in estimating long-term effects, such as carcinogenesis and genetic effects; limited and uncertain data; and low-level or very-long-range effects such as increased levels of carbon dioxide and low doses of radiation.

Flaws include: broad ranges of estimated effects

Critique. This study focuses on specific sources of energy-related health effects and attempts to delineate impacts associated with various stages of the major fuel cycles. The authors are aware, however, that there are significant problems associated with using data from several sources. They indicate very large ranges in their data without discussing why the ranges are so large or how such large ranges affect their conclusions. In the comparisons of total deaths or impairments in Table 3, the ranges are spread from factors of 6 to 170 or more.

Estimates for different technologies overlap

Such large ranges raise questions about the utility of the exercise and the validity of the conclusions. For example, if the low and high values are equally possible, then in

Table 3. Comparison of Health Effects for Alternative Fuel Cycles**

Fuel	1975-kW-hr. Electric 9 Units X 10	Equivalent No. of 1,000 Megawatt Electric Plants	Estimated Deaths		Estimated Occupational Impairments
			Occupational	Nonoccupational	
Coal.....	844	128	69.0-1,024	207.0-39,168	3,330-20,000
Oil	292	44	6.0-57	44.0-4,400	530-4,100
Gas	297	45	3.0-13.....		180-1,080
Nuclear ..	168	26	0.9-25	0.3-4	100-340
Total**	1,601	243	79-1,119	251-43,572	4,140-25,000

*For electric power production in the United States in 1975.
**Some totals do not add up because of rounding.

Major types of impact are omitted

several cases the low and high estimates of different fuel cycles overlap, suggesting that there may be little difference in the expected health effects from the different fuel cycles. The coefficients for almost all fuel types (coal and oil) for all health effect categories overlap as shown in Table 4. The study does not address energy demand or conservation. Neither are ecological impact, risk assessment, or benefits addressed. Human impacts are noted with caveats. As such, it is incomplete according to our ideal taxonomy.

Table 4. Enhanced Risk of Death per Year from Electricity Production*

Age (years)	Normal Risk of Death per Year**	Enhanced Risk of Death per Year	
		Coal and Oil	Nuclear
10.....	1/3,800	1.38/3,800	1.0008/3,800
25.....	1/700	1.07/700	1.0001/700
45.....	1/200	1.02/200	1.00004/200
65.....	1/40	1.004/40	1.000008/40
All ages.....	1/100	1.01/100	1.00002/100

*Adapted in part from C. L. Comar and L. A. Sagan, "Health Effects of Energy Production and Conversion," *Annual Review of Energy*, Volume 1, 1976, pp. 581-600.

**Risk of death per year from natural gas as fuel for electric power production is equivalent to the normal risk.

Health Effects of Energy Production and Conversion

This study describes the health risks of energy production

This study by Comar and Sagan was published in the *Annual Review of Energy*. [12] It moves the issue of estimating health effects caused by energy technologies a step further by relating the health effects to a risk value. The study delineates a series of shortcomings of earlier analyses, including the fact that synergistic or additive effects among various pollutants have not been considered, health effects have usually been expressed in terms of single factors such as numbers of either premature deaths or serious disabilities, and finally, the limitation of using risk estimates that monetize impacts in terms of abatement costs.

The authors present damage functions

The authors describe damage functions in terms of exposure, from low to high levels of pollutants, and also the effect of exposure, ranging from no effect, undetectable effect with low probability, undetectable effect with high probability, clinical symptoms, and ultimate death. The low probability, little-effect area distinguishes between threshold and nonthreshold agents.

For the former, there are levels of pollution below which no effects occur. From this, the authors assert that to set

pollution standards for nonthreshold agents that have harm associated with any level above zero requires the acceptance of some risk, unless the agent can be totally eliminated.

They define their concept of risk partly in terms of the probability of death caused by energy-related pollutants. The effects of various forms of energy production are appraised in terms of their impact on the general population, although the authors recognize the risk of death of highly age-specific populations. They present their results by age cohort.

Using information from a variety of sources, they generate a comparative analysis of the health effects in terms of premature deaths and occupational injuries associated with the operation of a 1,000 MWe powerplant. The results are ranges bounded by high and low values for each stage of the coal, oil, natural gas, and nuclear fuel cycles (Tables 5 and 6).

*Coal related deaths are
larger in number*

Finally, the authors convert the health effects data to estimates of risk (Table 7). The table is age-specific and technology-specific, but relates the estimates of impacts from energy technologies to normal risks of death from any and all causes for the same age groups. The final conclusion of the study is that occupational deaths from the use of coal are considerably greater than for the other technologies. Premature deaths are also likely to be larger from the use of coal and oil than from natural gas or nuclear fuel.

*Questions arise about
damage functions*

Critique. Introduction of risk estimates for comparing different energy fuel cycles adds a new and more complex dimension to the issue of technology tradeoffs. However, in this specific study, the damage functions employed come under question because the calculation of final risk is not actually presented and documented. Although not explicitly stated by the authors, the health effects data seem to be translated to deaths and injuries per unit of output and then to risk of death per year. The risk table includes discrete values by age cohort, but the health effects table presents results with large ranges of uncertainty. As with most studies of this nature, the effects of long-term, low-level exposures to powerplant emissions are not adequately addressed. Sorting out such effects from similar impacts caused by other sources of pollution, such as smoking, vehicle emissions, and natural sources is very difficult. The information presented is in the form of coefficients and, therefore, is only an input into the taxonomy we presented at the end of the first section.

Table 5. Premature Deaths per Year Associated With Operation of a 1000-MWe Powerplant

	Coal	Oil	Natural Gas	Nuclear
Occupational				
Extraction				
Accident	0.45-0.99	0.06-0.21	0.021-0.21	0.05-0.2
Disease	0-3.5			0.002-0.1
Transport				
Accident	0.055-0.4	0.03-0.1	0.02-0.024	0.002
Processing				
Accident	0.02-0.04	0.04-1	0.006-0.01	0.003-0.2
Disease				0.13-0.33
Conversion				
Accident	0.01-0.03	0.01-0.037	0.01-0.037	0.01
Disease				0.024
Subtotals				
Accident	0.54-1.5	0.14-1.3	0.057-0.28	0.065-0.41
Disease	0-3.5			0.039-0.45
Total	0.54-5.0	0.14-1.3	0.057-0.28	0.10-0.86
General Public				
Transport	0.55-1.3			
Processing	1-10			
Conversion	0.06-100	1-100(17)		0.01-0.16
Total	1.6-111	1-100		0.01-0.16
Total Occupational and Public	2-116	1.1-101	0.057-0.28	0.11-1.0

From: "Health Effects of Energy Production and Conversion," C. L. Comar and L. A. Sagan, *Annual Review of Energy*, Volume 1, 1976, pp. 581-600.

Table 6. Occupational Injuries per Year Associated With Operation of 1,000 MWe Powerplant

Occupational Injuries	Coal	Oil	Natural Gas	Nuclear
Accident	22-49	7.5-21	2.5-21	1.8-10.0
Disease	0.6-48			
Transport				
Accident	0.33-23	1.1-9	1.2-1.3	0.045-0.14
Processing				
Accident	2.6-3	3-62	0.05-0.56	0.6-1.5
Conversion				
Accident	0.9-1.5	0.6-1.5	0.6-1.5	1.3
Totals				
Accident	26-77	12-94	4-24	4-13
Disease	0.6-48			

From: "Health Effects of Energy Production and Conversion," C. L. Comar and L. A. Sagan, *Annual Review of Energy*, Volume 1, 1976, pp. 581-600.

Table 7. Summary of Implications of Quantitative Assessments of Health Effects in the General Population Associated With Electricity Production
(All values rounded)

		Coal and Oil	Natural Gas	Nuclear
Premature Deaths/Year/ 1,000-MWe plant		2-100	0	0.01-0.2
Added Risk/Year*		1 in 10,000	0	1 in 5,000,000
Age	Normal Risk of Death/Yr	Enhanced Risk of Death per Year Because of Electricity Production*		
10	1 in 3,800	1.38 in 3,800**	1 in 3,800	1.0008 in 3,800
25	1 in 700	1.07 in 700**	1 in 700	1.0001 in 700
45	1 in 200	1.02 in 200**	1 in 200	1.00004 in 200
65	1 in 40	1.004 in 40	1 in 40	1.000008 in 40
All ages.	1 in 100	1.01 in 100	1 in 100	1.00002 in 100
Numbers of premature deaths in 30 years associated with routine operation of 300 plants***		20,000 to 1,000,000	0	100 to 2,000
Number of deaths statistically predicted from catastrophic accidents in 30 years from 300 plants§[Rasmussen estimated]				10

* Upper estimates.

** These estimates are undoubtedly quite high because premature deaths from fossil fuel combustion products fall almost exclusively in the older age groups.

*** This represents the total operation for a generation of power plants that would supply about 300 million people.

§ Based on 1 chance in 10 of an accident per reactor-year causing 1,000 immediate and delayed casualties.

Comparative Risk-Cost-Benefit Study of Alternative Sources of Electrical Energy [13]

This study compares cost and impact data for electric powerplants

This study, completed in 1974, was conducted by MIT for the U.S. Atomic Energy Commission. It compares cost and impact data for electric powerplants and examines the various basic fuel cycles. The study normalizes all comparisons to the annual energy produced by one 1,000 MWe unit operating at 75-percent capacity. The basic fuel cycles considered are coal, oil, gas, and nuclear. All fuel cycle parameters are normalized to annual unit energy outputs through equilibrium fuel material balances. The resulting evaluation is a static comparison of estimated costs and impacts associated with the alternative energy systems.

Cost comparisons for alternative energy systems derived in this study are given in Tables 8 and 9. Environmental impacts are directly related to emission rates normalized to a unit of electrical energy produced. These health and safety impacts were monetized and added together to arrive at

Table 8. Comparison of Costs and Impacts of Alternate Electrical Energy Production Systems

	Basis: 1000 HMe Power Plant, 75 percent CF 6.57 x 10 ⁹ kWhe			
	Coal	Oil	Gas	LWR
Power Plant and Energy System Efficiencies				
Electrical Energy (billion kWhe/year).....	6.57	6.57	6.57	6.57
Power Plant Heat Rate (BTU/kWhe).....	8,900	8,830	9,110	10,850
Power Plant Thermal Efficiencies (kW _e /kW _t) percent.....	38	39	39	32
Energy System Efficiency (kWhe consumer/kWhe input, percent).....	35	35	34	28
Consumption of Nonrenewable Fuel Resources				
Power Plant Fuel Consumption (annual)	2.3 M tons	10 M barrels	64 B cubic feet	130 M tons U ²
Fraction of Reserves Consumed (annual).....	0.000006	0.0001	0.0004	0.0002
Conventional Costs (mills/kWhe)***				
Plant	7.8	7.2	6.4	11.7
O&M.....	0.8	0.6	0.6	0.8
Fuel.....	9.8	27.4	36.0	6.0
Total	18.4	35.2	43.0	18.5
Selected Abatement Costs (mills/kWhe)***	4.7	2.0	0.6	0.6
Occupational Health and Safety				
Occupational Health (MDL/year).....	600	U	U	480
Occupational Safety				
Fatalities (Deaths/year).....	1.1	0.17	0.08	0.1
Non-Fatal Injuries (per year).....	46.8	13.1	5.3	6.0-7.0
Total Man-Days Lost (MDL/year).....	9,250	1,725	780	900-1,000
Public Health and Safety				
Public Health				
Routine Pollutant Release (MDL/year).....	U	U	U	180-210

10

	Basis: 1000 HMe Power Plant, 75 percent CF 6.57 x 10 ⁹ kWhe			
	Coal	Oil	Gas	LWR
Public Safety				
Transportation Injuries				
Fatalities	0.55	U	U	0.009
Non-Fatal Injuries (per year)	1.2	U	U	0.08
Total Man-Days Lost (MDL/year)	3,500	U	U	60
Environmental Degradation				
Land				
Land Use, Inventory (acres)	22,400	1,600	3,600	1,000
Land Use, Consumption (acres/year)	740	S	S	12
Air				
SO ₂ release, w/o abatement (tons/year)	120,000	38,600	20	3,600
, w abatement	24,000	21,000	0	720
NO _x release, w/o abatement (tons/year)	27,000	26,000	13,400	810
Particulate releases, w/o abatement (tons/year)	270,000	26,000	518	8,000
, w/abatement	2,000	150	4	60
Trace Metals releases (tons/year)	0.5 Hg	1,500 V	U	S
Radioactivity releases (Ci/year)	0.02	0.0005	S	250-500 T
Thermal Discharge, power plant stack (billion kWh/year)	1.64	1.71	2.2	0
Water				
Cooling Water Use (billion gal./year)	263	263	263	424
Process Water Use (billion gal./year)	1.46	1.75	1.42	0.095
Radioactivity releases (Ci/year)	0	0	0	500-1,000
Other Impacts (billion gal./year)	16.8	7.9	0	S
Thermal Discharge, power plant (billion kWh/year)	9	9	9	14

U = Unevaluated; S = Small; M = Million; B = Billion; T = Thousand

*The number of digits shown is not generally indicative of precision. In many cases, several digits are retained merely for calculational purposes.

***1980 dollars.

From: U.S. Atomic Energy Commission, *Comparative Risk-Costs-Benefit Study of Alternative Sources of Electrical Energy*, USGPO, Washington, D.C. 1974.

Table 9. Comparison of Conventional Costs and Some Evaluated Non-Conventional Costs of Alternate Energy Systems
Basis: Annual Operation of one 1000 MWe Power Plant and Supporting Fuel Cycle (6.57 billion kWh, 1950 dollars.

	Coal	Oil	Gas	LWR
Conventional Costs (\$10 ⁶)/yr)				
Capital Plant.....	51	47	42	77
Fuel Cycle.....	64	180	237	39
O&M.....	5.4	4.0	3.7	5.2
Rounded Totals.....	120	231	283	121
Abatement Costs				
Cooling Towers.....	3.6	5.9	7.1	2.4
Sulfur/SO ₂ Removal.....	25.9	4.9	NA	NA
Strip-Mined Land Reclamation (\$10 ⁶ /yr).....	150	242	290	125
Near-Zero Radwaste.....	NA	NA	NA	1.2-1.0
Rounded Totals.....	30	11	7	3-4
Conventional & Abatement (\$10 ⁶ /yr).....	150	242	290	125
Abatement Component (percent).....	20	5	2	3
Safety (\$10 ⁶ /yr)				
Occupational ^a	0.46	0.086	0.039	0.05
Public.....	0.18	U	U	0.003
Subtotal.....	0.64	> 0.086	> 0.039	0.053

Table 9. Comparison of Conventional Costs and Some Evaluated Non-Conventional Costs of Alternate Energy Systems
Basis: Annual Operation of one 1000 MWe Power Plant and Supporting Fuel Cycle (6.57 billion kWhe), 1950 dollars. (Continued)

	Coal	Oil	Gas	LWR
Health (\$10 ⁶ /yr)				
Occupational.....	0.03 ^c	U	U	0.024 ^d
Public.....	U	U	U	0.01 ^d
Subtotal.....	>0.03	U	U	0.034
Total Human Health & Accident (\$10 ⁶ /yr)				
Costs.....	>0.67	>0.086	>0.039	0.087
Environmental Effects (\$10 ⁶ /yr)				
Water Base.....	0.4	0.4	0.4	0.6
Air Base.....	0.8	0.6	0.1	S
Land Base.....	0.2	S	S	S
Subtotal.....	1.4	1.0	0.5	0.6
Total Human & Env. Effects (\$10 ⁶ /yr)	2.1	1.1	0.5	0.7
Percent of Conv. (percent).....	3	1	0.5	0.9

Key: U = Unevaluated; NA = Not Applicable; S = Small

Footnotes:

- (a) Conventional injuries in routine industrial accidents, including fatal and non-fatal injuries; 1 death = 6,000 MDL = \$300,000.
- (b) Conventional injuries in accidents in transportation of fuels; 1 death = 6,000 MDL = \$300,000.
- (c) Coal Workers' pneumoconiosis (CWP).
- (d) Radiological health effects, including lung cancers among uranium miners.
- (e) Radiological health effects from routine emissions.

From: U.S. Atomic Energy Commission, *Comparative Risk-Cost-Benefit Study of Alternative Sources of Electrical Energy*, USGPO, Washington, D.C. 1974.

estimates of total costs of human health and accidents for the alternative energy systems. The authors state that

Risks are treated as costs in this study: the product of the probability of an undesirable event (per unit of electrical energy) times the consequences of the event.

Occupational health and safety and public health and safety are admittedly hard to quantify fully.

The dose-response is the weakest link in this chain. Radiation effects are said to be better understood than those from coal but some attempt can be made to compare the costs of alternate energy systems.

Study limitations are cited This study cites the following limitations:

- The costs tabulated do not form a complete set, nor are they mutually exclusive, for this reason, the table does not yield total social costs of producing electricity;
- In several categories, only very crude estimates of nonconventional costs could be made; in general, it was found that small quantities are attended by the greatest uncertainty; and
- The unit costs of \$50/man-days lost and \$30,000/death, assigned more or less arbitrarily to permit comparisons of health impairment and injury costs with conventional costs, are highly subjective and may be challenged on emotional and moral grounds.

None of these shortcomings, however, invalidate the major conclusions and findings of the study, reviewed in the next section. The salient point is that even drastic changes in the very small quantities in question will not propel these quantities to dominant importance.

Choice of life value, if applied consistently, will not distort the relative impacts of the competing energy systems.

Further, whatever value is assumed, within reason, the health and injury costs will remain small compared to the conventional costs of producing electricity. Similarly, the figures do not alter the conclusion that these costs are small compared to conventional costs. The same general argument could apply to overlaps and omissions in the Table.

In summary, according to this study, the costs of human health and injury (both occupational and to the public) of new power stations are small in relation to conventional energy costs. Because of this, resource availability is apt to have greater influence than environmental considerations. Health and injury impacts are greater for occupational personnel than for the public.

The use of coal, the most abundant domestic fuel for electric generation, causes the most serious environmental problems. Nuclear power is portrayed as having minimal environmental problems:

Though relatively small in mass and volume, material flows and the residuals in the nuclear fuel cycles are not without very substantive potential hazard. For this reason, nuclear systems are designed, fabricated, and operated with numerous safeguards, high performance radwaste systems, redundancies, and with increasingly vigilant quality assurance programs and standards.

Data are missing or uncertain

Critique. This is a comprehensive and ambitious study in terms of consideration of risk, the conceptual design, and the data collection for the analysis. However, as the study progresses from the engineering phases of the fuel cycles, to the pollution and abatement calculations, to the pollution transport estimates, and finally to the projected effects of pollutants, the data become more uncertain. The authors believe that the key limitation of this study is the fact that the individual impacts and costs displayed in the report are derived quantities. Data were rarely found in the desired format.

Considerable manipulation—disaggregation, interpretation, averaging, normalization—was necessary to reduce the quantities of interest to consistent and meaningful information.

This study also bases its comparisons on a single, normalized unit of output (a 1,000 MWe powerplant). Because of this, the values relate energy policy to environmental and economic impacts. The largest question raised by this form of analysis in terms of our taxonomy is whether the impacts and effects are linear.

Risk of Energy Production—Atomic Energy Control Board, Canada [14]

A recent study by Inhaber sponsored by the Atomic Energy Control Board of Canada considered 11 technological

methods for generating electricity-equivalent energy; coal, oil, natural gas, nuclear, hydropower, solar thermal heating, methanol, wind, solar photovoltaic, solar space heating, and ocean thermal. These were chosen, not because they represent an exhaustive set of energy technologies, but rather because the data necessary for the analysis were available.

Catastrophic and non-catastrophic risks are considered

Inhaber considered two types of risk for the analysis, catastrophic and noncatastrophic, the latter consisting primarily of risks to human health from industrial and occupational sources or from pollution effects. These risks were quantified for each fuel cycle from extraction to energy end-use, based on a variety of sources and assumptions about the current state of technological development. Seven sources of risk, corresponding to the seven stages of each fuel cycle were considered: material and fuel production, component fabrication, plant construction, operation and maintenance, public health risk, transportation, and waste disposition and deactivation.

Several types of data sources were used

Three major types of data sources were used: statistics on (1) health effects due to pollutants, (2) industrial damage and disease, and (3) materials and labor used for energy systems. By calculating or estimating a risk value in terms of mortality or morbidity for each stage of the cycles, Inhaber concludes that nonconventional energy systems can create substantial risk for human health (Table 10).

For coal and oil, most of the risk results from electricity production or end use (air pollution); for natural gas, nuclear, and ocean thermal, the risk is due to materials acquisitions; and for wind, solar thermal heating, and solar photovoltaic the risk results from the backup systems required (assumed to be coal).

The total man-days lost per megawatt-year net energy output over the lifetime of each energy system were determined (Table 11). Natural gas and nuclear power had the lowest values, and most of the nonconventional technologies had values similar to coal and oil. The large volume of construction materials required and the risks associated with backup energy storage resulted in high values for nonconventional energy sources.

Critique. This comparison makes a significant contribution to the literature in terms of risk analysis. However, to arrive at related estimates for health effects, the author used data from a large number of studies designed for other purposes. Normalization of values to one common unit resulted in "apples being added to oranges." As with the previous two studies, this analysis does not go beyond the

Table 10. Proportions of Risk by Source*

(In Percentages)

Risk Categories	Energy Sources										
	Coal	Oil	Nuclear	Natural Gas	Hydro-Electricity	Wind	Methanol	Solar Space Heating	Solar Thermal	Solar Photo-Voltaic	Ocean Thermal
Waste Management.....			10								
Energy Backup.....						65			80	70	
Emissions from Material Acquisition.....						4		12			5
Transportation.....	8		3	7	24	10	10	18	10	8	13
Gathering and Handling Fuels or Materials Acquisition & Construction....	12	2	75	85	45	10	60	45	3	14	70
Energy Storage.....						4			3	5	
Electricity Production or Operation and Maintenance....	80	98	12	8	30	7	30	25	4	3	12

* Approximate values taken from Inhaber, Reference 7.

Table 11. Total Man-Days* Lost per Megawatt-Year Net Output over the Life Time of the System

(Includes Public and Occupational Risk)

Energy Sources	Total Man-Days Lost
Coal	2,800
Oil	2,000
Nuclear	10
Natural Gas	7
Hydroelectricity	50
Wind	100
Methanol	380
Solar—Space Heating	150
Solar—Thermal	800
Solar—Photovoltaic	1,000
Ocean Thermal	34

* Approximate values taken from Inhaber, Reference 7.

Four general criticisms are: coefficient stage of data presentation. There seem to be four general criticisms of the Inhaber analysis:

- Misinterpretation* • The author interpreted the data in a fashion not intended from the perspective of the original source.
- Tenuous Data* • Data on specific technologies were insufficient so the analysis was based on tenuous assumptions used to cover data gaps.
- Technical Errors* • The author made errors in assembling or presenting the data that justified his bias.
- Static Approach* • The comparative technique used yields a static analysis without allowance for future technological development.

Although Inhaber's approach clearly captures a relatively large number of cross-technology comparisons, modifications are in order in two areas. First, making the approach more dynamic over time would make his results more useful. The study does not take into consideration the mix of technologies and the health effects of shifting this mix by specific geographical region or energy supply/demand circumstances. Such logic would require an analyst to discuss health effects in terms of ambient conditions in which a populace resides. It is not possible

to capture different regional pollutant background levels in a static, technology-by-technology presentation. Second, a static analysis tends to lose the secondary impacts of future decisions to select one mix of energy technologies over another. The resources and economic activity that are required to establish and maintain one technological mix of energy systems or another lead to more or less energy of various forms and more or less pollution and occupational risks, depending upon the mix chosen.

Solar Energy: Its Economic and Environmental Consequences

This study addresses increased use of solar energy

This assessment by Dossani, Watson, and Weygandt was presented at the American Institute of Chemical Engineers meeting in April 1979 in Houston. [15] The paper examines the economic and environmental consequences of utilizing more solar energy in the United States during the next 25 years. The study compares seven different solar energy use scenarios, three developed by the 1979 Solar Domestic Policy Review (SDPR). [16]

The authors analyzed the primary and secondary impacts of the scenarios using a macro-economic and environmental model. This discussion examines the environmental impact only. The authors used a three-step procedure for estimating air and water pollution damages. First, regional residuals were transformed into ambient concentrations using dispersion models with appropriate transfer coefficients for each region. Second, per-capita average damages in dollars were estimated as a function of average per-capita exposures. Finally, per-capita damages were multiplied by regional population and summed to obtain projected national damages. The authors then compared each projected solar-based scenario to a base case situation.

Solar energy has mixed effects

It was found that the use of solar energy leads to both decreases and increases in energy-related pollutants or residuals. On the whole, the scenarios that use more solar energy tend to have lower impacts. Nevertheless, use of solar energy can have a significant impact on pollution levels (Table 12). On the other hand, solar energy can displace coal and oil whose direct pollutant loadings are relatively high.

The authors conclude that when the increase in indirect residuals is compared with savings in direct residuals, solar energy, with a few exceptions, generates fewer residuals overall. One exception that they found was an increase in particulate matter, because particulates from combustion of wood and other biomass systems are almost completely uncontrolled.

Table 12. National Pollution Damages (Billions of 1972 \$)*

	1990					2000		
	1975	1985	Base	Maximum Practical	Technical Limits	Base	Maximum Practical	Technical Limits
Air	76.6	105.8	115.8	114.7	112.1	110.9	97.7	93.1
Water	25.8	28.0	33.0	32.8	32.3	38.9	36.2	33.9
Total	102.4	133.8	148.8	147.5	144.4	149.8	133.9	127.0

* For the purpose of evaluating adverse health impacts, specifically mortality, the statistical value of life is assumed to be \$200,000 in 1975 (Thaler and Rosen, 1976) rising to \$434,000 by 2000. The increase over time reflects increased willingness to pay for a cleaner and safer environment as income rises (Ridker and Watson, 1979, Appendix A). Injury costs are taken to be a tenth of these values.

Flaws include questionable assumptions and unevaluated types of impacts

Critique. This assessment used a method based on residuals generation to compare the relative impacts of different energy technologies. This study considers a number of factors missed in technology-by-technology comparisons and yet it too has certain inherent limitations. For example, some gaps exist in the information used in the assessment and the use of certain assumptions which, if incorrect, could lead to very different implications. A number of environmental impacts were not evaluated. These include disturbed land, environmental risk from industrial sludges and highly toxic nuclear wastes, and impacts on climate from carbon dioxide buildup. The amount of disturbed land could be higher with increased solar energy from biomass farms and windmills. In contrast, solar energy has an advantage in terms of reducing environmental risk from industrial sludges, nuclear wastes, and carbon dioxide accumulation. This assessment comes closer to an appropriate design for energy-environment tradeoff analyses. It misses both the ecological and human impacts areas, though. These effects are implied in the benefits results but are not presented explicitly.

Environmental Impacts of Alternative Energy Technologies for California [17]

Study treats environmental impacts in California

In 1977, the Office of Environment and Safety of the Energy Research and Development Administration investigated the feasibility of having the State of California subsidize entirely on solar-based technology. As a part of this study carried out by the University of California's Lawrence Berkeley Laboratory, John P. Holdren prepared an assessment entitled *Environmental Impacts of Alternative Energy Technologies for California*. Holdren conducted a general review and compilation of various studies and techniques for comparing the environmental impacts of alternative energy futures. He specifies certain difficulties in conducting these comparisons, such as:

Difficulties in conducting assessments are described

- The only data available are pollutant emissions, and these are not useful to measure impacts. Difficulties

- The relationship of emissions to health effects assessments is still largely guesswork.
- Temporal questions of immediate versus long-term harm and damage are still very difficult to determine.
- Many identified problems are difficult to rectify or prevent in the first place.
- It is often difficult to reverse an environmental insult.

In a generalized fashion, Holdren then specified the health and safety of a number of technologies. No attempt was made to rigorously quantify impacts or criticize the data, the technique, or the comparability of impacts across technologies. Holdren developed a table of subjective estimates for comparing the various forms of energy technology (see Table 13).

Coal central electric systems have the most severe environmental impacts

In Holdren's view, coal central electric systems embody the most severe environmental impacts in terms of land use, occupational health, small accidents, emissions, effects on climate, and effects of ecosystems. Coal fluidized bed has significant negative impacts in terms of small accidents and effects on climate. Nuclear technologies have significant negative impacts in terms of possible accidents and sabotage. Active solar heating and cooling is viewed as essentially benign, except for the use of nonfuel materials. Holdren notes a number of deficiencies with the technique he used and claims only that this methodology provides a framework for organizing information already available.

A limited literature survey was provided

Critique. It is difficult to critique Holdren's assessment in detail because it does little more than set out a program for testing feasible future courses of action. His survey of the literature, in terms of technology impacts and environmental effects, clearly covered a relatively limited literature set and would be considerably enriched by in-depth study.

The author used his personal, subjective opinion of relative impacts

The most serious analytical criticism is that Holdren uses his personal, subjective opinion of relative impacts. Clearly, this is not an approach that would be widely accepted by those whose environmental perspectives do not parallel those of the author. This methodology is far from the ideal assessment methodology we presented earlier. As such, it misses all areas, although it suggests that several similar variables are addressed in a qualitative fashion.

Table 13. Tentative Rankings of Environmental Impacts of Alternative Energy Technologies for California*

	Land Use	Water Use	Use of Nonfuel Materials	Occupational Health	Small Accidents (Public)	Large Accidents/Sabotage	Emissions/Public Health	Effects on Climate	Effects on Ecosystems	Aesthetic Effects	Direct Links to War
Passive Solar Heat/Cool	1	1	2	1	1	0	0	0	1	1	0
Active Solar Heat	2	1	4	2	2	0	1	1	1	2	0
Active Solar Cool	2	2	4	2	2	0	1	1	1	2	0
Solar Thermal Electric	4	3	5	2	1	0	1	2	2	3	0
On-Site Wind	2	0	2	1	3	1	0	1	2	4	0
Central Wind	4	1	3	2	2	1	1	2	3	5	0
Large Hydro	4	5	3	1	1	5	1	2	4	5	0
Small Hydro	3	4	3	1	1	3	1	2	3	3	0
Biomass Waste	1	1	1	3	3	1	2	1	2	1	0
Biomass Farm	5	5	1	3	3	2	3	2	4	3	0
Geothermal Heat	3	1	2	2	1	1	2	2	3	2	0
Geothermal Electric	3	4	3	2	1	1	3	3	3	3	0
Coal Cent. Electric	4	3	3	4	4	1	5	5	5	4	0
Coal Fluid Bed	4	3	2	4	5	1	4	5	4	4	0
Coal Gasification	4	3	2	5	4	3	2	5	4	3	0
Coal Liquification	4	3	2	5	4	3	3	5	4	3	0
Gas Domestic	2	1	2	2	2	3	2	4	2	2	0
Gas Imported Lng	3	1	3	2	2	4	2	4	3	3	3
Oil Domestic	3	2	2	3	3	3	3	5	4	3	0
Oil Imported	3	2	2	3	3	4	3	5	4	3	5
Oil Shale	4	3	2	4	3	3	4	5	5	4	0
Nuclear Lwr	2	3	3	3	2	5	2	2	2	2	5

* In each category, 5 denotes the most severe impact in this category, of the technologies considered. Thus there is always at least one 5, and the other values are scaled to it. 0 = negligible, 1 = small, 2 = moderate, 3 = considerable, 4 = large, 5 = worst. The divisions are necessarily coarse; identical numbers should not be taken to mean exactly identical magnitude or impact.

Summary

Some might argue with our treatment of several of the studies or with our attempt to measure the utility of the technique employed against the ideal presented in Section I. For our purposes at least, enough information was presented to allow the reader to make a judgment of the utility of the studies to policy formulation. Remember that we are attempting to demonstrate that several sources believe it is possible to assess the relative environmental benefits of different energy technologies. However, none of these studies has presented a case that uses sufficiently valid data to be the basis of a major policy decision.

All studies were flawed

In every case, either the method, the data, or the analysis was so flawed that no policymaker would support the conclusion with confidence. Without such confidence, the studies would be useless.

The research and analysis communities, however, are not bankrupt. Techniques are being developed to perform tradeoff analyses of these variables. However, are these techniques sufficiently mature to be used in day-to-day policy analysis? Section III will summarize some of these techniques, again in a capsulized fashion.

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III. Conceptual Methodologies

*Decisions cannot be
delayed*

Despite progress in understanding environmental effects, there is still considerable uncertainty about possible physical, biological, and social consequences of large-scale energy projects. Even when potential consequences are known, the likelihood of their occurrence is not. However, decisions on major energy projects cannot be delayed until enough data are available and understood to ensure that the related environmental impacts are acceptable. Such decisions will be made, and decisionmakers will select methods for analysis to use in formulating those decisions. In Chapter II we examined several attempts to compare the environmental impacts of promising energy technologies. These attempts were flawed for several reasons, including the inadequacy of the data on environmental effects and the use of analytical methods that were faulty.

*Data are often of poor
quality*

In this section, we will review methodologies for comparing technologies, some of which were used in the studies surveyed in Section II. Others have reviewed these methods to determine the relevant variables, collect data, and test the model. One of their major problems was the poor quality of the data used, since frequently the specific data called for in the original design cannot be found, or the expense to collect it is prohibitive. Consequently, analysts have modified certain model paradigms to be able to use available information. Such models frequently become "data driven," reflecting only the information that is available and not the information that should have been used if one were to address the issue properly. On the other hand, some extremely complex and quantitative methods focus on how decisions should be made (ignoring

*Models do not adequately
reflect complex technical
and political realities*

how decisions actually are made). Their supporters suggest that if the prescribed techniques were followed, good decisions naturally would result. The major difficulty with a normative approach such as this is that it does not reflect reality; it requires reality to be consistent with the model or the modeler's conceptual design. Just as models that do not capture the critical facts about a technology are not acceptable to the scientific community, those that ignore the significant political realities of a situation will be rejected by decisionmakers. As such, normative models, techniques, and analyses are often seen either as preaching or as intrusions onto turf that the decisionmakers see as their own.

*What is the value of
human life?*

Even if there were no problems with the data and the models adequately reflected reality, it would still be difficult to establish the relative importance of the variables in the model in terms of the decision at hand. Consider, for example, the problem of placing a monetary value on human life. Despite a reluctance to measure human life in economic terms, individuals by their actions actually do place a finite value on their lives. Decisions about installing safety features, buying life insurance, or accepting a more hazardous job for extra salary all imply judgments about the value of life.

Assigning relative measures of importance to the various impact categories is normative, based on the attitudes, beliefs, and opinions of the decisionmaker.

*These approaches attempt
to assess energy technologies
in a comparative fashion*

There are several ways to group the methodologies discussed here—by degree of objectivity or quantification, by the amount of importance given to the concept of uncertainty, or by the weight given to undocumented human opinion or judgment. No one taxonomy is inherently preferable. All of these approaches attempt to assess energy technologies in a comparative fashion using factors such as environment and economics as indicators of preference.

In every approach, some degree of human judgment is necessary to guide the analysis. Knowledge of the psychology involved in such judgments causes concern, because many people (including experts who have been forced to go beyond the available data and rely on their intuition) are unable to assimilate complex and sometimes questionable information and make valid inferences from it. Each method has some serious flaws that have become evident in actual use.

Delphi Technique

The Delphi Technique partially solves the problem of incomplete data in conducting tradeoff analyses. [18] This

This method attempts to improve upon the traditional expert panel approach

approach requires the analysts to be exposed to the views and opinions of experts and to one another through a program of sequential individual questions, with feedback reflecting consensus or conflict. It attempts to improve the traditional panel or committee approach to issue assessment by collectively estimating the most likely value, issue, or weight.

Iterative feedback is provided

The method (and its several variants) is designed to obtain iterative evaluations of a question in a fashion that imputes weights from a range of experts without undue influence from a dominant personality.

To eliminate dominant personality peer pressure, participants are often physically isolated, with the group consensus revealed only through written documentation provided by the analyst. This method attempts to distill the combined technical judgments from a group of experts, while reducing the importance of stated opinions, biases, and dominant personalities within the assessment system that would affect the decision process.

Problems include subjectivity and high cost

Critique. Although the Delphi Technique is a legitimate attempt to fill in an important gap by providing empirical data to the decisionmakers, several characteristics provide the basis for criticism. The experts *can* be biased (the technique works best when they represent one specialty rather than different disciplines). Studies using this technique are often prohibitively time consuming and costly. Because the technique allows the issue to be "enriched" by the participants, the number of questions that each participant has to consider often grows to an unwieldy size. The results do not have any unusual validity (and may not be better than subjective evaluation of the same issue).

Health Effects Assessments

The most common comparative technique to measure the environmental costs of emerging technologies found in the articles previously surveyed is health effects assessment. [10, 11, 12] Although the comparative techniques used to determine health effects vary slightly, and differences between the data sources and data manipulation methods are considerable, the methodology employed is conceptually similar:

Technologies are segmented

1. The energy technologies are segmented into the phases of the total fuel cycle: exploration, extraction, refining and processing, transportation, generation, and waste disposal.

<i>Effects are categorized</i>	2. Health effects types are categorized in terms of such items as occupational and public health, accidents, chronic disease, and fatalities.
<i>Values are assigned</i>	3. Values are then assigned to each technology. Usually, these values are in the form of coefficients, sometimes with ranges reflecting the certainty of the data.
<i>Effects are calculated</i>	4. Finally, the relative amount of each fuel used is mapped into this coefficient data base by scenario, and health effects estimates by technology are generated.
<i>Risk or damage may be estimated</i>	5. More sophisticated techniques go a step further to translate these estimates into risk or damage values. Others combine the health impacts with those of ecological insults such as acid rain, increasing carbon dioxide concentrations, and water use.

Only inadequate cause and effect data are available

Techniques are often expensive and time-consuming

Critique. This technique appeals to decisionmakers concerned with the ultimate environmental impacts of energy development. If reliable data could be obtained and the results presented in a meaningful fashion, this method could be useful in decisionmaking. Unfortunately, adequate cause and effect data specific to each phase of each fuel cycle are not yet available. Not enough research and analysis has been performed. Instead, inferences are made from laboratory tests on animals under controlled conditions to humans in real-life conditions. The techniques used are expensive, time consuming, and often of questionable relevance to real-world situations. On the other hand, the statistical studies of population reactions to exposures or insults are equally risky because it cannot be proven that the effect noted was caused by the pollutant being studied.

The methodology is limited to human health effects

More important [14] from the decisionmaking perspective is the fact that this methodology focuses only on human health effects. Even if accurately measured, such effects are only part of the overall environmental picture. Health effects assessment focuses on populations at risk and ignores the potential ecological impacts of energy technology development. Translating health effects estimates into units that can be compared with similar types of economic and energy parameters is an exercise for which acceptable methods and criteria are not yet available.

Net Energy Analysis

This technique derives the total energy required to produce a unit of useful energy

Net energy analysis examines the total energy required by an energy technology to realize a given amount of useful energy. [19, 20, 21] The energy components considered include that of the total fuel cycle and of the energy lost

in ecosystems that have been altered or destroyed. Total energy (necessary to generate useful energy for human purposes) is estimated for each alternative. Technologies can then be compared on the basis of net energy generated.

A simple example will illustrate the fundamental method. Let us consider the production of electric power by a hand generator. The output of electricity can be measured in kilocalories, say, 25 kilocalories per hour. To produce this output, typical economic units of labor (the person turning the crank) and capital (the generator) are required. The laborer is assumed to expend 5 kilocalories per hour in turning the crank. The generator takes 1,500 kilocalories to produce. (This latter amount is a stock, one-time cost, while the other units are in flow terms.) To convert the stock into flow units, assume that the lifetime of the generator is 100 hours, thereby providing 15 kilocalories per hour of capital input energy rate. Five kilocalories of labor and 15 kilocalories of capital are combined to produce 25 kilocalories of useful energy. The net energy produced, then, is 5 kilocalories. These are the fundamentals of the net energy approach, although other realistic effects like environmental damage caused by operation of the generator can also be included. The estimated energy content of the damage would be subtracted in the calculation of the net energy produced, to yield an even lower net energy.

Critique. This technique offers an absolute standard of value. Activities are assessed in terms of a ratio measure that is stable in the changing circumstances of the real world. This can be seen in the example of the electric generator. The amount of energy embodied in particular units of capital and labor is a physical relationship. Technical change, which is a socioeconomic phenomenon, may alter the nature of electrical generators before their production, but once they are produced, they are fixed in terms of energy content.

Unfortunately, at any particular time, the state of knowledge, the capital stock, or the composition of the labor force may not permit expeditious switching to alternative fuel sources. Assessing public policy alternatives requires the consideration of categories of energy supplies instead of merely energy content in a physical sense.

This technique ignores factors important in public policy

This procedure also misrepresents the decisionmaking process, which ideally allows direct human action towards collective goals. National energy policies, in general, try to alter the allocation of resources to achieve an acceptable balance in supply and demand for the public. Judg-

ing the impacts of energy policy on the environment only on the basis of energy used is too narrow. Net energy analysis also has other weaknesses. For example, it fails to illuminate or to aid in the assessment of impact from Government policies or regulations. It does not adequately contribute to the sequential and adaptive aspects of decisionmaking—there is no mechanism for dividing the analysis into sequential steps, or for taking into account possible future adjustments due to newly acquired information.

Cost-Benefit Analysis

This approach considers gains versus losses

The cost-benefit approach [22, 23, 24] is based on a method of assessing the value of the gains to all gainers and the value of the losses to all losers. This kind of analysis measures one's willingness to pay for an activity against the losses experienced if the activity does not take place. If gains (benefits) exceed losses (costs), then the project is worthwhile in the absence of budget constraints. When there is a budget constraint, then the funds are allocated among all projects so that benefit, less cost, is greatest from all projects. For an example of cost-benefit analysis application, consider the development of a hydroelectric facility. To estimate benefits one must identify the types of outputs associated with an activity.

The users of the outputs are the gainers. A hydroelectric dam may produce, in addition to electricity, recreational boating and flood control. The value of each of these outputs should be assessed in a cost-benefit analysis. The costs would include the expenditures for construction, operation, and maintenance. However, this is probably not the entire facilities cost. The site of the dam might have had an alternative use. In the construction of many hydroelectric facilities, low-use recreational hiking and camping is being displaced. Some dams have been proposed or constructed in areas that have unique scenic and natural wonders like the Grand Canyon or Hells Canyon. To correctly account for costs, the value of these foregone opportunities should be assessed.

The method is subject to commensurability problems

Estimating these types of benefits and costs is difficult. Monitoring gains and losses is complicated because of commensurability problems, e.g., comparing the loss of scenic vistas and flora and fauna to gains in conservation. This problem also becomes more complicated because of equity considerations. For example, an impact from an energy technology can be a benefit to some individuals, and a cost to others. An arid area that is strip mined and

then seeded with nonindigenous plants may appear aesthetically pleasing to some, while those with strong preferences for desert environments dislike it.

Two procedures are used to overcome these deficiencies. The first is observation of market prices. This is most applicable when the benefits are directly monetized in the marketplace. For example, a hydroelectric facility will generate at least one output (electricity) that is bought and sold. Data from extant facilities can be used in the development of benefits estimates. However, most environmental resources are not exchanged in markets and, therefore, benefits are not directly observable and monetized. In such cases, surrogates are often used, providing an indirect method for expressing benefits. Types of surrogates range from partial measures of total benefits to parameters that attempt to encompass total benefits. An example of the former would be travel cost measures. A hydroelectric facility's value to society could include a reduction in recreational costs for boaters who would otherwise have to travel farther to go boating.

Development models that attempt to optimize consumer behavior are examples of trying to account fully for the benefits of energy activities. In such cases, non-market-related environmental impacts may be treated as constraints upon the surrogates or benefit estimates obtained from the model. There is a wide variety of such models, and there is a common thread in their use of estimation of benefits by entering values to nonmarket activities from observed market behavior.

Critique. Cost-benefit analysis is not a sequential decision-making process. It assumes that the benefits and cost are relatively independent. This is a simplification of the real world, since a decision on the desirability of a project may affect the cost-benefits accruing from future development projects. Cost-benefit analysis also does not adequately handle the problem of uncertainty. While some aspects of uncertainty can be incorporated, this type of analysis has not traditionally handled the problem of uncertainty about future preferences. In essence, cost-benefit analysis has been used as a data reduction procedure that attempts to express political and social policies in economic terms. With its use, public policy formulation becomes an exercise of economy and efficiency, without due consideration of the broader goals of social equity and public welfare. Cost-benefit analysis has been classified as a decision framework that excludes all political, social, and institutional considerations, as well as all nonquantifiable variables.

Flaws include: inadequate treatment of uncertainty and failure to consider unquantifiable factors

Advocates of the approach naturally disagree with this characterization, claiming that cost-benefit analysis can help in selecting alternative programs to achieve broad policy goals. Quantitative measures are used to the greatest extent possible to assess each proposed alternative, but the analysis is not limited to the use of quantitative data. Advocates of this method argue that intuition, logic, common sense, and educated guesses are relied upon, are made explicit, and are clearly defined. They believe that once the alternatives are analyzed, selection among the proposals is basically the responsibility of the political arena.

To those on the receiving end of public decisionmaking, the distinction between the arguments of advocates and detractors of cost-benefit analysis is unclear. It is difficult, if not impossible, to distinguish between the analysis and the actual basis for the decision. The value of this approach depends heavily upon the decisionmaking abilities of the political official involved. If a cost-benefit analysis is incomprehensible, it has no value for policy formulation. If the political official works too closely with the analysts, then the analytical results tend to be biased in favor of the official's predetermined disposition.

Decision Analysis Under Uncertainty [25, 26]

Subjective and objective probabilities are considered

This technique incorporates the concept of uncertainty in the most comprehensive fashion of all the methods discussed here. All aspects of a decision analysis are treated stochastically, and it incorporates subjective, as well as objective, probabilities. The subjective aspects are aggregated measures of individual probability distributions.

In theory, individuals have opinions about the likelihood of various future events occurring, given certain assumptions about related circumstances. This is true whether or not there are data that would be useful for generating objective probabilities. For example, even though slurry backfilling has never been attempted in commercial oil shale in situ retorts, individuals do have opinions about the utility of this method and its chances for success. Recent work suggests that knowledgeable individuals can be induced through an interviewing process to reveal their subjective probability distributions. [26] This is best illustrated through a hierarchical decision tree.

An example of a decision tree is given

Consider the decision whether to invest in a coal gasification plant that uses a new technology. Assume that no such plants exist on a commercial scale, and that there is considerable uncertainty concerning the operational characteristics of the plant. For purposes of simplification,

assume that the major uncertainty concerns the level of air emissions and the efficacy of the emission control devices. The first decision point is to choose whether to construct the coal gasification plant or not. If one chooses not to construct it then there is no further decision problem. If the choice is to build, however, then there may be two possible outcomes; the level of emissions are below air standards for all pollutants, or the emission standard is exceeded for a given pollutant. If the first outcome occurs, no additional control technology for air pollution is required. But if the second is true, then emission control equipment may have to be installed at additional cost. At this point, assume that there are two possible types of control equipment that could be used, each with different probabilities of meeting the standard. This process of alternative courses of action is continued until all probabilities are examined. A simplistic decision tree with an array of possible decisions and outcomes with probabilities of each outcome occurring is constructed. The probabilities may be arrived at objectively or by consulting expert opinion. Various methods may be used to determine the value of the different branches of the tree, depending on the results being sought. A comparison of the values for each course of action or branch is used to make the final decision to invest.

Ranking functions are used

Because decision analysis is a relatively new technique, a brief description of its more important characteristics may clarify its comparison with the ideal. A distinguishing feature of decision analysis is the use of a ranking function. In cost-benefit analysis, an attempt is made to assess alternatives on the basis of "the people's" preferences. Within decision analysis, an assessment is made based on the preferences of the decisionmaker, who is assessed for his values, and the impacts are ranked according to weights derived from his values. Of course, when the decisionmaker generates the ranking function, one cannot preserve the value judgments associated with cost-benefit analysis.

Risk and uncertainty are dealt with directly

The most important advantage of decision analysis is its treatment of risk and uncertainty. Uncertainty about future goals and the state of the world presents problems for decisionmakers. The possible outcome of certain actions may have considerable policy significance, even though such an outcome is remote or unlikely. Actions may have risks of irreversible damage associated with them.

Conventional techniques inadequately assess such cases since they are neither sequential nor adaptive. Decision analysis offers the capability to acquire information and alter the choice of alternatives as an integral part of its methodology. It uses the decision tree framework to

break up the decision problem into partial alternatives. In doing so, it explicitly structures the problem in order to include an evaluation of the benefits of further information acquisition.

Ranking functions and subjective probabilities are complex concepts that are difficult to use in the public sector

Critique. The desire to treat uncertainty with analytic precision is a laudatory goal but one not likely to be realized in the near future, particularly with the information base currently in use. Its use of a ranking function and subjective probabilities may increase the difficulty of convincing decisionmakers of the utility of decision analysis. In addition, obtaining access to the decisionmaker in order to assess his preferences is, in most cases, difficult or impossible. The attempt to recognize the uncertainty in human decisionmaking by the use of probabilities is a step toward analytic elegance and may have some validity in the better-defined world of business. However, it has not yet been accepted in the public policy world.

Indicators Analysis [27, 28, 29]

This approach has been used in social analysis

Another major methodological approach for comparing energy technologies is indicators analysis. Actually, this is quite a broad category incorporating various types of approaches. Its fundamental goal is to arrive at indicators of a particular system's function or dysfunction. Historically, the most formalized embodiment of this approach has been in the area of social analysis. The formal work associated with various types of policy analysis presently used in Government social welfare programs. In the case of social indicator systems, formal structures are developed for aggregation into a single or a limited number of sets of goals or indicators. In certain types of conventional indicator analysis carried out by Government analysts, a descriptive mode is used to generate indicators that are considered to be critical for a particular decision. Those indicators may not adequately represent social welfare directly, but are usually viewed as indirect measures. For example, a model that predicts pollutant residual levels might be used because it is well known that certain types of residuals have health impacts. The model outputs do not provide direct predictions of health impacts, but rather are used to produce intermediate indicators, i.e., residuals. The analyst then utilizes the intermediate indicators to produce a formal analysis of health impacts based on residuals data.

Indicators are often indirect for surrogate measures

However, most indicator systems are more formalized than those described above. One approach will be elaborated upon here as representative of this type of comparative analysis. Our example is found in the report of the Technical Committee of the Water Resources Centers of

One representative method is described

*General goals are broken
down into components*

13 western States, which was produced for the Office of Water Resources Research. [30] In this approach, a hierarchical structure was developed with a general societal goal at the apex. In general, such a goal is not directly measurable, since its attainment is usually defined subjectively. For example, one might include promotion of the general welfare as a societal goal. This goal can then be divided into specific objectives whose attainment cannot be directly determined. Examples might be maintenance of security and enhancement of opportunity. These objectives can be subdivided further. Maintenance of security might be divided into environmental security, collective security, and individual security. Enhancement of opportunity might be divided into economic opportunity, recreational opportunity, and the opportunity for individual freedom and diversity of life styles. These might all legitimately be defined as goals that are hierarchically arranged.

*A hierarchy of objectives
building to general goals is
created*

These goals and objectives are disaggregated until levels are reached where particular characteristics become measurable. For example, environmental security might be continually subdivided until one arrives at various indicators of ecosystem function. These might include primary productivity, diversity, and secondary productivity. Of course, this is not comprehensive, but is merely provided as an example. What has been developed is a set of goals and indicators that has been hierarchically arranged so that the bottom rungs contain measurable and observable characteristics or indicators. The next step is identifying the connectives. In other words, the relationship between one level of the hierarchy and the next level up is determined formally. For example, there might be a direct functional relationship between the diversity of an ecosystem and its stability, which could be among the next higher level of indicators. Stipulating the connectives is sometimes a difficult task, but it is an important step if the system is to be useful. It may not be possible to state precise functional connectives for all levels of the hierarchy, and, in some cases, one may be reduced to merely specifying the general direction of change.

*This approach is neither
sequential nor adaptive*

Critique. In terms of our original criteria, an indicators system has a number of difficulties. No formal procedure for dealing with risk and uncertainty is incorporated in this methodology. Therefore, it is not at present sequential and adaptive, although it might be made so with further thought and design changes. The implications of not being sequential and adaptive have been discussed elsewhere in this section. It should also be noted that in practice this method will almost inevitably have commensurability problems. The development of connectives will be difficult at the higher levels of the hierarchy. In most

*Incommensurable units
prevent ultimate tradeoffs
from being made*

cases, the quantification of the hierarchy will stop short of the most general social goal. Therefore, if the indicators system is used to compare the impacts of various energy technologies, the problem of examining the tradeoff issue with incommensurable units becomes overwhelming.

*Other methods are also
examined in this paper*

Just as no single discipline can adequately address all aspects of an energy technology tradeoff issue, none of the approaches discussed above provides a sufficient basis for determining what levels of environmental protection and safety are acceptable to the general public. In attempting to resolve the problems inherent in these methods, each new approach engenders problems of its own. Therefore, we will now describe a number of other methods that attempt to use an integrated or combined approach to comparative analysis.

Battelle Memorial Institute's Integrated Assessment

The first combined approach is a study plan developed by Battelle Memorial Institute. [31] Although not unique in form, this plan was an attempt to perform an integrated assessment of coal-based technologies and is useful for illustrative purposes. The study framework is outlined in Table 14. To turn this conceptual plan into more useful output, specific research tasks given in Table 15 are performed.

*This method may work for
long-term issues*

Critique. This approach is rather ambitious, certainly comprehensive, but it has many of the problems of the more limited methods discussed earlier, especially in terms of the capability for quantifying subjective values. The complexity of this method, although intellectually appealing as the way things "ought" to be done, tends to force the required tasks to be completed in a timeframe that is too lengthy for most short-term policy decisions. Its value would be enhanced for those long-term issues for which analysts have more time for research.

Comparison Matrices [32]

The use of matrices for comparing the environmental impacts of significant elements of various energy technologies can provide some insight into the issue of impacts tradeoffs. Such an approach involves three basic steps:

1. The Element Comparison step delineates each technology in terms of basic physical and value elements. Each element is made up of component units.

Table 14. Methodological Steps for Integrated Assessment of Coal-based Energy Technologies

(1)	Identify Issues, Alternatives, Policy Options
(2)	Review Past and Ongoing Related Research
(3)	Identify and Select Coal Processing and Utilization Alternatives
(4)	Identify and Describe External Future Changes
(5)	Develop Systematic Procedure for Relating Elements
(6)	Develop Baseline Futures
(7)	Identify and Describe Decisionmaking Procedure and Parties of Interest
(8)	Perform a Series of Sensitivity Analyses
(9)	Identify "Important" Alternative Futures
(10)	Identify and Describe Impacts of External Changes on Model
(11)	Identify Potential Impacts
(12)	Evaluate Impacts of Alternative Futures
(13)	Conclusions and Recommendations (Alternatives Strategies)

Table 15. Research Tasks to be Applied in the Conduct of an Integrated Assessment of Coal-based Energy Technologies

(Developed by Battelle Memorial Institute)

1.	Review, evaluation, and update of pertinent coal and coal-related previous and ongoing research
2.	Definition of problem areas and identification of issues related to coal-based technologies
3.	Selection and prioritization of technologies and supply systems to be assessed
4.	Selection and prioritization of end uses to be assessed
5.	Identification and description of social and energy alternative scenarios which will influence energy demand and coal-based technology choices
6.	Identification of configurations of technologies, supply systems, and end uses to be assessed
7.	Description of the existing biophysical and socioeconomic environment at appropriate local, regional, and national levels
8.	Interactions that may occur between the technologies and supply systems and the biophysical and socioeconomic factors
9.	Refinement of existing energy-demand projections for appropriate regional and national levels
10.	Development of alternative scenarios for various technological mixes and the rates, levels, and timing of development
11.	Identification and description of relevant legislation, regulations, and decisionmaking processes and involvement of the parties of interest
12.	Identification of significant attributes in the process model (sensitivity analysis)
13.	Assessment and comparison of the biophysical, socioeconomic, and energy impacts of each composite scenario ("important" alternative futures)
14.	Aggregation of local, regional, and national impacts
15.	Assessment and comparison of the long-range cumulative impacts of coal-energy technology deployment
16.	Identification and analysis of the social, economic, biophysical, political, legal, institutional, and technological constraints and alternative strategies for policy implementation to avoid or mitigate undesirable impacts
17.	Communication of the study results to EPA policymakers and other users and audiences

2. The Factor Comparison step aggregates elements into certain basic categories or factors, compares each factor among technologies, and aggregates factors by technology.
3. The Value Comparison step examines the factors across technologies and across value elements by technology.

*Adequate, reliable data are
often not available*

This sequential approach faces the problem of inadequate reliable data for new and emerging technologies, as well as limitations associated with cross-technology comparisons due to incommensurables. This three-stage process has the advantage of encouraging analysts to consider scientific as well as social aspects of various energy technologies. It also requires analysts to make their assumptions and value orientations explicit. It gives some latitude to those for whom the analysis is targeted, allowing them to adjust the weights given to various elements and factors according to their own value systems.

In general, each matrix would take the form shown in Figure 2. The rows might represent the technologies being examined, and the columns might represent the units being examined with the appropriate normative weighting factors. A composite score is calculated. For simplicity, the simple weighted average for the row values may be used.

*Technologies are divided
into component elements*

For example, suppose a comparison of potential impacts is to be made of the following energy technologies: coal liquefaction, hydrothermal electric and direct heat, urban waste energy recovery, enhanced gas recovery, and oil shale. These technologies are redefined in terms of smaller pieces or elements that are then reaggregated according to factors common to each. The first division may be by elements, such as the physical environmental qualities, health and safety qualities, material and production qualities, ecological concerns, and aesthetic and recreational qualities. These elements are then broken into small units. For example, physical environmental qualities may be divided into air quality, water quality, land use, water consumption, and noise.

*Impact categories are
defined*

Thus, air quality can be divided into units such as sulfur oxides, nitrogen oxides, photochemical oxidants, particulates, and hydrocarbons. Each element must be broken into the smallest practical unit that can be compared and analyzed.

Figure 2. Illustrative Matrix

Technology \	Item	y_1	y_2	•	•	•	y_i	$\sum_{j=1}^n y_j w_{jn}$
	Weight	w_1	w_2	•	•	•	w_i	
x_1		R_{11}	R_{12}	•	•	•	R_{1i}	•
x_2		R_{21}	R_{22}	•	•	•	R_{2i}	•
•		•	•	•	•	•	•	•
•		•	•	•	•	•	•	•
•		•	•	•	•	•	•	•
x_i		R_{i1}	R_{i2}	•	•	•	R_{ii}	•

Categories are not always mutually exclusive or exhaustive

The classification scheme does not necessarily have mutually exclusive and exhaustive categories. In fact, the elements are usually not mutually exclusive or independent of each other. Also, the numeric estimates and corresponding weights are value judgments related to the units being compared. Adjustments are possible and desirable at a later point in the process when the values themselves are being examined. The tradeoffs between factor elements are value judgments to be adjusted later.

After the lowest level comparisons are made and a composite score is generated from an averaging algorithm, the resulting numerical value is then entered onto a factor value matrix. The factors are then weighted according to the value structure of the analyst. After the lowest level comparison values are determined, only relative weighting (i.e., value judgments dependent on societal, political, and professional criteria) are needed in further matrices. The subjective value judgments are a problem because there are no recognized standards for performing comparisons across several dimensions.

This technique makes value judgments explicit

Comparison matrices assign scientific and value weights to technologies and help to determine which parts of the decision process depend on subjective criteria. This approach clarifies the selection process by making value judgments explicit and points to additional research that is needed or desirable. Use of a factor matrix may indicate, for example, that the impact of particulates on human mortality is relatively minor compared to the impact of nuclear radiation. However, perhaps it will be shown that the estimates are not reliable enough to make judgments because of the high-risk considerations and uncertainties involved.

Problems include lack of data and subjectivity

Critique. A comparison matrix determines the point at which normative and scientific judgment intersect in order to more effectively allocate research priorities. Its purpose is not to determine the "best" technology, but rather the set of most promising technologies.

The data difficulties are compounded as the layers of sophistication are added in this approach, and the possibility for subjective bias is enormous. The Value Matrix is particularly likely to be subjective, even though it does not attempt to make value judgments explicit.

Multitechnology Approach

Payback and risk are approached by using shadow prices

Another approach to cross-technology comparisons involves the quantification of payback and risk through the use of shadow prices. Such an approach can incorporate economic, environmental, and energy criteria. The metho-

dology attempts to replicate private sector decisionmaking, while incorporating the concept of risk as perceived by public policymakers. Risk is introduced by establishing certain thresholds for the cross-technology comparisons. Risk parameters used for economic considerations include: need, cost, dependability, marketing, and competition. Environmental risk parameters can be pollution control costs and market imperfections in providing control equipment. Energy threshold parameters include feasibility, research and development time, professional experience, and complexity of technology and physical facilities.

Hurdle rates would be developed

National objectives for energy could be viewed as requiring the development of technologies to meet energy, economic, and environmental needs. This logic would force policy decisions into a three-stage process. Hurdle rates for a portfolio of energy technologies would be developed. The hurdle rate for economic benefits would be an economically acceptable rate of return.

The hurdle rate for environmental acceptability would be costs of compliance for new energy systems with pollution controls vis-a-vis conventional systems. The hurdle rate for energy benefits would be total energy saved or generated by one technology in comparison to another. In the concept described here, the approach centers on the quantification of the risk before and after Federal involvement.

Perceived risk is evaluated

The portfolio theory involves decisionmaking under conditions of risk. Risk is defined here as the perceived probability that the nominal or potential benefits associated with the proposed product innovation will be realized. Perceived risk is evaluated in relation to economic, energy, and environmental shadow prices:

1. Commercial feasibility (economic threshold or hurdle);
2. Institutional feasibility (environmental hurdle); and
3. Technical feasibility (economic and energy threshold or hurdle).

Using these criteria, a rate of return is calculated before and after Federal involvement.

Cost and benefits are subject to uncertainties

Conceptually these issues are not difficult to grasp. Whenever an individual, a corporation, or for that matter, the Federal Government contemplates an investment, there are perceived costs and benefits. In many instances these costs and benefits are subject to uncertainties that, in turn, have an impact on the decision to invest or not to invest.

Federal support for private sector research and development can affect all of these investment decision parameters. By subsidizing the research phase, the Government can reduce the overall cost of product development for the private sector. The involvement of the Government can enhance the credibility of the demonstration and encourage wider dissemination of research results, which may tend to broaden market exposure and increase the rate of market penetration. Undoubtedly, these factors play an important role in stimulating the private sector to seek Federal support of innovations.

However, these benefits could also be provided for projects that the private sector might pursue independent of Federal support. Therefore, in weighing the economic costs and benefits of projects seeking Federal support, the question is how to differentiate between those projects that the private sector should undertake without Federal support and those that require Federal support.

The first step is base case assessment

The first step is to conduct a base case assessment where the objective is to assess the risk of investing in the product or technology from the perspective of the innovator. This step requires the analyst to simulate the innovator's perception of risk prior to and during the research program. Economic, environmental, and energy factors are evaluated relative to investment, including research and development expenditures. The resulting risk parameter derived from this first stage of the analysis provides an initial assessment of the project's position relative to private sector investment criteria.

Postresearch assessment is the second stage

The second stage is to analyze hurdle rates during the postresearch phase of the project. The postresearch assessment attempts to evaluate the program in relation to a situation in which the research program has been successfully completed and public sector participation has improved the commercial feasibility through active support and removal of institutional and technical barriers.

The major barriers to the successful commercialization of a product without Federal aid are indicated by those subelements that have the lowest base (preresearch) scores, together with the highest weights. For example, the barriers to be overcome by a Federal program might include stringent pollution control requirements, the opposition of public interest groups to potential SO_x problems, and the need to demonstrate the feasibility of the technical concept.

Summing the weighted raw scores assigned to the economic subelements yields a weighted average score for each of

A risk index is derived for each factor

the economic, environmental, and energy factors. This weighted score is then transcribed to yield a risk index, or probability of success, for each factor. The weighted feasibility score therefore corresponds to a risk index or probability of success. The barriers that would retard the successful commercialization of an energy technology are expected to be removed through the efforts of the proposed Federal research and development program. For example, a preresearch risk index of 0.61 determined as the product of the economic, environmental, and energy risk values is expected to be improved to a postresearch score of 0.92. This improvement would be achieved primarily through the removal of significant environmental constraints and through the creation of a greater perceived need among the general public for the energy benefits afforded by the project. Combining risk with the rate of return during the third stage of the analysis, the investment criteria can be keyed to an after-tax return on investment.

The political process is important in establishing weighting factors

Having calculated a rate of return for emerging technologies, it is then necessary to complete new technological systems against improved conventional processes. Although the method can calculate rates of return for conventional and nonconventional systems under uncertainty, it cannot calculate rate of return where markets and consumer preferences are not homogeneous. This indicates the importance of the political process in establishing the weights for the decision parameters, energy, environment, and economics.

Incremental decisionmaking is ignored

Critique. There are a number of problems with this analytical approach. First, it does not take into account the fact that the decision process is serial, remedial, and incremental. The risk assessment approach can only make explicit the assumptions that are used to select a specific technology or portfolio of technologies. It is assumed that if an analyst can delineate the major hurdles that must be addressed, he can then focus the attention of decisionmakers. Such hurdles need to be acknowledged by public officials as realistic constraints to the accomplishment of stated goals. If there is disagreement about the objectives of a program, the methodology is of limited utility. Such an approach allows the decisionmakers to identify the uncertainties that stem from lack of information.

Disagreement about program objectives limit usefulness of the approach

The methodology misses several key factors

Some aspects of an integrated analysis are not incorporated into the methodology. They are the explicit inclusion of political considerations into the decision model; the role and importance of the staff in presenting consistent data on environmental, economic, and energy

parameters; the importance of a constituency in the general acceptance of the design and implementation of an innovative assessment tool; executive participation and acceptance of the technique and its utility in policy formulation; and the use of thresholds as a guide to reduce quantitative complexity in multitechnology tradeoff analysis. These aspects, however, are not readily incorporated in most formal assessment methods. Both the comparison matrix and the multitechnology approaches make legitimate attempts to push the state-of-the-art another step forward in multitechnology assessments. However, critics can find flaws even in these sophisticated techniques. The comparison matrix approach requires that someone provide subjectively determined weights for the Factor Value Matrix. The multitechnology approach reduces environmental tradeoffs strictly to pollution control expenditures, leaving out ecological preservation, aesthetics, and other environmental factors considered essential by many. Both approaches require shadow prices or some other simplified quantitative method for evaluating noncommensurables. This becomes particularly difficult in attempting to evaluate new and emerging energy options for which pollution control standards have not yet been formulated. The most important contribution of the two combined approaches is the explicit recognition of nontechnical and political factors.

Summary

Clearly, this section seems biased against a number of the formal methods presently suggested for use in policy analysis. The conclusions or assertions made about any one of these (or all of them) are not meant to be denunciation of the methods per se. That is beyond the scope of this paper, and obviously not enough evidence has been developed to support such hypotheses. The main intent here is to indicate that the failure of the studies in Section II to present a complete case for intertechnology comparisons is both a failure of the state of the data available and a failure of possible methodologies.

The methods examined fail to meet minimum standards of usefulness

The next chapter attempts to offer some suggestions of where to go from here. Responsible researchers are not really permitted to be simply iconoclasts but are expected to offer some solutions of their own. Clearly, the "better" way is still a long way off, given the state of our information base. We also suggest that what we now know about intertechnology impacts is not enough to support judgments of which technology is the "best" from an environmental perspective.

IV. Cross-Technology Comparisons: Some Resolution

Another Possibility

Analysis could be performed using selected significant variables

Even if purely analytical cross-technology approaches for comparing energy system impacts are not feasible, some form of comparison for political or budgetary purposes may be desirable. Without violating our finding that no least common denominator exists to perform such assessments, the next best possibility is to carefully select a number of significant variables that are common to each energy technology and, to the extent possible, compare each technology in terms of such variables. For example, if air pollution, land use, and proliferation of nuclear weapons were chosen as the variables, it would be possible to get some idea of the value of the individual energy systems within the technological areas of coal, nuclear, and solar. What could not be presented adequately, however, is the relative importance of these measures in terms of each other. Nor are these either all or the most important variables, only some of them. With the present state of knowledge, comparisons between the variables used and their significance in terms of those not used would have to be evaluated either through the political process or in a subjective fashion by the policymakers.

This process has several disadvantages

This process has several obvious disadvantages that are apparent to anyone who understands the differences between competing energy technologies. Analysts would have to ensure that as many relevant variables as possible were displayed. Assuming that a large number of categories required consideration, then sufficient data

*Information is missing or
of poor quality*

would not be available to quantify all the requisite impacts. Thus, the analyst and the decisionmaker would be faced with the quandry of either using "best guesses" for the missing information or eliminating the value of the variables in question. In either case, the lack of data potentially reduces the quality of the analysis. Finally, the presence of a large number of variables means that the weighting job implicit at the policy level will be demanding and risky. Given resource and reality constraints associated with most policy issues, there is usually no way to make this weighting process explicit, thereby suggesting to some that the utility of the exercise is open to question. It is easy to envision situations in which so much information is presented that is of a questionable or unknown quality that the decisionmakers could more or less ignore it and would formulate policy based on other factors.

Recapitulation

Formal methods for determining comparative impacts do not solve tradeoff problems between energy and the environment

Thus, our discussion has been far-ranging. We have shown that attempts to perform comprehensive examinations of energy technologies in terms of their potential environmental impacts are very complicated, with little agreement concerning the adequacy of data or methods that should be used. A two-way tradeoff as complex as energy versus environment is clearly difficult to accomplish, and the use of formal methodologies that rely on expressing variables solely in economic terms does not solve our problem.

If a two-dimensional array could be constructed, with energy technology utility on one vector and environmental impacts on the other, a complete tradeoff analysis would have all of the affected cells filled with the values that are comparable to each other. Reading across any row would give the impacts of producing a unit of a given energy technology. Reading down a column would give the relative efficiencies of energy technologies or concepts in terms of a specific environmental impact. By expanding this matrix to a third dimension, while still limiting the type of variable used on any axis, strategies could be analyzed in terms of their energy, economic, and environmental dimensions.

The creation of such a three-dimensional array of information is ideal for those who wish to improve the decision process. However, practical limits on the types of variables that can be used prevent this approach from accurately simulating reality. Further, as complex, costly, and difficult as creating such a static array would be, the integration across these cells for the purpose of comparing technologies in a global fashion moves us once more into the area of weighting with all of its attendant difficulties.

Figure 3. Cross technology comparisons

A Viable Approach for Emerging Technologies

Formal comparative analysis does not provide useful answers to questions about energy-environment tradeoffs. Technologies, including new or developing ones, however, must be compared and policy decisions made. The Office of Environment in the Department of Energy has developed an approach that stops short of formal comparisons for such emerging technologies. It does, however, allow the decisionmaker to make comparative judgments about such technologies that are based on the best available technical information and scientific estimates. For the larger issue of intertechnology tradeoffs, including both old and new systems, this paper concludes that there are no analytically-based answers.

The Office of Environment's approach for emerging technologies is based on Environmental Readiness Documents. These documents are prepared in order to ensure the development of environmentally sound energy systems. As stated above, the Environmental Readiness Documents themselves do not contain direct intertechnology comparisons, but provide information to be used in such comparisons. In each document, estimated probabilities (on a scale of 0.1–0.9) are provided for three outcomes: (1) the probability that further research and development will result in an adverse finding as to the ability of the technology to meet existing and projected environmental standards; (2) the probability that such an adverse finding would result in significant delays in development and deployment of the technology; and (3) the probability of increased energy cost as a result of incorporating necessary environmental control technology. A recently completed summary of Environmental Readiness Documents that used such estimated probabilities as a mechanism for comparing 24 technologies is shown in Figure 3.

The principal conclusions from the Environmental Readiness Documents are as follows:

- Seven technologies were judged to have minimal environmental constraints. They are small in scale and operate at decentralized locations close to the user. Four are solar technologies.
- The minimally constrained technologies nevertheless have some potential environmental, health, and safety problems, which will require careful management.
- Eleven technologies, many of which are high-technology systems with great promise for meeting the nation's energy needs, were judged to have

moderate environmental constraints. Those constraints are expected to be mitigated with present or near-future state-of-the-art control technology.

- The moderately constrained technologies are, with few exceptions, in the predemonstration stage, with demonstration and environmental readiness likely to be achieved by 1980-1990.
- Six technologies, enhanced oil recovery (micellar polymer), hydrothermal, coal gasification, coal liquefaction, diesel cogeneration, and in situ oil shale, were judged to have significant environmental constraints that will require extensive environmental research and development before they can be widely used or before they can be deployed in some environmentally sensitive areas.
- Except for hydrothermal energy, the significantly constrained technologies are based on fossil fuels. None of these technologies are new, and most are already in use in one or more locales. Their large scale and their use of new processes, chemicals, or materials are chief causes of concern.
- The areas of common concern where productive research will relieve environmental constraints on many energy options are as follows: airborne emissions, respirable fine particulates, water pollution, solid waste disposal problems, toxic materials, and disruption of geologic formations or strata. Much of this research is ongoing but will require multi-year programs.
- Major uncertainties affecting the assessment of environmental readiness of the technologies are the application of new, planned, or proposed environmental standards and the costs of controlling recognized pollutants.
- Existing, proposed, or possible Federal and State standards under the Clean Air and Clean Water Acts, Resource Conservation and Recovery Act, Toxic Substances Control Act, Mine Health and Safety Act, and Occupational Health and Safety Act can affect the siting or compliance cost of nearly all of these technologies.
- The possible increase in energy or product costs because of stringent control measures required by existing standards is estimated at 10 percent or

higher in the case of 12 of the 24 technologies. In the highest cost scenario (very stringent future standards), energy or product cost could rise by 25 to 50 percent for many of these technologies.

From the standpoint of comparing the environmental effects of energy technologies, this summary of Environmental Readiness Documents is indicative but certainly not conclusive. The summarized documents represent collective informed judgments, but they were prepared separately with no attempt to "calibrate" judgments for intertechnology comparisons. The cross-cutting look at technologies provided by the summary, however, allows the reader to form some opinions concerning the relative significance and intractability of environmental problems potentially associated with the individual energy technologies. The grouping into categories of low, medium, and high impact does accomplish a rough sort of comparison of classes of technologies. There was no attempt made, however, to judge whether the technologies in these categories are more or less acceptable from an environmental standpoint. The summary merely states that to deploy them in a way that is consistent with standards designed to protect the environment, different technologies require different levels of effort. Such comparisons appear to be as far as we legitimately can go at this time.

Summary

This paper was intended to survey the potential for analytically comparing energy technologies in terms of their impact on the environment. As noted earlier, no judgment is made whether it is proper to analyze energy issues from such a myopic perspective.

A sampling of studies was examined

The second section included a representative sampling of studies all of which purported, in one way or another, to measure the environmental impacts of one technology as compared to another. In the previous section, a so-called "ideal" taxonomy was introduced that could be used to produce a more or less complete environmental assessment of an energy technology. We believe that if one were going to take on the ambitious goals of cross-technology impact assessment, such studies ought to address themselves, in some fashion or another, to each of the areas listed. For one reason or another, none of the studies surveyed compared favorably with the ideal. In general, the authors admitted that the principal deficiency with their own analysis was the quality of their data. There seemed to be a pervasive feeling that the data available to perform energy-environment impact analyses was fairly primitive

and that the results that could be honestly drawn were relatively tentative.

*Common methodologies
were reviewed*

The third section accepted the rather disappointing findings of the study survey and turned to an investigation of many of the more common methodologies used in public analyses and assessments. Once more, no attempt was made to be exhaustive but rather to see if any of the techniques could be expected to produce analytically defensible environment, energy, and economic tradeoffs. Again the findings were largely negative.

This is not to say that none of these methods are useful in performing analyses in other areas; however, given the state of the information base in the areas in question, they cannot be expected to perform well.

*Environmental protection
is guaranteed in many
areas*

In the last section, we suggested that all was not lost. We stated that comparisons of energy and environment were done, but usually only on a single technology, a specific issue, or on technologies of a similar type (all solar, for example). We close by suggesting that the desire to do energy analyses with environmental protection as the objective function may not be necessary. This is the case because environmental protection is guaranteed in many areas, particularly in the areas of human health and safety. It is on this point that one might investigate the reasons for doing such cross-technology tradeoffs. Some who are concerned with environmental protection apparently believe that one technology is preferable to another, and indeed, some of these preferences are apparent in analyses of the type presented in Section II. Another perspective is that such adversarial analyses are not necessary if there are adequate laws and regulations to protect human health and welfare. If these laws are enforced for each technology, should the environmentalist care which energy technology is chosen if, indeed, they can all be made equally benign? Possibly the more fruitful path for those who engage in adversarial activities in energy-environment matters would be to ensure that each technology is made benign, in and of itself, rather than try to figure out a defensible way to measure its impacts in terms of the others.

*Adversarial analyses
should be avoided*

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