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DISCLAIMER

SOCIAL AND ENVIRONMENTAL COSTS OF ENERGY SYSTEMS

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INTRODUCTION

An issue of growing importance in contemporary society is the assessment of the environmental and social costs of various technological policies and activities. It is by now widely recognized, first, that these "secondary" costs have often not been negligible compared to the economic costs of the enterprises in question; second, that the growing power of technology and the growing number of people on whose behalf it is exercised are steadily enlarging the potential, frequency, and magnitude of actions that may later be deemed environmental or social mistakes; and, finally, that responsible decision-making accordingly requires the best possible prior analysis of environmental and social costs of proposed activities. The embodiment of this perception in laws requiring formal environmental impact statements on major technological enterprises is surely a step forward, even if the literary ingenuity applied to early examples of such statements has occasionally exceeded the technical competence.

Environmental and social costs cover a wide spectrum of concerns (for example, occupational safety, public health, economic productivity, environmental diversity, social stability) and each policy or action produces a different mix of impacts and costs. (We distinguish at the outset between impacts, meaning disruptive influences exerted on the physical and social environment, and costs, meaning measures of the response of the environment to those influences.) This wide spectrum has led to an equally wide variety of methods for analyzing and weighing the impacts and costs. It is the aim of this article to review the available methods for such evaluations as they relate to energy technologies. Of course, in many cases the methods have been developed specifically for assessment of particular impacts and costs of particular technologies, so it is only sensible to discuss methods in the context of these substantive examples.

TYPES OF IMPACTS AND COSTS

Some coherence and manageability can be provided to this immense subject by agreeing on some sort of logical structure with which to subdivide it. It seems useful for this purpose to distinguish among:

(a) the <u>origins</u> of impacts on the physical and social environment, meaning the fuel cycles used to supply energy (coal, petroleum, fission, etc.) and, within each cycle, the various stages or operations (exploration, harvesting, transportation, etc.);

(b) the <u>character</u> of the impacts themselves, meaning what is added to or done to the environment (accidents, solid, liquid and gaseous effluents, heat, noise, other environmental transformations, etc.);

(c) the <u>costs</u> of the impacts, meaning the nature of the damage produced by what is done to or added to the environment (illness, loss of life, loss of economic goods and services, etc.);

(d) the types of <u>indices and criteria</u> by which the costs can be measured quantitatively or otherwise evaluated (days of life lost, dollars of economic damage, etc.); and

(e) the methodologies that can be used to arrive at the values of these indices.

A classification of impacts and costs based on categories (a) through (c) is given in Table 1. In the remainder of this section, we elaborate on the character of these impacts and costs. Indices, criteria, and methodologies are taken up later.

Death and Disease

Of all environmental impacts and social costs of energy production and use, it might be expected that none would be easier to quantify than human mortality. Certainly, one would think that statistics should be easily available and compilable, and that such a dramatic effect as death would command significant attention.

This expectation is only partly correct. Death from occasional catastrophic accidents or from more frequent small accidents can be quantified rather well, and, where there is adequate operating experience, predicted. Unfortunately, this is not the whole story. When the 'total deaths' associated with or attributed to some technology must be quantified, the task is not nearly as easy, because it is necessary to understand such effects as long-delayed deaths from earlier exposure to toxic substances and life-shortening by aggravation of existing morbidity.

This discussion points up one of the most important problems in analysis of environmental impacts: if mortality is difficult to quantify, how can any other phenomena which are less dramatic and less easily measured be understood quantitatively? For example, human illness (morbidity) is unarguably more difficult to quantify than mortality, even when the effect is direct causation of illness; when the effect is aggravation of existing morbidity, the task is even more difficult.

There are several different effects whose quantification will be discussed. Both mortality and morbidity effects can be divided into occupational and non-occupational categories (the latter often termed 'environmental'). Within these categories, one distinguishes further among:

1) Acute mortality or morbidity from an 'accident'
2) Latent (i.e., delayed) mortality or morbidity from an 'accident'
3) Effects of chronic exposure to some pollutant
4) Effects in future generations from genetic damage.

The methods employed in quantifying the various effects are numerous; they can be conveniently divided as follows:

1) Direct observations of specific individuals (i.e., after accidents)
2) Epidemiological studies of suspect population samples
3) Controlled dose/effect studies with animals, or occasionally with humans
4) Biological-biomedical studies of physiological indices or system functions.

It is also important to differentiate between the quantification of effects which have already occurred and the attempt to predict possible effects which might occur from possible future environmental, insults. Obviously, past experience must be the basis for prediction, but prediction also makes use of other information such as accident-probability analyses and pollutant-emission data.

In what follows, we discuss the quantification of death and disease by means of several examples, which serve to illustrate both the usefulness and the limitations of the available techniques.

DEATHS AND INJURIES FROM MASSIVE INDUSTRIAL FIRES This is the easiest class of effect to quantify. Usually, the incidents are well studied by investigatory teams after the fire has been put out, and both deaths and serious injuries are accounted for with good accuracy. Because these incidents are relatively rare, it should be possible in principle to gather data on the frequency with which they occur at various types of energy-related facilities (refineries, etc.), and hence to predict the likelihood of occurrence at some individual facility - taking into account, of course, that fire-prevention and fire-fighting techniques are improving steadily from one year to the next.

DEATHS AND ILLNESS FROM ACUTE DOSES OF RADIATION This type of effect presents more difficulties than the case of industrial fires, for a number of reasons. Again, the incidents are quite rare, and a historical tabulation of their number, character, and severity is in principle as achievable as for the fires. However, much more is involved here, if one is interested not only in the historical record but in prediction of possible future acute radiation effects. Of course, if only the frequency with which one or two occupational workers receive radiation injuries is of interest, it is probably safe to extrapolate recent historical data, again taking into account improvements in industrial safety. However, the prediction of acute effects from an accident such as a major release of radioactivity from a nuclear-reactor accident is very much more difficult. Here, even if the amount of radioactivity to which a postulated individual is exposed is known (or predicted), the dose actually received by the critical organs and the biological effects are not very well known. There are data on the amount of whole-body external radiation required to produce an acute fatality (death within 30 days of exposure), but even these data may not be usable directly; an exposed individual may be subject to several different types of exposure simultaneously (external whole-body, inhalation of several radioisotopes, ingestion, etc.), and in many cases the way these different doses act together is not understood. Neither human data (rare indeed) nor even animal data (which exist for a very few situations) are at present adequate to resolve the matter. Thus an investigator attempting to analyze impacts on health of possible massive acute radiation doses must rely on incomplete information. This limitation is borne out by the calculations in the draft of the recent AEC Reactor Safety Study(1) in which acute fatalities were calculated for a variety of release scenarios from accidents in light-water nuclear power reactors. The authors themselves indicate that the range of uncertainty shows values three times smaller to three times larger than the figures they present for acute fatalities (assuming no uncertainty in the doses received), but other investigators have stated that the uncertainties could be much greater (2, 3).

DEATHS FROM ACUTE AIR POLLUTION EPISODES This type of effect is extremely difficult to quantify, despite a few famous examples in the lore of the air-pollution field (Donora, Pennsylvania in 1948; London in 1952; the Meuse Valley, Belgium in 1930). Analysis of these incidents(4) has shown that the increased mortality, while statistically significant, is not of the type in which numbers of otherwise healthy individuals suddenly die of acute symptoms. Rather, much of the change in death rates reported in these episodes can be attributed to aged or infirm patients whose life expectancy would normally be considered very short. Also, in none of these few classic episodes has the air quality been well characterized, in terms of measurements of all the many possible trace pollutants now known or suspected to be important (SO_2, NO, NO_2, CO. oxidants, particulate sulfate and nitrate, particulate metals and organics, etc.). Morbidity in these acute air episodes is easily documented (apparently, nearly everybody in Donora suffered respiratory symptoms in the 1948 episode, for example), but again quantitative data are lacking or poor. One complication is that, in situations such as these, people tend to report symptoms when they 'know' the air quality is particularly poor, causing a systematic bias in epidemiological studies.

BLACK-LUNG DISEASE (PNEUMOCONIOSIS) IN COAL MINERS Black lung disease, prevalent in underground miners throughout the world, occurs with a reasonably long latent period, and seems to be associated with long-term, chronic exposures to the poorly ventilated air in the mines. While much improvement has occurred in the mines almost everywhere in the world in recent years, significant numbers of miners will probably die in the coming decades from exposures already incurred, and many others will be exposed in the future, even with the improvements. This type of effect is well-studied, at least insofar as the effects are concerned; as in many other such situations, however, the exposures (expressed as concentrations of the various air pollutants) are poorly known at best.

LUNG CANCER IN URANIUM MINERS Here the toxic agents are known quite well: they are the short-lived, chemically-active, radioactive daughters of the inert radioactive gas radon-222, which emanates from uranium-bearing ores within the mines. The daughters become attached to dust particles, are inhaled, and deposit in the lungs, where their radioactive decay provides doses to the lung tissues. The doses from specific concentrations of these daughters are reasonably well understood(5), and epidemiological studies have established the association between radiation dose and the lung-cancer effect(6). The association is shown in Figure 1. Within the last few years, actions have been taken which should reduce the doses of the miners by factors of at least ten and in some cases a hundred or so(7). Such improvements will produce a corresponding reduction in illness and death - depending in detail on the (unknown) dose-response relationship at the much-lower doses now involved.

CHRONIC EFFECTS OF GASEOUS AND PARTICULATE SULFUR COMPOUNDS We have already discussed briefly the few, rare acute episodes of air pollution in which large numbers of deaths and illness reports occurred. The much more common situation is human exposure, in urban environments, to non-fatal but significant concentrations of various air pollutants. In today's newspapers, the villain is often considered to be sulfur compounds, usually from combustion of fossil fuels such as coal, petroleum products, and natural gas. While a detailed discussion cannot be given here, it is certainly recognized by all workers in the field that the response of humans to air pollutants is a very complicated, possibly synergistic response whose etiology is only beginning to be understood. The Environmental Protection Agency's standard for gaseous SO_2 is based upon an analysis(8) which recognizes the possible role of other sulfur compounds, especially sulfuric acid mist and sulfate on particulate matter. However, there has never been definitive work to demonstrate how the various compounds, separately or together, produce the effects observed. Here, animal experiments are possible, and a series of important ones have been underway for many years(9), but definitive dose-response relationships still elude the investigators, partly because of the difficulties in generating realistic polluted air in a controlled laboratory. Epidemiological studies have produced associations with various respiratory diseases and pulmonary function impairment, but no completely satisfactory studies have been performed: there are always intervening variables in air-pollution parameters, socioeconomic effects, and/or other disease symptomatology. Recently, the entire situation has been cast into a new light by experimental data which reveal that the chemical and physical properties and transformations of the sulfur compounds are much more complicated than previously supposed(10).

TRACE METALS IN ENVIRONMENTAL AIR AND WATER It is by now well documented that many components of the energy-delivery system (e.g., petroleum refinery complexes, coal-fired electrical plants, coal mines, petroleum extraction) result in the presence of trace metals in environmental media such as air and water. However, rather little is known about the ultimate effects on humans in terms of disease and possible death from these pollutants. Only recently have there been studies attempting to associate burdens in selected body tissues (blood, urine, hair, etc.) with metals in particulate aerosols, and little is known about the relationship between air levels and such body burdens. Even less is known about the effect of metals brought into the body by inhalation or ingestion on essential biochemical systems such as various enzymatic systems, cellular membranes, or genetic mechanisms(11). Here research on a basic cellular and physiological level is badly needed, along with epidemiological studies where appropriate.

Impact on Goods and Services

The costs in terms of human well-being that result from the adverse impacts of energy technology take many forms in addition to death and disease as direct effects of effluents and accidents. One such class of problems is interference with the production or enjoyment of economic goods and services. A parallel set of difficulties arises from disruption of environmental processes which, while "free" in the economic sense, perform a variety of functions supportive of human well-being. Interference with economic goods and services and with environmental processes may result from the same kinds of effluents and accidents that produce direct damages to human health, or from other forms of environmental transformation. In either case, the final consequences for human beings can range from nuisances and aesthetic impacts, to substantial destruction of property, to tolls of death and disease that in some instances may exceed those produced by the more direct pathways.

ECONOMIC GOODS AND SERVICES The most dramatic and visible losses of economic goods and services through damage to property are those potentially associated with major accidents at energy facilities. Even excluding damage to the energy facility itself, the property losses associated with a major dam failure, the explosion of an LNG tanker in port, or a catastrophic accident at a nuclear power reactor could in the worst cases reach hundreds of millions and even billions of dollars. Probably somewhat smaller in terms of economic impact outside the facility itself are fires at oil refineries, accidents at nuclear facilities other than reactors, and major oil spills. The damages in the smaller but much more frequent accidents that occur at the application end of energy flows--e.g., electrical fires and gas explosions in individual buildings--should also be recorded as a debit on energy's economic balance sheet. The kinds of property principally at risk in different types of accidents are summarized in Table 2.

Less dramatic but often more significant in integrated economic impact are the damages to property that arise from the routine effluents of energy technology. Dominant here, as in direct impacts on health, are the combustion products arising from use of fossil fuels, both in stationary sources and in transportation. Oxides of sulfur and nitrogen attack nylon, rubber, metal, and stone, shortening the lifetime of clothing, tires, structures, and works of art. Most seriously, plants are damaged by oxides of sulfur and nitrogen, by ozone, and by various hydrocarbons, at concentrations regularly recorded in and around urban regions in the U.S.(12).

Economic damage through environmental transformations other than effluents and accidents has until recently been less commonly discussed, but is often serious. A nearly ubiquitous example is ground subsidence resulting from underground coal mining and from the extraction of petroleum, natural gas, or geothermal steam. Principally at risk are residences and other structures, since agriculture generally can still be carried out on subsided land. Surface disruption by strip mining and open-pit mining of coal, uranium, tar sands, and (potentially) oil shales, including damage done by the motion of spoil banks, is another expensive type of environmental transformation, with agricultural and recreational values chiefly at risk. Hydroelectric dams, through the increased evaporative losses associated with their reservoirs, may decrease stream flow enough to aggravate salinity problems downstream, with expensive effects on agriculture. Unsightly facilities, such as oil derricks and offshore production platforms, refineries and port facilities, and electric transmission towers and wires, may sufficiently change the character of coastal and inland regions to impair recreational and property values. The effects of air pollution on visibility and the odors from refineries are other aesthetic impacts with potential economic consequences.

ENVIRONMENTAL GOODS AND SERVICES The class of impacts on goods and services that traditionally has received the least attention is perhaps the most important one--interference with environmental processes that provide essential services in support of human well-being. To evaluate the seriousness of this set of problems, one must know three things: the nature of the environmental services and their links to well-being; the mechanisms and extent of human disruption of these services; and the possibility and costs of replacing disrupted natural services with technological substitutes. A good deal of qualitative understanding and a growing body of quantitative information exist concerning the first two subjects(13, 14, 15). Concerning the third, the actual evidence that is available has not been organized into a coherent picture, but even casual reflection suggests enormous economic and logistic barriers against substituting technology for basic natural processes on a global scale.

The greatest apparent potential for harm in the near future in the category of disruption of natural processes involves impact on agricultural productivity. Agriculture depends on natural systems for control of most potential crop pests (through natural enemies and environmental conditions), for maintenance of soil fertility (through natural nutrient cycles and regulation of the pH of surface water), and for maintenance of regional climatic conditions favorable to the crops now growing there. Production of protein in the sea, of great importance because of the shortage of protein in the global diet, depends on the integrity of estuarine habitats and on maintenance of appropriate chemical and structural characteristics of near-shore waters. Perversely, the productivity of the oceans is concentrated precisely where the potential impact of civilization is greatest--close to the continents.

Beyond loss of food production, the principal threats to human well-being through disruption of environmental services consist of accumulation of toxic substances (including carcinogens, mutagens, and teratogens) in the environment--owing to circumventing or otherwise intervening in natural chemical cycles--and alteration of environmental conditions governing agents of epidemic desease and the vectors that spread them (16).

Energy technology in particular has the potential to disrupt essential environmental services in many ways. Global climate can in principle be influenced by the buildup of carbon dioxide and particulate matter in the atmosphere from the combustion of fossil fuels. Local and regional climates can be affected by increased humidity from hydroelectric reservoirs and cooling towers for electric power plants, by waste heat discharged to the environment by power plants, and by the ubiquitous end-use degradation to low-grade heat of essentially all the energy used by civilization.

Chemical cycles and especially the chemical balance of surface waters can be influenced over large regions by the oxides of sulfur and nitrogen produced in fossil-fuel combustion, and over somewhat smaller areas by the acid and/or salt-laden runoff from surface mining operations and spoil banks. Chemical problems can also arise from the disposal of brines from oil-drilling operations, from exploitation of wet-steam and hot-water geothermal resources, and from the storage of solids or slurries produced by scrubbing sulfur from power-plant stack gases. Hydrocarbons added to the oceans by drilling operations, tanker operations and accidents, refinery discharges, atmospheric fallout (originating largely as automobile emissions) and river discharges (crankcase oil and industrial effluents) can be directly toxic to marine organisms or disruptive of marine ecology in other ways (e.g. interference with chemical messages), and under some circumstances could influence climate.

The uses to which energy is put also have profound effects on ecological systems and processes. (That the environmental transformations brought about by the application of energy are intentional does not mean they are always beneficial in an ecological sense.) Abundant, cheap energy has had a major role in making possible a U.S. agricultural system often characterized by overloaded or broken nutrient cycles (overfertilization and attendant eutrophication, feedlots), the inefficient pattern of settlement described by the term suburbanization, a transportation system whose backbone is land-gobbling highways rather than railroads, and an economy which has chosen to turn resources into pollutants after only a single use. The consequences have been a reduction in the areas of unexploited or lightly exploited ecosystems, and an increase in the stresses on ecosystems of all kinds, reducing overall the capacity of these systems to perform their various services in support of human well-being. These generalized consequences of the pattern of end-uses of energy deserve far more attention than they have yet received, as an important part of energy's environmental impact.

Consumptive Use of Resources

Part of the economic cost of energy technology is the value of physical resources, other than fuels themselves, which are used in the construction and operation of energy facilities and the energy delivery and end-use systems. Land, water, and nonfuel mineral resources are three examples. It is not obvious that the apparent economic value of these resources--the price that energy enterprises must pay to use them--is always an adequate measure of the real cost to society of making the resources unavailable for other uses now or in the future.

In other words, as is well known, the market as a determinant of costs is imperfect. If the prices of electric power and wheat are such that electric utilities can outbid wheat farmers for water in regions where water is scarce, heavy social costs--both to the farmers and to the nation that suddenly faces wheat shortages--may accrue. Energy operations that require land and can pay for it may pay far too low a price if the competing land use exerts no influence in the marketplace--as is the case with lightly exploited or unexploited land performing ecological services on which there is no price tag. Certain chemical elements with unusual properties - cesium, beryllium, helium - could in their scarcity eventually constrain specific advanced energy technologies and competing applications all out of proportion to the present price of these materials.

One cannot assume, therefore, that the economic cost of any energy technology subsumes all the important resource questions. The demands of energy technology on resources subject to competing demands must for completeness be reckoned not only in the currency of dollars but also in the physical currencies of acres, gallons of water, tons of steel, and so on. These currencies, like dollars, often lend themselves to direct and instructive comparisons among the technological alternatives for supporting a given level of energy use.

Among the most interesting resource demands associated with energy technology is the demand such technology makes on energy itself. That is, the construction and operation of energy facilities - mines, refineries, pipelines, uranium enrichment plants, and so on - naturally require some energy. It might seem at first glance that variations in the energy inputs needed to obtain a unit of energy output in different forms would be reflected in the straightforward way in the price of the output - in other words that economics makes superfluous a separate discussion of the energy costs of energy. That economics is in fact not sufficient is due in part to widely varying subsidies and other irregularities associated with how energy is used to get energy, and in part to differences in usefulness and thermodynamic quality among different kinds of energy. (That is, one BTU is not the same as another, either economically or thermodynamically - an idea made persuasive by the fact that a million BTUs of coal is worth about 80 cents, a million BTUs of electricity 5 to 10 dollars, and a million BTUs of hamburger about 700 dollars.)

It is characteristic of rich energy resources, such as thick coal beds near the earth's surface, that only a small amount of energy must be invested in exploration and harvesting in order to reap a large energy reward. If the resource is deeper or leaner, or if it must be processed extensively before use, the necessary energy investment increases. Naturally, society has tended to exploit first those resources that could be harvested with the smallest investment of energy, and the visible trend today is in the general direction of heavier energy investments. It is possible to envisage an energy resource so lean or so difficult to produce that more energy must be spent to obtain and process the fuel than it contains. If the form of energy has especially desirable properties, this may still be an economically viable enterprise; this is the case with food, the production and processing of which in the U.S. consumes 6 to 10 times as much energy (as fossil fuels) as the food contains(17). It is also the case with pumped-hydroelectric storage schemes, in which there is an energy debt paid for the benefit of availability during peak periods of demand.

Such examples aside, it is clearly desirable when comparing alternative technologies of energy supply to include the associated energy requirements as a criterion distinct from other economic parameters. The study of energy investments needed to get energy is termed "net energy analysis". One should distinguish in such analysis among three general kinds of investments and/or losses: (a) the part of the resource that is dispersed or left in the ground in nonretrievable form during extraction and processing operations; (b) the part of the resource that is directly used as energy to support extraction and processing operations; and (c) the inputs of other energy forms (fuel, electricity) needed to support these operations. Care must also be taken to account for the thermodynamic quality and the spatial availability of the energy involved at different stages.

Accurate figures for energy investment in the construction of facilities are difficult to obtain. These inputs are especially important when an energy system is growing rapidly. In such circumstances, the ratio of facilities under construction to facilities in operation is high, and, accordingly, a substantial part of the energy flows associated with the system is being invested in the facilities under construction, which will not yield an energy output until they are finished. Some analysts argue that light-water-cooled nuclear reactors as a system actually become net consumers of energy during periods when the system is growing very rapidly, even though each such reactor is a substantial net producer of energy over its operating lifetime(18). Other analysts have disputed this result in detail (although at some growth rate it would certainly be true). The resolution of the uncertainty is central to the issue of how rapidly reliance on fossil fuels can be reduced by means of the growth of nuclear power. The same question must be asked of other new technologies of energy supply - solar, geothermal, fusion - and indeed of the technology of energy conservation.

Political and Sociological Effects

It is generally agreed that energy production, conversion and use have impacts in the political and social arenas. We will discuss a few of these here. Two themes will be apparent throughout the discussion: first, the range of potential impacts is extremely broad; second, in many cases the causal links between energy technologies and the impacts are not conclusively established at this time, or not well apportioned among energy technology and other putative causes.

In the broadest sense, energy's productive role in economic systems is not only an economic function but a social "impact" - generally taken to be a positive one. Clearly, availability of energy is an essential element in the high productivity of the economies of industrial nations, in manufacturing, agriculture, transportation, and the provision of services. Whether continued growth of economic prosperity is contingent in a one-to-one way on growth of energy availability is not so clear - indeed there is growing evidence that the link between energy and prosperity is flexible, not rigid(19). Nor have the degree and kind of industrialization made possible by cheap and abundant energy always been, on balance, a benefit in social terms - perhaps there would be more numerous and more interesting job opportunities in a somewhat less mechanized society, for example. We will not dwell further here on the complex question of the social impact of how energy is used, however, but confine ourselves instead to the social and political ramifications of how and where it is obtained.

INTERNATIONAL EFFECTS In a number of important cases in recent history, the political implications of energy availability have been far-reaching. The thirty-year-long conflict in the Middle East is an example, wherein the presence of large petroleum reserves has been the main bargaining point of the otherwise weak Arab states in the conflict over Israel. The recent 1973-74 oil embargo and price increase has important implications in world politics, as all recognize. Other examples include the German interest in Rumanian petroleum in World War II, which had a major effect on the course of that war, the French-German dispute over the Saar, and Japanese interest in oil-rich Indonesia.

The international spread of nuclear fission reactors for the generation of electricity is accompanied inevitably by the spread of the capability to manufacture nuclear weapons. Although it is argued by some that "the genie is out of the bottle" in any case in terms of the spread of nuclear weapons, there is no doubt that the proliferation of reactors is accelerating the process beyond what would otherwise be possible or likely. To the extent that the likelihood of a nuclear conflict increases with the number of nations in possession of nuclear bombs, this acceleration threatens to deprive statesmen and political scientists of time they desperately need to fashion an international political system that can permanently prevent a nuclear war. This is an awesome "social cost" indeed.

A rarely discussed but important social-political impact of the choices of energy technology made by industrial nations is the influence of these devices on the prospects for narrowing the rich-poor gap between nations. To the extent that rich countries focus their own research and development on technologies that are heavily capital intensive, technologically sophisticated, unforgiving of errors in operation and maintenance, and attractive economically only in large units, there will be minimum useful technology transfer to benefit developing countries. Were the rich countries, on the other hand, to devote some effort to development of durable, forgiving, perhaps labor intensive energy technologies that make sense in small packages (naturally at some cost in efficiency and potential economies of scale), one result could be the great social benefit of a tangible contribution toward narrowing the demoralizing and destabilizing rich-poor gap that divides the world today.

DOMESTIC EFFECTS Even within the boundaries of the United States, the character and distribution of energy sources have important political and social implications. Thus California, which with 10% of the U.S. population is approximately self-sufficient in energy from its own oil, gas, hydro, and geothermal resources, has vastly more economic and political power than would be the case if it had no native energy resources. On the other hand, energy-poor New England suffers politically because of its lack of native resources; much of its national political muscle has historically been devoted to maneuvering to avoid national energy policies (such as oil import quotas) detrimental to its energy interests.

The political impacts of energy reach into other spheres as well. For example, the regulation of interstate commerce in natural gas has been a vehicle of social control on a broad front, because the availability and price of natural gas have had major impacts on the distribution and scale of economic growth in the country. Another example is the possibility that plutonium might be diverted from nuclear fuel cycles for illicit use by terrorists which may lead to the use of military, police, or quasi-police guards on an extensive scale. This potential extension of the security umbrella into the energy arena has been viewed with alarm by some civil libertarians, but urged by analysts in whose opinion reducing threat of diversion seems worth the cost.

Another social-political aspect of various energy technologies is their relative vulnerability to disruption, by natural, purposeful, or accidental events. Separate from (but associated with) the vulnerability of a particular energy technology is the vulnerability of <u>society</u> to the consequences of such a disruption. Examples here are numerous. On one end of the range are routine (or statistically anticipated) disruptions, such as the abnormally low rainfall in the Pacific Northwest in late 1973, which led to power shortages on the hydroelectric network in early 1974. On the other end of the spectrum is the vulnerability of energy-poor regions (New England, Hawaii) to sabotage, labor strikes, or other purposeful interruptions in petroleum or electrical energy distribution. Associated with this vulnerability is the political pressure for control to prevent it, and sometimes even political blackmail. The consequences of disruptions, of course, may include not only loss of energy but also direct damages from the event - e.g., sabotage at a nuclear reactor or hydroelectric dam.

The development of abundant energy in a region, especially if done in too short a period or with inadequate planning, can have sociological impacts because of built-in social, demographic, or economic inequities. As an example, the American southwest is one of the fastest growing regions of the country, in both population and economic activity. One of the spin-offs of continued construction of coal-fired electrical capacity in the region is the fact that, with much of the coal on Indian lands, development of these resources might bring both employment and more widespread prosperity without forcing these citizens to leave their native lands. Unfortunately, unless planning is done with great care, both the social and the environmental impacts of this development may be borne disproportionately by these same Indians - existing mechanisms may be inadequate to enable them to protect their environmental and social integrity.

ANALYSIS OF IMPACTS AND COSTS: METHODS, CRITERIA, EXAMPLES

The variety of methods for analyzing environmental impacts and social costs is as diverse as the impacts and costs themselves. Indeed, many analysis methods are specifically tailored to individual problems. However, a few methodologies have such wide applicability, and are already in such common use, that they can be considered in a more general manner. We shall discuss here a number of these methodologies, usually in the context of substantive examples.

Critical Pathways Method for Trace Substances

This approach has as its philosophical basis the idea that one can isolate from among all possible effects a few which can be represented as the most important 'pathways' of a trace pollutant substance in the environment. This method is now more-or-less institutionalized in the analysis of low-level radioactive emissions from nuclear electric power plants, having been required by the U.S. Atomic Energy Commission in all Environmental Reports since 1972(20).

Each 'critical pathway' is a specific, identifiable, inter-connected system in the environment which provides an important route for transport and transformation of some potential hazard from its source to man. There may or may not be successively larger concentrations of the hazard in the chain. We will discuss here perhaps the best studied of the radionuclide pathways around nuclear power stations, the transport of radioactive iodine-131 in the chain: stack → air → grass → cow → milk → human consumption → thyroid. This chain has been studied extensively, and it turns out that if a human drinks milk (1 liter per day) from a cow constantly grazing on grass exposed to iodine-131, his thyroid receives a dose about 1000 times greater than the thyroid dose which would be received by merely breathing the same air. For this reason, measurements of the milk are now considered essential to assure that such iodine-131 emissions as do occur are below permissible levels. The various elements in the chain are as follows:

i) Thyroid dose from inhalation: The International Commission on Radiological Protection(5) has set the occupational exposure limit for iodine-131 in air at 3000 picocuries/cubic meter (pCi/m^3), for continuous (round-the-clock) exposure; such an exposure will produce a thyroid dose of 15 rem/year in an adult. For children, the breathing rate, thyroid mass, and uptake fractions differ, but there is uncertainty about the exact values of the parameters; the best estimates(21) are that for ages 1-9, the dose is about the the same for children (with a factor of perhaps 2 uncertainty either way).

ii) Concentrations in air and in milk: Depending on whether deposition is 'dry' or 'wet', it is reported(22) that if a cow eats grass grown under an air concentration of 1 pCi/m^3, the cow's milk will contain 700 to 1200 pCi/liter. Another worker(23) finds the value 560 pCi/liter.

iii) Dose from ingestion of milk: Morley & Bryant(24) find that an infant consuming 1 liter of milk daily containing 400 pCi/liter of iodine-131 will receive a thyroid dose of 2100 mrem/year.

When it is all put together, an air concentration of 3000 pCi/m^3 produces an adult thyroid dose of 15 rem/year from direct inhalation(5). Drinking cow's milk, if the cow eats grass growing below that same air mass, will result in a dose of 10,000 to 20,000 rem/year (child's thyroid), and an adult dose presumably about the same. Thus it can be seen that the dose is bigger by a factor of (10,000 - 20,000)/(15) or a factor of about 1000, when the milk chain is considered.

Methods for Resources Subject to Competing Demands

The analysis of the true social costs of using resources subject to competing demands is complicated by the need to consider both explicit dollar costs and externalities (costs not now paid by the resource user and sometimesnot even tabulatable in dollars). There are two main types of resources to be considered: those for which replenishment is possible (whether or not practiced), and those for which it is essentially impossible. In the first category are such resources as wood, water, wildlife caught for food (e.g., fisheries), and some natural chemicals (e.g., some fertilizers, some fibers); in the second are most mineral resources, the fossil fuels (replenishable only on a geological time scale), trace gases (e.g., helium), and endangered species of permanently-damaged ecosystems (e.g., whales, tropical rain forests, dammed rivers).

For many replenishable resources, continued replenishment is regularly practiced: the water resources of the United States, crucial for all energy technologies, provide an example. In such cases, the true dollar cost of the resource can usually be determined, since the assurance of continuing steady-state availability has a dollar cost and value. However, it is much more difficult to do correct cost-accounting when replenishment, though possible, is not practiced: the construction and operation of hydroelectric dams is an example, since in nearly all cases the silting up of the artificial lake limits the lifetime of the resource, transfers a large environmental impact to future generations, and could be prevented. In this case, not only is the direct balance sheet skewed, but the true lost future economic value is not even determinable with much accuracy. Also, whether replenishment is practiced or not, there are social costs associated with such effects as the future loss of recreational opportunities in the affected regions; the possible harm to watersheds or wild fauna; or the long-range effects due to interruption of the natural growth/death/detritus cycles by the presence of dams and the transportation of water over great distances for other uses.

The case of depletable resources is quite different in kind, as well as in degree. Here, an analysis might take into account the various competing uses for a particular resource. Thus it is sometimes claimed that the burning of fossil fuels is wrong because it is destroying a resource which should be saved instead for use as a petrochemical feedstock. The analysis of whether this is true is incomplete without answers to the questions of how much resource still remains (or is likely to exist); at what rate it is being consumed (1% per year? 0.01% per year?); at what prices the remaining resources are extractable; and what competing uses exist or can be foreseen. The pitfalls here are obvious: depletion only happens once and lasts 'forever', while foresight into the future seldom extends very far. Thus, who in 1900 (when known petroleum reserves were miniscule by present standards, but usage was also low) could have foreseen the tremendous petrochemical industry of today? Similarly, who would have realized, in the 1930's, that the element niobium, now used for superconducting wire, might someday play a role in future electrical transmission or even electricity generation? [Even today, this possible future role is unclear, but at least its potential is recognized.]

Given these difficulties, how can any net assessment be arrived at on whether to deplete or to save a non-renewable resource?

In harsh economic terms, an answer can of course be given: if the value of the resource as used now, including its value as capital to be invested for the future, exceeds its (presently apparent) economic worth over the long haul if saved for future use, then economics com-commands society to "deplete, now, all of it". While quantifiable environmental impacts and their costs (the costs of providing by other means the services environmentally disrupted) must be properly accounted for in the economic balance sheet, there is, sadly, no way to put in the cost of an unforeseen technological opportunity.

Methodologies from Economics

There are a number of impacts and costs in the general area of economics, the discussion of which is beyond the scope of this Review. Among them are:

1) the economic costs of environmental pollutants, covered

in the article by Lave & Silverman in this volume of Annual Reviews of Energy;

2) the impact of energy technologies on the national and world capital marketplace, also covered in another article in this volume, by Pelley, Constable, & Krupp;
3) the impact of energy technologies on labor markets, both directly through labor involvement in the fuel cycles, and indirectly through secondary effects such as impacts due to availability of energy for industrial use;
4) the impacts of energy use on the general levels or patterns (geographical or demographic) of economic activity.

Methods Viewing Environmental Systems as Systems

There is an important class of environmental impacts that is not amenable to analysis by the 'critical pathways' approach, because the impacts affect an entire system. The systems under consideration are of two broad kinds, ecological systems and social systems, the former including such physical subsystems as geological, hydrological, and atomospheric systems, as well as their inter-relationships.

The methods of analysis of impacts on such systems must necessarily address the properties of the systems involved, conceived as complicated entireties. Such systems analysis methods, brought to maturity two decades ago for management of defense procurement and operational programs (e.g., the Polaris submarine program), have only recently begun to be applied to environmental systems. The methodology, now applied to many other problems in the field of operations research, involves development of a mathematical model (typically suited for execution on a high-speed computer), which treats each important but discrete segment of the larger system separately, characterizing it by selected variables and linkages significant for the issue at hand. The many important inter-relationships and interactions between segments of the model are also represented mathematically. The analytical procedure consists first of describing the equilibrium or steady-state properties of the system through the identified variables, and then of describing the various modes of departure from equilibrium.

It seems clear that much more use of the systems analysis methodology in environmental impact analysis will occur in the future. Up to the present time, only a few examples exist.

Perhaps the most important recent manifestation of the maturity of systems analysis is the establishment in 1972 of IIASA, the International Institute for Applied Systems Analysis. IIASA is sponsored by an international consortium of governmental and quasi-governmental bodies, such as the National Academy of Sciences in the United States; it has gathered at its headquarters near Vienna a group of analysts who are now applying the methodology of systems analysis to a wide range of problems, including many related to energy and its environmental impacts. Examples of recent IIASA work in these areas are that of Holling(25) on environmental impact analysis and that of Avenhaus and Häfele(26) on environmental accountability. The environmental accountability work describes the benefits of a materials-accounting approach for understanding of large, complicated environmental systems such as the global carbon-dioxide cycle.

Criteria, Indices, and Examples

Criteria with which to characterize the impacts of energy technology fall into three broad categories: (a) those that are quantifiable (at least in principle) and amenable to comparisons among different technologies; (b) those that are quantifiable but difficult or impossible to compare from one technology to another; and (c) those that are difficult or impossible even to quantify for a single technology. Table 3 provides a listing of some of the most important criteria, arranged according to this scheme. For those in the two quantifiable categories, the indices that provide a quantitative measure of harm are also listed.

The basic raw material for a systematic environmental assessment of a given energy technology is a tabulation of the values of indices associated with the quantitative criteria, for all the phases in the fuel cycle (Column 2 of Table 1). Several such tabulations have been published in the past few years, covering most of the major fuel cycles existing or envisioned for the generation of electricity(27-32). These studies cover, in substantial measure, the impacts of many nonelectric energy flows as well, inasmuch as such general processes as coal mining, coal gasification, oil transportation, and oil refining are all treated.
A useful format for the presentation of the most readily quantified information is the fuel-cycle flow diagram, a simplified example of which, for residual fuel oil(32), is shown in Figure 2. For a better example of the enormous amount of information that can be crammed into this format, the reader should consult the article by Pigford in the 1974 Annual Review of Nuclear Science(33).

Perusal of the published data of these kinds reveals that (a) wide discrepancies exist from one work to the next, often owing to different "accounting" procedures, and that (b) the heaviest impacts in different fuel cycles occur at quite different stages (routine discharges to air in the coal-electric fuel cycle are most serious at the power plant itself, while in the fission fuel cycle they are most serious at the fuel-reprocessing plant). These points underline the importance of making comparisons on the basis of the entire relevant fuel cycles, and the desirability of establishing agreed-upon consistent accounting procedures for the most frequently occurring indices.

In the remainder of this section, we discuss some of the intricacies and difficulties involved in using the criteria and indices summarized in Table 3, in the context of some data from the published literature. The ranges of data given in Tables 4-7 were compiled except where otherwise noted from References 27-32, and rounded to one or two significant figures. The figures are normalized to correspond to power plants of 1000 MWe capacity, operating at a load factor of 75 percent (i.e., delivering 6.57×10^9 kWhe per plant per year). Thermal efficiencies (electrical output ÷ thermal input) assumed at the power plants themselves are: light water reactor (LWR)=32%, residual fuel oil (RFO)=37%, coal with lime scrubbing=37%, combined cycle burning low-BTU gas from coal=47%, solar-thermal=10%.

QUANTIFIABLE, COMPARABLE CRITERIA Even among criteria that are readily quantified and that lend themselves to comparisons, there arise enough ambiguities and methodological problems to make using and comparing the literature of environmental impact a frustrating experience. Counting accidental deaths is straightforward enough, for example, but deaths from energy-related diseases may be concentrated in certain age groups, making it important to count lost days of life as well as numbers of deaths. Similarly, numbers of accidents or illnesses are not in themselves very instructive without the additional measure of severity provided by the number of days of work lost per event. Data for occupational accidental deaths and injuries in the electric-power fuel cycles for coal, residual fuel oil (RFO), and uranium (light-water reactors--LWRs) are summarized in Table 4.

Some economic damages, such as damages to crops, may be relatively easy to quantify; others, such as loss of recreation, stimulate controversy as to the proper methods of accounting. There is also the uncertainty as to the appropriate discount rate for determining the present value of future damages.

Quantifying resource use also poses questions. Does one distinguish between water that is evaporated and water that is polluted but returned to the surface? In fuel cycles for electricity generation, evaporative cooling towers (if used) invariably dominate the water use, whether water polluted and returned is counted or not (Table 5). Concerning land use, accounting problems arise in discriminating between temporary and permanent commitments of land. It is probably useful to distinguish inventory commitments (km^2 per MWe installed, committed for the duration of the facility's operation--e.g., the land on which the plant sits), temporary commitments (km^2-years per MWe-yr of delivered electricity--e.g., km^2

strip-mined per MWe-yr, multiplied by the mean number of years required to restore the land to other uses), and permanent commitments (km^2 per MWe-yr--e.g., repositories for radioactive wastes). Very few land-use data are available disaggregated in this detail. Some figures are collected in Table 6. Another question related to resource use is how far one traces these impacts. In net-energy accounting, for example, one would usually ascribe to the energy costs of coal-fired electricity generation the fuel burned by trains hauling the coal. Should one also count the energy used to manufacture the trains? Or the gasoline used by workers commuting to work to manufacture the trains?

QUANTIFIABLE, HARD-TO-COMPARE CRITERIA Difficulties in comparability between different technologies arise even with easily quantified impacts such as use of nonfuel minerals. If construction of a solar power plant were to require 100 kilograms of aluminum per electrical kilowatt, for example, and a nuclear power plant required 10 kilograms of stainless steel per electrical kilowatt, how would one decide which is the more serious impact (aside from price, which as noted above may not reflect the full social costs)? Measuring the material demands against known reserves, annual consumption for other purposes, and estimates of eventually recoverable resources provides indices that are a step toward comparability, but still imperfect. (Resource estimates are flawed, and consumption for other purposes may change.)

The same problem arises with respect to material effluents. A kilogram of carbon monoxide is not equivalent in social costs to a kilogram of sulfur dioxide. A curie of tritium is not equivalent to a curie of plutonium. An increasingly popular index that supplies some measure of camparability in these sorts of instances is the number (in units of volume) obtained by dividing the quantity of the material by the maximum concentration permitted by applicable regulations. In this way, the impact of discharges is represented in terms of the volume of air or water needed to dilute the effluent down to the permissible concentration. Thus a kilogram of SO_2, divided by the primary Federal (U.S.) standard of 80 micrograms per cubic meter of air, corresponds to a "dilution index" of 12.5 million cubic meters of air. A curie of tritium (about a tenth of a milligram), for which the Recommended Concentration Guideline (RCG--formerly Maximum Permissible Concentration, or MPC) for public exposure is 0.2 microcuries per cubic meter of air, has a "dilution index" of 5 million cubic meters of air. Dilution volumes for several fuel cycles are shown in Table 7. The main shortcomings of this approach to comparability are (a) that the standards for different substances are often neither equally well founded in terms of evidence of harm nor set with equal presumed margins of safety; (b) that the very different physical and chemical properties of different effluents influence how rapidly and under what circumstances the indicated dilutions are actually achieved; (c) that the persistence of the need for dilution varies greatly among different pollutants (e.g., some are transformed into innocuous substances, some leave the medium and enter another); and (d) that even for similar effluents in two different fuel cycles, the availability of air or water to serve as the receiving body varies widely and may depend on technology-specific factors (e.g., acid-leaching from coal mines is spatially limited, but different from acid waste disposal from uranium mills).

When one is concerned with ecological disruptions, it generally is useful to compare the scale of the technological disturbance against the yardstick of the relevant natural process. For example one can compare additions of CO_2 to the atmosphere with the "natural" concentration of CO_2 or with natural flows into and out of the atmosphere, one can compare technological energy flows in a specified area with the natural energy flows that govern climate, and so on. Some comparisons of this kind are presented in Table 8. It is hard sometimes to know, however, which of several candidate natural yardsticks is most meaningful, and the comparison between completely different kinds of impacts is not straightforward in any case. For example, human inputs of sulfur into the atmosphere amount to about half of natural inputs(34); human inputs of CO_2 have increased the natural background concentration by about 10 percent(14); and human inputs of tritium to the atmosphere, mostly from nuclear weapons tests, have produced inventories almost a million times those naturally occuring(35); which is the most serious ecological problem? Not tritium, as it turns out, but between the other two there is no way to be sure.

It is important and often possible to specify the way in which social and environmental costs are distributed in space and in time. One distinguishes among local, regional, and global effects, and among effects that are borne essentially at the time of the causative event (e.g., accidental deaths), later in the life of the exposed person (e.g., cancer), or in future generations (e.g., genetic disease). In practice, people seem more impressed by costs that are concentrated in space and time (and society is usually willing to pay more to avoid them). As an ethical problem, however, perhaps more attention should be given to those cases in which the bearers of the costs are far removed in space and time from those who reap the benefits of the acitivity in question. How assessments that compare different technologies should weigh differences in the spatial and temporal distribution of impact is not at all clear.

CRITERIA DIFFICULT OR IMPOSSIBLE TO QUANTIFY The boundary between quantifiable and nonquantifiable criteria is a fuzzy one, as the foregoing paragraph illustrates. Areas and times affected can be specified quantitatively, at least in principle, but the associated issues of the degree of voluntarism in imposed risks and the degree of coincidence of risks and benefits lend themselves to no tidy index. (See the article by Starr in this volume for additional discussion of these points.)

Two other criteria that are clearly important but, at the same time, quite resistant to quantification are degree of irreversibility of harm and quality of evidence of potential harm. These aspects are not unrelated. The greater the degree of irreversibility potentially associated with a particular course of action, the heavier should be the burden of proof upon those advocating this action, to show that the irreversible harm will not in fact materialize--or, in other words, the less conclusive the evidence <u>against</u> proceding should have to be in order to stop the action. Some semblance of a quantitative index for irreversiblity can in principle be supplied in the form of the time period required to repair the damage, but this is enormously uncertain in many cases of greatest interest (e.g., nuclear war or climatic change). Quality of evidence can be characterized (e.g., as speculation, hypothesis based on limited data, theory with extensive empirical support, etc.), but hardly quantified.

Comparing Apples and Oranges

The foregoing brief survey of criteria and indices underlines some of the difficulties of weighing the social and environmental costs of alternative energy technologies. Those aspects that lend themselves most readily to quantification may not be the most important ones at all, and often the problem seems to boil down to the proverbial one of comparing entities that are fundamentally incommensurable--apples and oranges. How does one weigh a small chance of a big disaster against a persistent routine impact that is significant but not overwhelming? How much social disruption should be tolerated to implement an energy technology that diminishes air pollution?

Often, attempts are made to compare apples and oranges by the expedient of forcing them into common units, such as dollars. Usually, such attempts have proven to be unsatisfactory, as examples to be cited below will reveal. The central thrust of this discussion, therefore, is that such comparisons require the utmost caution, with particular attention paid to the motivation for the comparison and the use to which it is put.

Consider one of the simplest of issues, the dollar value of a lost day of labor due to personal injury. When a large employer purchases insurance to cover the cost of this class of loss, he is paying the actuarially determined cost. The dollar value is well defined and accepted by society at large: it covers not only direct costs such as medical expenses, but also costs of occasional litigation, awards for liability, and other fees. This is considered satisfactory <u>for the limited purposes of insurance</u>, but it contains only a rudimentary way of accounting for items such as human suffering, dislocation, or the disruption of the labor which the individual would have performed had the injury not occurred. This rudimentary accounting comes about due to the dollar value of occasional tort awards for the suffering and dislocation, which is actuarially factored into the insurance premiums.

There are several other types of impacts to which, for better or worse, a monetary value can be assigned. Loss of life is one: recent large awards of substantial damages in tort cases reveal a remarkable upward trend, with the death of, for example, a non-working housewife/mother sometimes resulting in ∿\$500,000 awards rather than the ∿\$100,000 awards common only a few years ago. While the 'value of human life' may be indeterminate in philosophical terms, the dollar value as measured in this way has some accepted range, depending of course upon age and social status.

In a similar way, the dollar value of an acre of despoiled land has been determined, for example by the willingness of society to pay for its reclamation to one or another productive (or non-productive) use. Thus, 'reclamation' of strip-mined land may cost from a few hundred to a few thousand dollars per acre, varying with land type and nature of desired use. Whether these costs are paid (and sometimes they have been) depends on the perceived 'value' of the land in its spoiled vs. restored states.

This technique of attempting to determine dollar values for various environmental effects has both uses and abuses. The uses arise, for example, when a decision must be made on expenditures to improve or prevent some particular environmental degradation. The abuses arise, as often as not, from just the same source: such decisions often consider only the direct dollar expenditures, indeed perhaps only the costs whose consideration is forced by external pressures or regulations. A good example is the land reclamation problem, in which a fairly low level of reclamation may be considered 'acceptable' in some situations, thereby imposing hidden (if not indeterminate) ecological or other environmental costs.

There are a number of attempts in the literature to put a variety of environmental impacts on a common dollar basis. An example is the work of Morgan et al.(37) on the various costs of producing electricty from coal in the U.S. These authors cite a 'direct' cost of 7 to 8 mills/kW-hour as the price paid in 1970, and calculate a 'social' cost of 11.5 ± 2 mills/kW-hour. [1 mill=$0.001]. This 'social' cost includes dollar values for SO_2 pollution, particulate air pollution, thermal pollution, land reconstruction, health hazards in coal mining and from air pollution, and several other effects. The 'direct' costs are now paid by purchasers of electricity, while the 'social' costs are borne by society at large.

The usefulness of this approach would be if it could guide some action or policy. Morgan et al address this point by determining an 'optimal control strategy' - that which minimizes the sum of direct costs and social costs. Their analysis indicates that the optimal strategy costs perhaps 3 ± 1 mills/kW-hour, but reduces the 'social' costs by perhaps ∿7 ± 2 mills/kW-hour. The control strategy is dominated by abatement of SO_2 and thermal pollution, and by land reclamation, all of which are found to be cost-effective. The strength of this analytical approach is its ability to highlight areas whose social costs are greatest, and to determine costs for various levels of abatement. The pitfalls arise if the numerical analysis is taken too seriously, since the whole range of non-monetary effects and costs certainly cannot be represented by dollar equivalents.

Another example of an attempt to put an environmental impact on a dollar basis is that of several investigators who have studied the dollar cost of imposing on an individual a dose-equivalent of one rem of ionizing radiation. The typical calculation uses data such as those in the recent BEIR Report of the National Academy of Sciences(38), in which estimates are derived of the probability of contracting latent cancers or genetic defects many years after delivery of rather high doses (∿hundreds of rems). Using the linear hypothesis that these probabilities <u>per rem</u> are equally valid at low doses, and using one or another 'dollar value for human life' as discussed above, various investigators have quoted the 'cost' of one rem dose-equivalent to one adult in the range from a few tens to a few hundreds of dollars(39). Recently, the U.S. Nuclear Regulatory Commission has suggested as an interim measure "the conservative value of $1000 per total body man-rem for . . . cost-benefit evaluations."(40)

Besides dollars, there are a variety of other units in which comparisons of environmental impacts are feasible. One important class is pollution indices, in which each of several pollutants is assigned some weighting factor in the determination of an overall air-pollution or water-pollution index(41, 42). Since the uses to which these indices are put are usually rather limited, they are not often as susceptible to mis-use as are the dollar-cost comparisons. However, some important distortions can still occur. Consider an air-pollution index keyed to effects on human health. Consider also the widespread public image of air pollution in terms of visibility degredation. It is at least conceivable that public outcry would largely disappear if the particulate pollutants responsible for much of the poor long-range visibility were to be abated, even if no improvement were made in other health-degrading air pollutants. In that case, an 'air pollution index' based on the effects on health would not reflect an important public concern, yet would still have value if used properly.

Particularly knotty problems arise when comparisons in common units are either impossible or very controversial. This is the true 'apples and oranges' problem. Examples are abundant in all areas where decisions must be made, and it is unlikely that much can be said to cast light on the problems involved.

Handwringing aside, there is one philosophical point which is of enormous importance: it is that in such cases the most important role of technical analysis is the clarification of technical issues. This clarification takes the form not only of quantifying those items to which a number can be assigned, but also of determining ranges of uncertainties or of likely errors in the numbers. This is sometimes given short shrift when the analyst knows or feels that decisions will be made on other grounds, but it is no less important than in any other situation.

CONCLUSIONS

Perhaps the most salient feature of the discussion presented in this article is the apparent inadequacies in most of the methodologies now available for detailed analysis of environmental impacts of energy technologies. The inadequacies range over the entire spectrum of analytical tools: the criteria and indices by which impacts are judged and compared are under dispute; the methods for quantifying impacts and costs are in many instances poorly developed or seriously flawed; and the inability to 'compare apples and oranges' makes the final goal unattainable in many (perhaps all) important situations.

Is the situation really all the bleak? In fact, it is not: the apparent inadequacies in methodology are counterbalanced in part by vigorous (and often fervent) activity in environmental analysis itself. While analyses using weak methods are often of dubious worth, the mere level of activity is providing an ever-larger data base, as well as continually-refined understandings of which criteria and intercomparisons are most valid. These understandings are then being used iteratively to point toward inadequacies in the data bases. This stimulation goes full circle, and our understanding is, indeed, growing rapidly, perhaps at this time exponentially.

Despite the difficulties with detailed methodologies, there is enough information available to support at least four important points:

First, the available data suggest the possibility of significant interference in critical environmental processes, as well as direct effects on human health. Such interference is plausible in some cases at the present time, in many others in the immediate future (over the next few decades).

Second, there is no such thing in the energy business as a free lunch. No existing or proposed energy technology is so free of environmental liabilities as to resolve satisfactorily the central dilemma between energy's role in creating and enhancing prosperity and its role in undermining it through environmental and social impacts.

Third, where high degrees of irreversibility are possible, the burden of proof must be shifted from the opponents of further growth to the proponents. Although it will never be possible to eliminate environmental mistakes, we must strive to reduce the chances of irreversible ones.

Finally, the situation that civilization has reached the predicament where large-scale environmental disruptions are not only possible but perhaps likely, without having developed the knowledge to understand the possibilities in detail or to cope with them, gives reason to slow greatly the growth in energy consumption. Only such a slowdown can buy the time needed to obtain more knowledge of the threats, and to develop and deploy more benign technologies.

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TABLE 1. CLASSIFICATION OF IMPACTS AND COSTS

fuel cycles	phases	impacts	costs
coal	exploration	accidents	death & disease
oil	harvesting	gaseous effluents	genetic effects
gas	concentration	liquid effluents	loss of economic goods & services
oil shale	refining	solid effluents	loss of environmental ("free") goods & services
tar sands	transportation*	heat	aesthetic loss
fission	conversion*	resource consumption	undesirable social & political change
fusion	storage*	environmental transformation	
solar	end-use	noise	
geothermal	management of final wastes	altered opportunities	
etc.			

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*may occur more than once

TABLE 2. PROPERTY AT RISK IN ENERGY-RELATED ACCIDENTS

Accident	Property at Risk
LNG tanker explosion	docks, warehouses, commercial buildings
hydro dam failure	farmland, towns
nuclear reactor accident	farmland, residences (contaminated)
refinery fire	adjacent chemical plants, rocks
oil spill	beaches, pleasure boats
radioactive waste leakage	farmland, ground water
electrical fires, gas explosions	buildings

TABLE 3. CRITERIA FOR EVALUATING SEVERITY. (INDICES FOLLOW COLONS)

Quantifiable, Readily comparable

- deaths: number, days of life lost
- accidents, illnesses: number, days of productive activity lost
- damages to economic goods and services: dollars
- use of land, water, energy: square meters, liters, joules
- material effluents: kilograms (of the same substance)
- nonmaterial effluents: joules, decibels
- dollar costs of reducing quantifiable impacts by specified degrees

Quantifiable, Difficult to Compare

- use of nonfuel minerals: kilograms (of different substances)
- material effluents: kilograms (of different substances), curies
- magnitude of perturbation in a natural process: dimensionless fraction
- spatial and temporal distribution of harm: area, time

Difficult of Impossible to Quantify

- degree of irreversibility of harm
- degree of voluntarism in risk
- degree of coincidence of risks and benefits
- quality of evidence of harm
- political implications

Table 4 Occupational accidental deaths and injuries in fuel cycles for electricity generation. (One significant figure.)

fuel	deaths per plant-yr	injuries per plant-yr	10^3 man-days lost per plant-yr[a]
deep-mined coal	2 - 6	30 - 100	10 - 40
surface-mined coal	1 - 4	10 - 60	7 - 30
oil (RFO)	0.1 - 0.2	4 - 10	1 - 2
uranium (LWR)[b]	0.1 - 0.3	5 - 10	1 - 2

a. evaluated at 6000 man-days/death and 50 to 100 man-days/injury, depending on fuel cycle and stage

b. range encompasses surface and underground uranium mines

Table 5 Use of water in fuel cycles for electricity generation.
10^6 m^3/plant-yr

fuel	evaporated in wet towers at power plant	blowdown water in plant cooling towers[a]	fuel-processing water use [b]	waste management water use [b]
standard coal[c]	11.	6.6	0.3	1.7
coal gasification/ combined cycle[d]	6.6	4.0	0.5	--
oil (RFO)	10.	6.0	1.5	--
uranium (LWR)	17.	10.	0.5	0.01

a. returned to surface polluted

b. some evaporated, some returned

c. wet lime scrubbing for SO_2 removal

d. combined-cycle power plant efficiency = 47%; fuel-cycle thermal efficiency ≈37%

Table 6 Land use in fuel cycles for electricity generation

fuel	inventory, km^2 per plant[a]	temporary commitment, km^2-yr per plant-year[b]	permanent commitment, km^2 per plant-yr
deep-mined coal	12 - 15	10 - 29	--
surface-mined coal	12 - 15	20 - 240	--
oil (RFO)	3 - 14	--	--
surface-mined uranium for LWR	1	1 - 2	0.001
solar-thermal[c]	56	--	--

a. includes facilities for processing and transportation, but not transmission

b. 10 yr mean time for restoration to other use

c. plant capable of delivering 1000 MWe-yr per yr at 100% load factor (18 MWe average per km^2)

Table 7 Dilution volumes in air for routine effluents of fuel cycles for electricity generation 10^3 km^3/plant-yr

fuel cycle	effluents	dilution volume, power plant only[a]	dilution volume, all other steps
coal with lime scrubbing	NO_2, SO_2, HC	200 - 550	7 - 8
	particles, heavy metals	23 - 48	29 - 370[b]
coal-gas/ combined cycle	NO_2, SO_2, HC	8 - 77	7 - 8
	particles, heavy metals	5 - 48	29 - 370[b]
oil (RFO)	NO_2, SO_2, HC	66 - 450	21 - 58
	particles, heavy metals	12 - 120	1 - 4
uranium (LWR)	H-3, Kr-85	0.0003 - 0.027	0.013 - 1.9
	Rn, trans U	--	0.5 - 1.6

a. Standards used, per m^3: NO_2 = 100 μg, SO_2 = 80 μg, HC = 160 μg, particles = 75 μg, heavy metal = 1.5 μg, H-3 = 0.2 μCi, Kr-35 = 0.3 μCi, Rn-222 = 0.003 μCi, transuranium nuclides = 5×10^{-8} μCi

b. high figure includes coal losses in transport, probably not comparable to other particulate emissions

TABLE 8: ENVIRONMENTAL INPUTS FROM ENERGY CYCLES AS FRACTIONS[a] OF NATURAL YARDSTICKS

energy-related input	natural yardstick	input/yardstick	references
petroleum in oceans	natural seepage	6 - 20	13
CO_2 in atmosphere	atmospheric CO_2 reservoir	0.1[b]	14
particles in atmosphere	volcanoes, sea salt, dust	0.05 - 0.5	14
Sulfur in atmosphere	sea salt, biological processes	0.5	34
Nitrogen fixation ($N \rightarrow NO_x$)	biological processes, lightning	0.7	36
heat dissipation at surface	sunlight absorbed at surface	<0.0001 global <0.01 large urban regions	14

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[a] ratio of annual flows on a global basis, unless otherwise noted

[b] cumulation perturbation in inventory

FIGURE CAPTIONS

FIGURE 1 Observed and ecpected annual lung cancer mortality per 10,000 uranium miners, and 95-percent confidence limits, in relation to exposure in cumulative working-level-months (WLM). 1 WLM= exposure for 1 month (170 working hours) to a concentration of any combination of radon daughters in one liter of air that will result in the ultimate emission of $1.3\text{x}10^5$ MeV of potential alpha energy. For details see Reference (6).

FIGURE 2 The residual fuel oil cycle for electric power generation. The basis is annual operation of one 1000 MWe electric power plant at 75% capacity factor. Figure from Reference (32).

Figure 1

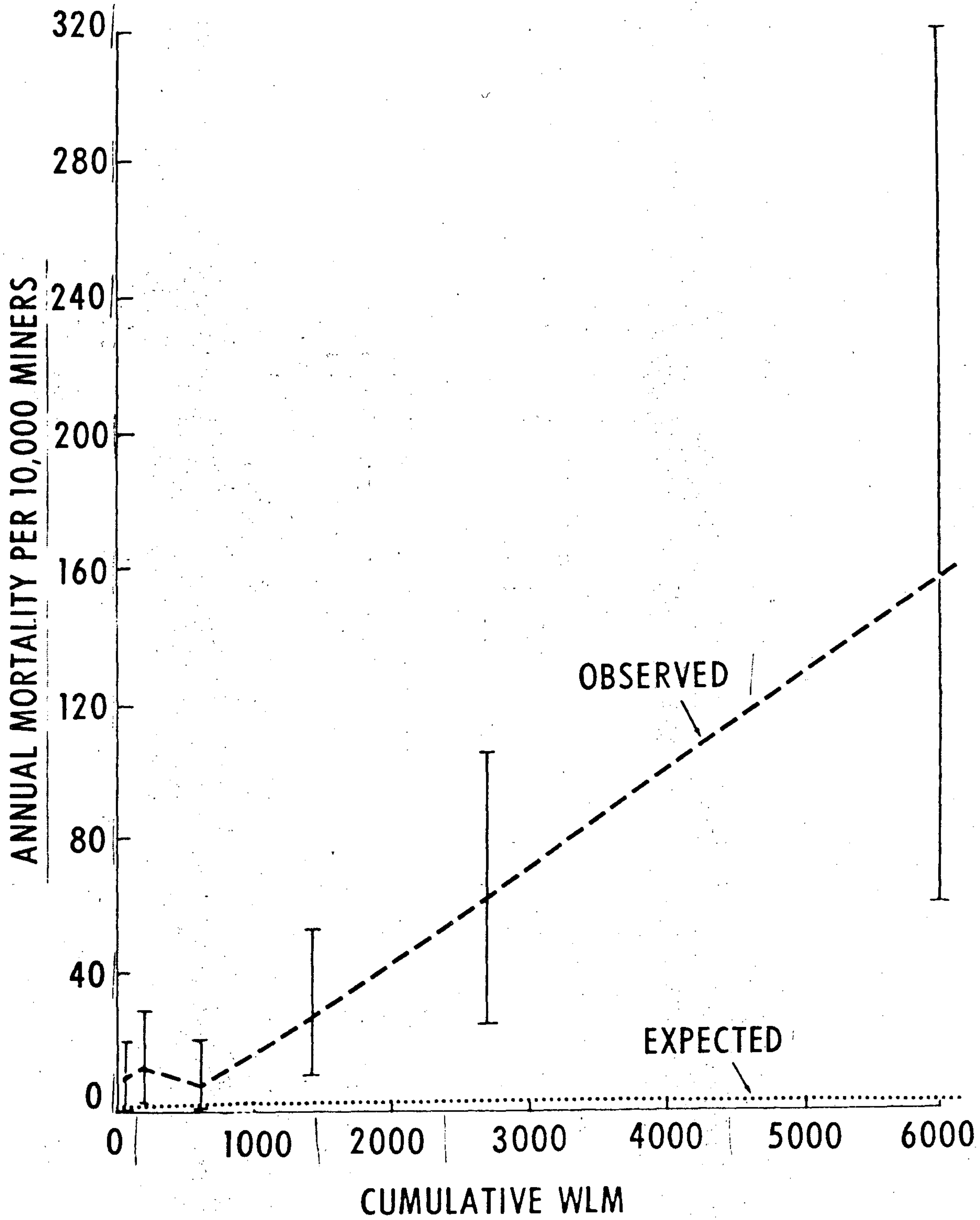

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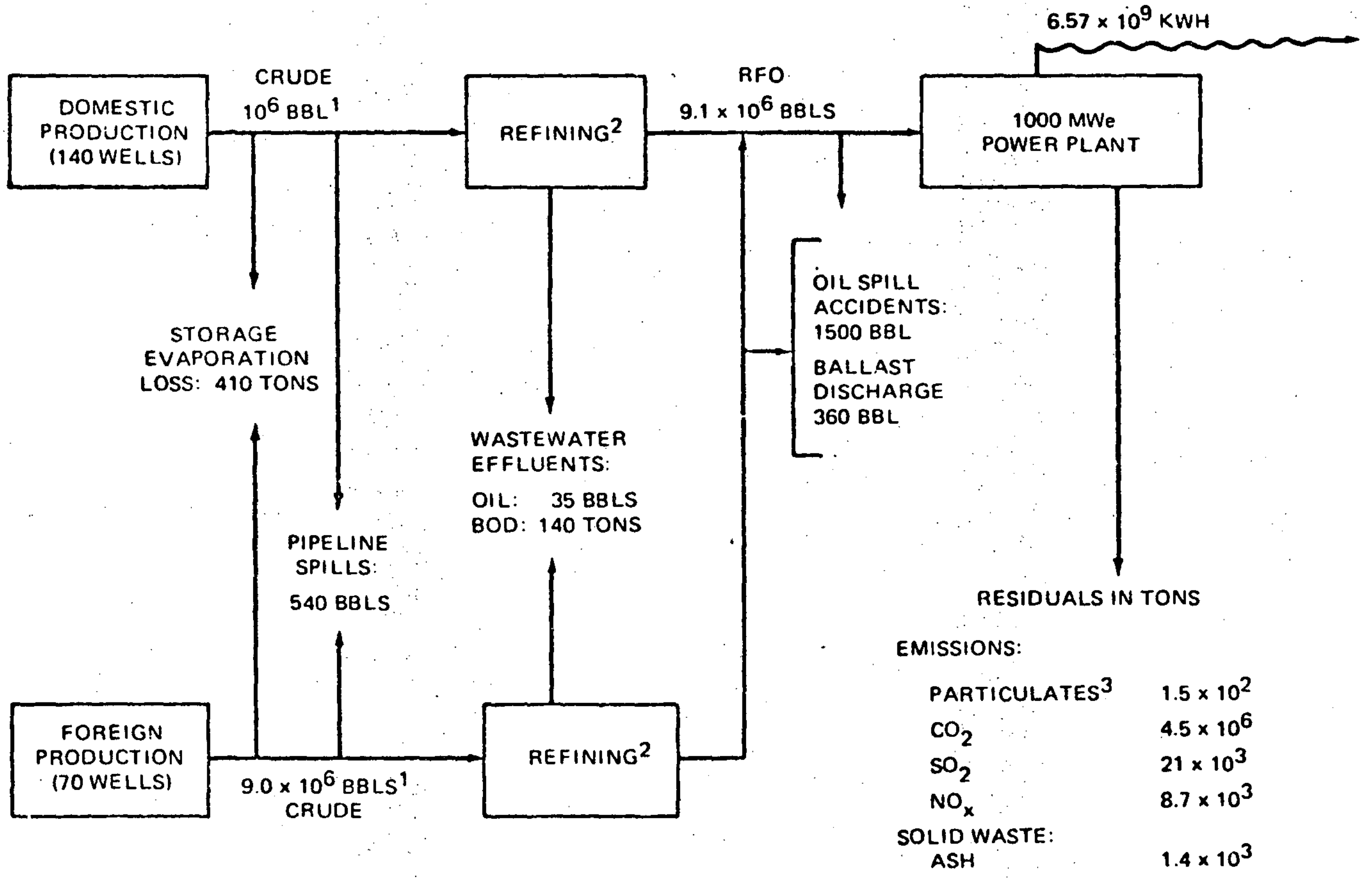
FIGURE 2



[1] PORTION OF REFINERY INPUT ATTRIBUTABLE TO RESIDUAL FUEL OIL PRODUCTION: CALCULATED ON A Btu EQUIVALENT BASIS.

[2] RESIDUAL FUEL OIL YIELD OF U. S. REFINERIES, 10%; FOREIGN REFINERIES, 40 TO 50%.

[3] ASSUMES A 90% COLLECTION EFFICIENCY FOR ELECTROSTATIC PRECIPITATORS.

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