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ENERGY TECHNOLOGIES AND NATURAL ENVIRONMENTS: THE SEARCH FOR COMPATIBILITY

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INTRODUCTION

In what ways will present and future energy activities disrupt ecosystems, and what will be the consequences to human society of ecosystem degradation. What are the major uncertainties in our present knowledge of ecological impacts of energy activities, and to what extent can these uncertainties be reduced? Are untraditional energy activities, such as the use of dispersed technologies, more ecologically benign than the traditional ones? These are the questions we explore in this review.

The first section presents an overview of the major energy activities. In it we assess the anticipated ecological risks and uncertainties associated with each energy source and discuss what is known about the human consequences of ecological degradation from energy activities. A tabularized literature review (Table 1) provides the reader access to more detailed treatments of the ecological impacts of energy technologies. This overview is followed by a critique of methods of assessment used in ecosystem impact research. Problems of measuring stresses on ecosystems, of prediction of ecological responses to these stresses, and of valuation of goods and services provided by undisrupted ecosystems are discussed. A final section takes a critical look at a number of proposals that have been generated recently to restructure energy policy along untraditional lines, and assesses the ecological gains and losses that might result if these proposals are accepted.

There are a number of important topics relating to the subject of impacts of energy activities on ecosystems that we do not discuss in any depth here.

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Table 1 References to articles on ecological impacts of energy activities

Energy activity	Ecosystem	Stresses	Ecological effects	Human consequences
Hydropower	freshwater lake	4, 5, 7, 8, 12, 17, 27	4, 7, 8, 12, 16, 17, 18, 19, 27	4, 5, 7, 8, 12, 13, 19, 27
	river	5, 7, 8, 11, 12, 13, 15, 17, 20, 24, 26	7, 12, 17, 20, 24, 26	7, 11, 12, 15, 20, 24
	grasslands	22	22	22
	estuary, delta, and salt marsh	6, 7, 14, 25	6, 7, 14, 25	6, 14
	beach and tide pool	7, 23	7, 23	23
	agricultural crop lands	7, 12, 15	12	12
	canyonland	7, 9, 12		
	marine	21	21	21
Solar space heating and cooling	urban or suburban open spaces	28, 29	28, 29	
Biomass conversion	agricultural crop lands, forests, lakes, rivers, and marine	28, 30, 31	28, 30, 31	30
Wind conversion	general	28, 32, 33	28, 32, 33	
Solar central receiver systems	desert	34, 35	34, 35	34
Ocean thermal conversion	marine	28, 36, 37	28, 36, 37	28, 37
Geothermal conversion	freshwater lake	38, 41, 42, 43		
	river	38, 40, 41, 42, 43	40	
	forest	39, 43	39	
	agricultural crop lands	38		
	grasslands	39	39	
Surface mining of coal	freshwater lake	44, 45, 46, 47	44, 45, 46, 47	44, 45, 46
	river	44, 45, 46, 47	44, 45, 46, 47, 48	44, 45, 46, 48
	grasslands	44	44	44
Deep mining of coal	freshwater lake	48, 49		
	river	48, 49	48	48
Cooling	freshwater lake	45, 50, 51, 52. 53, 54	50, 51, 52, 54	50, 52
	river	45, 50, 51, 52, 53	50, 51, 52	50, 52
	marine	50, 55	50, 55	55
	estuary, delta, and salt marsh	50, 56, 57	50, 56, 57	57

Table 1 *(Continued)*

Energy activity	Ecosystem	Stresses	Ecological effects	Human consequences
Combustion of fossil fuels	freshwater lake	59, 62, 63	59, 62, 63	59
	river	59, 62	59, 62	59
	grasslands	58, 59	58, 59	58
	forest	58, 59, 60, 61, 62, 64	58, 59, 60, 61, 62, 64	58
	agricultural crop lands	58, 60, 61, 64	58, 60, 61, 64	58, 64
	urban or suburban open spaces	60, 61	60, 61	61
Petroleum drilling, transport, and handling	freshwater lake	65		
	river	65		
	estuary, delta, and salt marsh	57, 65, 66, 67, 68, 69, 70	57, 65, 66, 67, 68, 69, 70	57, 66
	beach and tide pool	65, 66, 67, 68, 69, 70, 71	65, 66, 67, 68, 69, 70, 71	66
	marine	65, 66, 67, 68, 69, 70, 71	65, 66, 67, 68, 69, 70, 71	66, 71
	tundra	72	72	72
Nuclear fuel cycle	freshwater lake	73, 75	73, 75	
	river	73, 75	73, 75	
	ocean	73, 75, 76	73, 75, 76	
	forest		77	
	general	74, 78		
Oil shale mining and conversion	river	45, 79, 80, 81, 82, 83	80, 81	
	forest	81, 83		
	agricultural crop lands	79		
	canyonlands	79, 80, 81, 83	80, 81	
Coal conversion to synfuels	freshwater lake	45, 79, 80, 84	79, 80, 84	80
	river	45, 79, 80, 84	79, 80, 84	80
	grasslands	80, 84	80, 84	80
	agricultural crop lands	45, 80, 84	80, 84	80

Three of these pertain to climate, war, and outer space. Climate change could be initiated by carbon dioxide production from fossil fuel combustion. The ecological changes that would occur on an earth warmed by an anthropogenic greenhouse effect could be enormous—possibly greater than any of the ecological impacts from energy that are considered here. Similarly, should war erupt among or within nations as a result of conflict over energy resources, or over water rights, or as a result of easier access to weapons-grade nuclear materials by way of nuclear power fuel cycles, the ecological consequences could be staggering. And should society pursue a commitment to develop space colonies in an attempt to push back natural limits to growth on our planet, again there would be major ecological consequences.

Topics like these tend to fall between the cracks set up by neatly structured studies and reviews. Ecologists can say some very important things about these subjects, but not without collaboration with others who can help resolve the multidisciplinary uncertainties. Until such collaboration takes place, speculation about these topics would provide little but the illusion that they have been studied seriously.

We are confronted with two futures. One is the future of preservation of natural beauty and wildness. The other is the future of further energy development. Human welfare is enhanced in some ways by preservation of natural systems and in other ways by expansion of energy consumption. To the extent that the two futures are incompatible, the freedom available to society is the freedom to trade parts of one future for parts of the other. As discussed in what follows, serious conceptual and practical problems prevent a comprehensive analytical solution to the problems posed by incompatibility. We nevertheless can seek out those energy technologies for which the problem of incompatibility is minimized, namely, those technologies least disruptive to ecosystems for a given level of fulfillment of the goals energy satisfies. This review focuses on identifying these most benign technological approaches, as well as on the problems one faces in the process of identification.

OVERVIEW OF ECOLOGICAL IMPACTS OF ENERGY ACTIVITIES

One function of a scientific review is to acquaint the reader with the contents of the technical literature in the subject at hand. In this section we discuss separately each of the principal energy activities and point out what is known or speculated about their likely ecological impacts. The immensity of the subject precludes a detailed treatment of any one impact and precludes even mention of all impacts discussed in the literature. Therefore, we discuss the most important ecological problems associated with each of the energy activities and provide references to selected research papers and reviews. Our assessment of the major ecological impacts has two purposes. One is to identify the most likely and worrisome ecological impacts of each energy source or activity. The second is to evaluate the level of uncertainty in our knowledge of these impacts and to point out the most glaring gaps in the literature.

An Impact Nomenclature

The totality of impact resulting from an energy activity such as coal mining, petroleum burning, or dam building can be viewed as a sequence of steps. The nomenclature we adopt to describe these steps is shown in Figure 1, along with examples of each of the steps in the sequence. We have chosen a nomenclature similar to that used in a recent study by the National Academy of Sciences (1) and a recent review (2). The reason for paying attention to the somewhat pedantic issue of nomenclature is to help clarify to humans. In addition, because natural ecosystems provide many goods and services of benefit to humans, the direct and indirect ecological effects of energy activities can have adverse consequences for society. The response of society to the loss of goods and services often is to take remedial action, thus initiating another pass through the sequence of stages of impact.

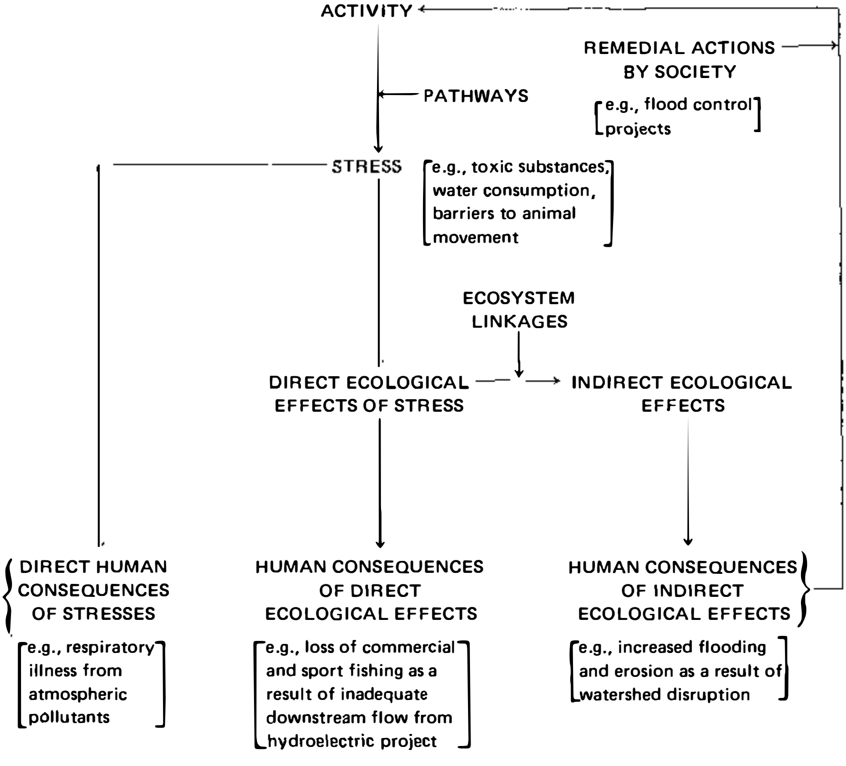

Figure 1 Chart of the stages of ecological impact. Energy-related activities (such as dam building, fossil fuel burning, or slurry pipelining) generate, via pathways, stresses on ecosystems. These stresses can affect ecosystems directly (e.g. by toxic action on organisms). Because of the complex interconnectedness of ecosystems, these direct effects can lead to longer term indirect effects.

a situation that has been confused by imprecision. For example, much of what passes as ecological impact analysis is really stress analysis. And much of what passes as analysis of human consequences is an assessment of only the direct human consequences of stress rather than of the human consequences of ecosystem degradation (3). Having a map in front of us of the many stages of impacts helps show us where we have not yet traveled.

Our discussion below highlights the fact that the relative amount of attention that, in the past, has been focused on each of the steps in the full sequence comprising an impact varies tremendously from one energy technology to another. The analysis of indirect human consequence of ecosystem degradation has been neglected in comparison to the assessment of stresses and of ecological effects. Moreover, most of the work on ecological effects is limited to direct ecological effects of stress rather than to indirect or induced effects. Thus, for example, the literature on toxic effects of a particular effluent on a particular species is far more thorough than the literature on ecosystem or community response to the demise of a particular group of sensitive species.

Our literature review is in tabular form. For each energy activity, Table 1 presents references to technical articles and reviews. These listings are broken down according to the type of ecosystem discussed. Then a further division is made into three categories of ecological impact assessment—stresses affecting ecosystems is one; ecological effects is a second; and human consequences of ecological degradation is a third. The list of references for each energy activity is not intended to be complete. For most of the topics, it is likely that more than 99% of the authors who have written on the subject will not find their work referenced. Our goal is to provide a list of references that portrays the breadth of the subject and includes prominent reviews containing more complete bibliographies.

Hydropower

There exists a thorough and diverse literature on the ecological impacts of hydroelectric power. All three categories of impact from stresses to human consequences have been discussed at length and it is likely that most of the major impacts have been identified. This level of assessment is in part a consequence of the long experience that mankind has had with the construction and operation of river dams. It is also a result of the profound and visible alteration of a river which occurs when its flow is interfered with. Quite recently, it has been augmented by the intense concern of many for the preservation of the world's rapidly vanishing free-flowing rivers.

Ecological impacts occur primarily within three types of habitat—the artificially created lake, the downstream reaches of the dammed river, and the estuary into which the river flows.

The major stresses include altered timing of river flow, increased evapotranspiration and seepage water losses, barriers to aquatic organism movement, thermal stresses, changes in sediment loading and nutrient levels, and loss of terrestrial habitat to artificial lake habitat.

The ecological effects of greatest concern are eutrophication of the impounded lake and possibly downstream sections of the river; effects on estuarine organisms resulting from disruption of the natural mix of salt water and inflowing freshwater; effects on riparian organism nesting, mating, and other behavior, resulting from altered river flow and barriers to movement; and effects on wildlife in the former watershed habitat.

Human consequences associated with the ecological effects of river damming are the aesthetic changes resulting from the dam and lake itself, as well as from taming the downstream reaches of the river; impacts on commercial uses of the estuaries; water loss from evaporation, seepage, and from increased transpiration originating from macrophyte populations colonizing the artificial lake; adverse health effects stemming from disease vectors inhabiting artificial lakes; loss of wild river recreational opportunities including fishing and river touring; and possible loss of agriculturally beneficial nutrient loading in flood plains.

An important gap in our understanding of the ecological impacts of hydropower is in the area of estuarine effects resulting from altered river flow. Adequate minimal flow standards for sensitive species have yet to be established, and knowledge of community effects in estuaries resulting from altered circulation and freshwater mixing is deficient.

The New Solar Technologies

The solar energy technologies other than hydroelectric are, to a large degree, rapidly advancing, and as yet untried on a scale significant enough to generate environmental impacts. As a result, our first hand knowledge of ecosystem impacts of most solar technologies is scanty. Those studies that do exist point to the conclusion that the environmental impacts of solar energy are likely to differ greatly from one technology to another. The diversity of technological opportunities and ecological impacts is reflected in the subdivisions below.

SOLAR SPACE HEATING AND COOLING Passive and active, space heating and cooling are surely among the most ecologically benign sources of energy. Studies to date have identified aesthetic problems as the only ones of potential consequence. In particular, the incompatibility of solar home heating with the existence of evergreen trees near homes could become a consideration in some locations. Rooftop collectors will change the albedo and therefore will affect the weather. These changes, while difficult to predict, are not likely to be significant nor are they expected to pose threats to ecosystems. The materials requirements for construction of rooftop systems are not trivial on a per-unit-energy basis. The most detailed work on materials requirements for a solar technology has been done for the central receiver; these requirements and their ecological implications are discussed below.

BIOMASS CONVERSION Ecological impacts associated with the use of vegetation as an energy source can arise during the growing of biomass, during its conversion to useful fuels such as methane or alcohol, and during its consumption. The first of these—impacts resulting from the growing of the crop—have received the greatest attention and are undoubtedly the most serious. Of greatest concern are the water, fertilizer, and land requirements. Stresses have been assessed fairly thoroughly for a variety of terrestrial crops, including sugar beets, and a number of tree species, but ecological effects and human consequences have not received much attention. The absence of specific plans for the operation of biomass plantations makes ecological impact assessment difficult. Will nutrients be returned to the soil after extraction of useable fuels? How much of the green plant will be left in the soil to enhance soil binding? Are monocultures or diverse cultures to be grown? Will pesticides or herbicides be used? All of these factors will be decisive in estimating the extent of ecological damage from energy biomass plantations.

In addition to setting aside lands for terrestrial biomass plantations, a variety of other schemes have been considered. One is to combine algal production and waste water treatment into one operation, and a second is to make use of agricultural or feedlot wastes as a source of energy. The ecological uncertainties surrounding these schemes are great, although their overall impact is likely to be less, even on a per kilowatt basis, than that from energy plantations. Finally, the harvesting of marine plants for energy has been suggested; here the ecological impact analysis is most scanty.

WIND CONVERSION Habitat destruction, noise and other aesthetic degradation, and interference with bird flight, are the major ecological problems that have been considered. One possible stress to ecosystems, which could result from extensive wind generation of electricity, is a consequence of reducing wind speeds. Lakes that are downwind from the windmills might become warmer because of reduced evaporation from their surface. Soil moisture might also increase. Overall, wind is likely to prove the most ecologically benign source of energy for electricity production. One very important advantage of wind energy relative to nuclear, geothermal, fossil, and solar central receiver, is that wind generation of electricity does not need cooling water. Wind also offers attractive opportunities for decentralization of energy production—a topic that will be discussed in greater detail below.

SOLAR CENTRAL RECEIVER SYSTEM Included here are all the technologies designed to collect a relatively large quantity of sunlight in a central location and produce with it useable forms of energy either by means of a thermal cycle or photovoltaic materials. Such systems are likely to be located in areas with ample and dependable sunlight, and inexpensive, flat land. Ideally one would also want to locate them not too distant from population centers (to avoid distribution losses and expenses) and near ample supplies of water (for cooling purposes). To a large extent these objectives are incompatible, and the most likely locations for central receiver systems in the United States are likely to be in the arid Southwest. Thus ecological impact studies have focused on desert ecosystems. In addition, because of the large materials requirements (primarily cement, steel, and glass) for the collectors themselves and for structural support, analysis of the pollutant emissions expected during the manufacturing process has been made.

The results of the analysis of pollution emissions associated with the materials requirements for central receiver systems are expressed by comparing these emissions with those from an oil or coal burning plant producing the same average power, and operating over the lifetime of the solar plant. What such a comparison shows is that for those pollutants considered environmentally harmful, the emissions associated with the central receiver system are lower by about an order of magnitude as compared with an oil- or coal-fired plant.

The desert ecosystem impacts that have received the most attention in preliminary impact assessments are direct destruction of desert habitat for burrowing animals and other desert wildlife (including more than two dozen rare and endangered species), ecological effects stemming from both increased water consumption for cooling purposes and from disruption of ground and surface water flow patterns, and ecological effects resulting from possible local climate alteration due to the presence of collectors.

Uncertainties that hamper accurate prediction of ecological impacts arise to a great extent from technological uncertainties, which in turn are a result, partially, of economic factors. Of these, one of the most important and uncertain is the cooling mode for steam cycle electricity production. If either Rankine cycle generation with dry cooling towers or Brayton cycle generation is employed, then the particularly worrisome potential impacts arising from water consumption in an already water scarce region will be lessened.

OCEAN THERMAL CONVERSION This is an untried and largely unspecified technology. Ocean water will be circulating through the heat exchangers of an ocean thermal system at an enormous rate and so entrainment of marine organisms is likely to be a problem. Carbon dioxide and phytoplankton nutrients will be brought to the surface waters at unknown rates and with uncertain ecological effects. The use of biocides as antifouling agents may also pose a risk to marine life. Much of the uncertainty about ecological effects of ocean thermal systems is a result of a lack of good site-specific data on marine biomass concentrations.

Geothermal Conversion

More ecological impact experience has been gathered here than with solar technologies because geothermal energy operations have been in existence for many years. The Geysers in California, and the geothermal plant at Wairakei, New Zealand, have been the most extensively studied. Most of the assessment work has been directed at baseline measurements and effluent monitoring—in other words at stresses rather than at ecological effects. Because future geothermal facilities in the United States are likely to be in areas in which no geothermal plants now exist, and because impacts are likely to be highly site-specific, a large degree of uncertainty surrounds speculation as to anticipated impacts. In addition, there are technological uncertainties over the feasibility of brine reinjection, and a lack of experience with some of the newer technologies such as those involved in tapping hot dry rock sources.

The major stresses expected on ecosystems from geothermal plants are pollutants such as hydrogen sulfide and boron, noise, land subsidence, and water consumption for cooling.

The problem of cooling poses some interesting choices. Thermodynamic efficiencies are generally below 25% in geothermal plants and therefore cooling water requirements are quite large, even compared with fossil or nuclear plants. Dry cooling is of course one option, but economic factors today are prohibitive. Ordinary sources of water such as rivers or aquifiers could also be used, but the large cooling requirements plus the fact that geothermal energy tends to be available in arid or semiarid regions could put a very great strain on local water resources. A third choice, and one actually employed at the Geysers, is to use geothermal condensate water for cooling. However, this polluted and foul-smelling condensate water is responsible for a good part of the aesthetic problems of the Geysers. Yet to be shown technologically and environmentally feasible is a fourth choice—distillation of briny geothermal waters and use of the distillate for cooling.

Surface Mining of Coal

The potential for land reclamation or restoration following surface mining of coal in the Western United States is quite uncertain. Natural soils contain living organisms and organic and inorganic materials in a highly structured assemblage. The ability of soil to retain moisture and operate as an effective chemical factory and recycling plant can be drastically impaired as a result of surface mining. Long term land rehabilitation in arid or semiarid regions, such as those containing most of the Western US coal deposits, will require resources, presently unestimated, of which freshwater is the most worrisome. Neither annual water requirements per acre of reclaimed land, nor the number of years irrigation will be necessary, are now well understood.

Even were the water requirements known, further uncertainty surrounds the possible impacts on downstream water users, including aquatic ecosystems, that will arise as a consequence of upstream water consumption for reclamation. In estuaries and in rivers the timing and magnitude of freshwater flow is critical to the well-being of plants and animals. Subnormal flows reduce aquatic habitat and increase pollution concentrations. Organisms adapted to high velocity river water may find their niche destroyed by a reduced flow. As a larger fraction of river water sits in still pools during times of low flow, water temperature rises; as a result, oxygen levels drop and ecological damage can occur. The literature on ecological impacts of surface mining also has been concerned with the related problems of erosion, of downstream siltation, and aesthetic degradation at the mining site. Discussion of indirect human consequences has also focused on effects on meat production as ranch land gives way to mines in the west.

Deep Mining of Coal

The major ecological impacts that have been identified originate with water pollutants reaching rivers and lakes through contaminated ground and surface flow. Acid mine drainage is a prime example. Erosion and flooding are also of concern, especially when mines are located in steeply sloped countryside in areas with high rainfall. Despite the many years of experience with deep mining, many uncertainties over ecological effects and human consequences remain, in part due to the difficulty in monitoring the fate of effluents from mining operations.

Cooling

The cooling requirements of electric generating plants (or other types of energy facilities such as coal gasification or liquefaction plants) can stress ecosystems in four ways. Physical damage can occur to organisms during passage through cooling condensers; thermal discharge can affect wildlife;

water consumption for cooling can affect downstream aquatic ecosystems; and, should it be necessary, in order to ensure adequate cooling water supply, the construction of artificial storage by backing up river flow will bring about all the ecological problems attendent upon the damming of rivers. Many technological options are available for cooling energy facilities. Once-through cooling leads to the most serious thermal discharge problems. Moreover, its large withdrawal requirements can lead to problems of entrainment in cooling condensers and to the necessity of providing water storage. Wet tower cooling reduces the water withdrawal requirements and the aquatic thermal pollution problems, but increases the water consumption required for cooling above that of once-through cooling without storage. Once-through cooling with storage has yet higher consumption, typically, because of the consumptive loss of water by evapotranspiration from the reservoir surface. Use of the oceans for cooling entails thermal pollution and entrainment problems, but avoids water consumption and storage problems. Dry cooling is ecologically preferable on all counts, yet disadvantageous in terms of direct dollar cost.

The impact assessment literature on cooling is extensive. Stresses, effects, and human consequences have all received considerable attention. The biggest uncertainties now probably fall in the area of assessing ecological effects of habitat loss from either water consumption or thermal stress. The loss of aquatic habitat, like the loss of any other type of ecological habitat, has effects that are difficult to predict when they are the sum of a large number of individually small losses. Knowledge of thresholds for critical habitat size is scanty and, more importantly, knowledge of synergistic effects resulting from the combination of stress to species from loss of habitat and from other sources such as toxic substances is practically nonexistent.

The various energy sources discharge differing amounts of waste heat to make a unit of electricity by steam cycle. Geothermal, as noted above has a particularly low efficiency. The nuclear light water reactor discharges about 40% more waste heat to water than does a modern, coal-burning plant of similar electric output. Many of the new energy technologies, such as geothermal, solar central receiver, and perhaps coal conversion, will be located in the Western United States where the freshwater supply/demand problem is particularly acute. The overall ecological impact of these technologies will depend to a great extent on how cooling is carried out.

Combustion of Fossil Fuels

All three categories of impact-stress, ecological effects, and human consequences, have received considerable attention. Origins of photochemical smog and the composition of acid rain have been the subject of much of the work on pathways and stresses. Research on ecological effects of coal- and oil-burning has focused on damage to vegetation, including agricultural crops, although recently there has been considerable interest in the problem of effects of acid rain on fish and salamanders in freshwaters of the Northeast. Assessment of human consequences of ecological degradation from fossil fuel air pollutants has included study of declines in agricultural crop yields, and aesthetic blight because of damage to trees and shrubs. An area of uncertainty is chronic pollution impacts.

For obvious reasons, field data on effects of high levels of pollutants has been the prime source of information; long term effects of low concentrations of pollutants are not likely to be resolved in the foreseeable future. A more serious uncertainty, that of climate alteration from carbon dioxide and particulate emissions, lies outside the scope of this review, although it must be stressed that even slight climate shifts could have important ecological repercussions. With present understanding of ecosystems, these repercussions would be very difficult to predict in detail, even if one could precisely characterize how climate had altered. Technological uncertainties over future cleaner combustion methods (such as fluidized bed combustion of coal) also make it difficult to predict the future ecological impacts of fossil fuel burning. The use of new technologies to control air pollution emissions from fossil fuel burning facilities will, to some extent, trade air pollution for water pollution. The ecological implications of this tradeoff are rarely discussed. Finally, there is considerable uncertainty over the potential for acid rain damage to ecosystems in areas such as the Western United States if greatly increased burning of coal were to take place there.

Petroleum in the Environment

An extensive literature exists on both acute stresses and ecological effects of petroleum in marine ecosystems. The marine impacts that have been of most concern are the direct effects of massive oil spills. Physical effects of petroleum on sea birds and other marine animals, direct toxic effects on many forms of marine life, and long-term effects resulting from incorporation of certain petroleum components into food chains have been of greatest concern.

An often ignored area of uncertainty concerns petroleum impacts in freshwater ecosystems; these include accidental spills and discharges from river and lake vessels and, more importantly, chronic runoff of oily water from roads. Ecological effects of this stress have received scanty attention, despite the fact that the relatively small mixing volumes and calm surface of many lakes create conditions in which such effects are likely to be great. Yet another source of uncertainty stems from the fact that studies of the effects of petroleum on individual organisms are usually carried out with adult organisms, despite the evidence that juveniles and larvae are generally more sensitive to any kind of stress.

The Nuclear Fuel Cycle

A considerable amount of research has been done on the effects of radiation on plants and animals. Nearly all of this has been in a laboratory setting, although in the aftermath of certain accidental and planned discharges of nuclear materials, some field studies have been carried out. It is useful to distinguish two types of concern: damage to individuals, and damage to whole populations or ecosystems. Most studies have concluded that during routine operation of nuclear energy systems (i.e. except in cases where serious accidents or leaks occur) damage to individuals is likely to be undetectable above the background of natural wildlife mortality. On the question of damage to whole populations or ecosystems from massive or routine releases there is less direct field experience, and of course no laboratory experience, available. Evidence at hand, however, suggests that the likelihood of wildlife species alteration because of mutation from the nuclear fuel cycle is extremely small, even if there were a release of radioactive material catastrophic to humans.

One potential hazard of conventional (nonbreeding) nuclear power arises because of the relative scarcity of highly concentrated uranium sources. A society reliant upon these concentrated sources will have little choice of sites to mine, compared with coal. Should the available sites happen to lie beneath especially valuable wilderness lands, then considerable ecological impacts are likely to result. An alternative to these concentrated ores is the more dilute deposits typified by the chattanooga shales with an energy content per unit weight only twice that of coal. Mining of these ores will generate ecological effects roughly comparable to those from strip mining of coal.

Oil Shale Mining and Conversion

The oil shale deposits of commercial importance are located in arid and semiarid regions of the West; rugged and occasionally steep terrain characterizes much of the land above them. Conversion to useable liquid fuels can occur either underground by in situ processes or above ground after mining of the ores. Mining of shale ore and surface conversion leaves behind a bulky material waste that poses a serious disposal problem. Water requirements for surface conversion also are large in comparison with available regional water supply. In situ conversion processes present a very important "unknown probability, high consequence" problem. This is the problem of aquifier disruption leading to contamination of fresh water with the briny ground water that underlies much of the high-grade oil shale deposits. At worst, significant contamination of the White, Green, and Colorado Rivers could result from such disruption. The uncertainties here are very great.

Analysis of ecological impacts of oil shale extraction and conversion has been concerned primarily with pathways and stresses. Ecological effects have received some attention, while human consequences of ecological degradation have generally been ignored. If the technology proceeds and as first hand field experience with the technology accumulates, a great deal of effort will need to be directed to comprehensive impact assessment.

Coal Conversion to Synfuels

Impacts on aquatic ecosystems are of most concern. These impacts can result from two types of stress—water quality degradation and water flow reduction. A diverse assemblage of highly toxic substances (e.g. heavy metals, phenols and other hydrocarbons that are constituents of coal tars, sulfur compounds, and ammonia) results from the conversion process and may be released into freshwater systems. Water consumption for cooling, for chemical feedstock, and for processing, is likely to be considerable, compared with other energy sources on a per-unit-energy basis. Impacts will be site-specific and strongly dependent upon the methods and degree of wastewater treatment and the water conservation practices that are used. The product of coal gasification is generally a clean-burning fuel such as methane. Whereas in the direct burning of coal, most of the harmful substances it contains are released to the atmosphere, in the coal conversion process they are, to an appreciable extent, released to water. Thus, while air pollution problems from coal conversion pose a risk, it is generally less than that originating with the direct combustion of coal.

Uncertainties in stress, ecological effects, and human consequences are all quite large, primarily because of the absence of practical experience with this technology and because of a lack of specificity about what the future technologies for conversion will look like.

Energy Conservation

One way to achieve energy conservation is to increase the efficiency with which we use energy, without actually altering the nature of the goals energy accomplishes for us. A second way is to modify energy-consuming behavior. Improving the efficiency of the internal combustion engine exemplifies the former, while car-pooling exemplifies the latter.

The magnitude of the ecological benefits of saving energy by enhancing end-use efficiency is easily measured in terms of the harmful effects of expending that energy. For example, increasing the efficiency of the internal combustion engine decreases oil drilling, transport, refining, and combustion activities, and their resulting impacts (if the number of vehicle-miles driven stays constant).

Energy conservation arising from changes in behavior can bring about two kinds of ecological benefit. Because less of an energy source needs to be exploited, there are direct benefits similar to those just mentioned. In addition, energy-intensive end-use activities have indirect ecological effects that are independent of the type, or quantity, of fuel used. For example, fewer cars being driven means fewer animal deaths on the road, and less pressure to convert open spaces into new roadways to alleviate traffic congestion.

The ecological benefits of energy conservation efforts that result in less of a given fuel being consumed (by enhancing efficiency) are understood today to the extent that the ecological impacts of procurement and consumption of that fuel are understood. The indirect ecological benefits and costs that arise from conservation efforts directed toward changes in behavior have received little attention, however. One review of this subject (85) briefly surveyed four end-use activities—agriculture, transportation, housing, and industry, and concluded that indirect ecological damage initiated by the uses to which energy is put is not negligible compared to direct ecological damage initiated by fuel combustion effluents, mining of fuels, and conversion. Moreover, because the indirect impacts are independent of the type of energy supply used, it was concluded that development of a cheap, unlimited, and clean source of energy would not be an unmitigated blessing.

Cross-Technology Comparisons

Probably the most ambitious effort to date to assess all energy sources and evaluate and compare environmental impacts is the National Academy of Sciences' CONAES study (1). The Ecosystem Impacts Resource Group in that project reviewed what is presently known about the major stresses, ecological effects, and human consequences of the energy technologies currently being considered. The most important uncertainties were also characterized. A number of explicit criteria were developed to assess potential impacts. Because of the impossibility of assigning weights to the various criteria, no overall ranking of the energy sources was attempted, although certain clear-cut comparisons did stand out. For example, conservation and certain forms of solar energy were found to be the most benign energy source, and hydroelectric power the most destructive on a per-unit-energy basis. This study focuses attention on new energy technologies that could provide substitutes for petroleum and natural gas. It concludes that the most serious ecological impacts result from the water consumption requirements of these technologies, and that these water requirements could severely constrain their rate of development.

Several textbooks and other publications also include useful overviews of the energy-ecosystem interface (86–92).

Summary

Several common themes emerge from this overview. Ecological effects arising from habitat loss are of especially great concern. They are particularly difficult to assess accurately because habitat loss is a slow process of chipping away of life support systems for wildlife. Each additional loss from a new mine or conversion plant or end-use facility is often barely noticeable, yet the integrated process leads to sizeable destruction of natural habitat.

In general, stresses on ecosystems do not act in isolation from stresses due to natural fluctuations in quantities such as rainfall and temperature. The synergistic effects resulting from the coupling of energy-related and natural stresses is very poorly understood. Both better background statistical information about natural fluctuations in space and time, and far more field observation during conditions of combined man-made and natural stress will be needed to reduce significantly the important uncertainties here.

Water consumption impacts exemplify this point. In many parts of the United States, the magnitude of water supply, relative to demand, is not sufficiently large to permit future water-intensive energy activities to take place without severe ecological effects. These effects cannot be evaluated in the absence of information about precipitation, runoff, and stream flow variation across space and time. A given level of water consumption by a coal conversion plant may be perfectly innocuous in times of ample precipitation, yet will produce great stress to downstream ecosystems during periods of drought.

Uncertainties are seen to differ greatly within the three types of impact reviewed—stress, ecological effects, and human consequences. Stresses have received the most attention and are the best understood, while human consequence of ecological degradation are largely ignored and are most poorly understood. Of course, qualitatively, that is the way it must be, for you cannot understand effects without understanding the stresses, and you cannot understand consequences without knowing the effects. Yet the degree of imbalance is unnecessary, and without far greater emphasis on effects and human consequences the true cost to society of our energy systems will continue to go unnoticed.

PROBLEMS OF ECOLOGICAL ASSESSMENT

A convenient structure, used in the previous section, can be imposed again here. Thus we divide the large number of issues pertinent to ecological assessment into three general categories, representing a causal sequence connecting choice of fuel supply to the social consequences of this choice.

These three categories are: (*a*) The nature of the stress on an ecosystem resulting from a particular energy source; (*b*) the ecological response to this stress; and (*c*) the losses experienced by humans as a result of the ecological response.

As an example, consider the process of damming a river for hydroelectric power generation. Among the stresses or impacts on the aquatic ecosystem are a decrease in water velocity and an increase both in surface and in bottom area. One common ecological response to these stresses is the proliferation of aquatic vascular plants, due to the more placid hydrographic conditions, the larger area that can be colonized, and the increase in dissolved nutrients resulting from leaching of submerged soils and decomposition of submerged terrestrial vegetation. The social consequences of this ecological response are many, but the worst in tropical and subtropical regions is the increased infection rate of schistosomiasis, a disease caused by a parasitic flatworm. Numerous aquatic plant species serve as habitats for snail vectors of this flatworm, so that the spread of aquatic weeds contributes directly to the increased incidence of schistosomiasis. Lake Volta in Ghana, the largest freshwater impoundment in the world, serves as a current example of this phenomenon (4).

The inclusion of ecological considerations in decisions concerning the mix of future energy sources and technologies presupposes that certain fundamental difficulties in each of the three categories—stress, ecological effects, and human consequences—have been or can be solved. An ability to characterize the stress associated with an energy source, for example, requires that we possess instrumentation of sufficient sensitivity. In order to assess the ecological response to this stress, we must have a predictive capability based on a causal understanding of the functioning of ecosystems or on generalization from previous experience.

Finally, comparison of social consequences is possible in a straightforward manner only if there is some common basis on which to express the losses each of us experiences. These three kinds of assessment problems, which we can call, respectively, problems of measurement, problems of prediction, and problems of valuation, by no means have been solved. Together, they challenge our technological abilities, underline our naivety concerning complex biological systems, and question what we sometimes refer to as our "moral values."

In the rest of this section, we attempt to delineate the nature of these methodological difficulties in more detail. These difficulties are not confined to those environmental issues related to energy use, but rather are basic to all human activities that possess serious ecological consequences. Some of our examples, accordingly, will consider impacts not directly related to energy technology.

Problems of Measurement

THE IDENTIFICATION OF STRESSES How does one know beforehand which of the potential stresses associated with a particular technology should be monitored? There is never any guarantee that we have identified all of the different types of pollutants associated with a given technology, for the diversity of compounds, especially organic ones, is such that we can never be certain that we are looking for all of them. This point can be made especially clear by reference to recent analyses of drinking water supplies in the United States (93). The analysis of a relatively small number of tapwater samples led to the identification of 187 organic compounds in these water supplies, many of them with known toxic properties. Yet these identifiable compounds comprised only about 10% of the total organic matter present in the samples. The nature of the remaining organic matter, and its potential for ecological stress, remains unknown.

Our ignorance of the detailed nature of an environmental stress may not preclude identifying an association between a given energy source and environmental change. Certainly much of the epidemiological evidence relating respiratory ailments to air pollution is of value although the structure of the causative set of pollutants may be unknown. But lacking an understanding of the specific stress may postpone what would otherwise be an obvious and inexpensive treatment process, or may be responsible for a generalized and expensive, but unnecessary, treatment process. In addition, when the exact stress remains unidentified, it becomes an easier matter for those who think that they benefit economically from the technological status quo to evade responsibility for abatement of the impact.

The difficulty that must be faced, then, is of finding something that we do not know we are looking for. The nature of this difficulty is one of the most fundamental limiting factors in establishing a comprehensive and systematic approach to ecological issues in energy development.

THE DIVERSITY OF KNOWN STRESSES Certainly it may be possible at times to provide an exhaustive list of all potential ecological stresses associated with a given technology. For some energy technologies, however, the sheer number of the known stresses may be so overwhelmingly large as to preclude comprehensive monitoring. A look at aqueous coal conversion effluents is instructive in this regard. The analysis of two process streams from a pilot coal conversion plant for 55 elements (94) yielded measurable quantities of 23 and 30 elements, respectively. In one of the process streams, the concentrations of Al, B, Cu, Fe, Mg, Mn, Ni, Pb, and Zn exceeded 1 mg per liter. Thirteen elements (As, Co, Cr, Hg, in addition to those mentioned above) were present in the process streams at levels known to be responsible for reproductive impairment, growth inhibition, or mortality in aquatic organisms. An additional six elements (Bi, Cd, Ge, Se, Sn and Ti) demonstrated a potential for bioaccumulation in fish to levels capable of threatening human health.

At least 65 trace elements can be found in coal (84) and both the variation in coal composition and in coal conversion techniques imply that analyses of individual process streams, such as the one discussed above, cannot be considered definitive. In addition, the chemical nature of coal and the conversion conditions lead to the formation of a variety of organometallic compounds (95); the precise nature of the compounds will determine the toxicity of the trace metals and, consequently, the ecological effects. Conceivably, then, one might want analyses not only for the 65 elements that potentially can contaminate process wastewaters but also for the organic complexes peculiar to each group of trace metals.

Besides the inorganic constituents of coal conversion effluent, organic compounds themselves can number in the hundreds or even thousands (96) and include phenols, arylamines, aliphatic hydrocarbons, mono- and polycyclic hydrocarbons, and sulfur-containing compounds such as thiophenes and mercaptans. Many of these compounds, particularly the carcinogenic polycyclic aromatics such as 3,4-benzo[α]pyrene, benzidene, and β-naphthylamine, are already known to have deleterious effects on organisms. Yet only a small number of these have been tested for carcinogenicity (95). A recent Oak Ridge National Laboratory report summarizes the available information (84).

The point of this example is to suggest that the choice of certain energy sources forces us into mammoth monitoring schemes that not only seem doomed to inadequacy, but also may be extremely costly in terms of material and labor. The number of potential stresses can be so large that merely assaying the quantitative nature of the stress, regardless of any research on the ecological effects, is a bewildering task. It is naive to believe that our technological abilities and the organizational abilities of large monitoring agencies automatically will be equal to this challenge. Criteria for selecting substances for study have been examined in some detail (97), but the list of those known definitely to have ecological repercussions already is a lengthy one. Unless the size of our commitment to environmental monitoring is allowed to influence our decisions on energy sources, it will plague us increasingly in years to come.

INSTRUMENTATION AND SENSITIVITY The previous two sections each have outlined a weakness inherent in environmental monitoring programs, namely that (*a*) we cannot be certain that we have considered all the important parameters, and (*b*) the number of parameters that have been identified as potentially important may be beyond our capacity to monitor in the necessary detail. To these we can add a third: (*c*) a stress associated with a particular energy technology may have significant effects at levels below the sensitivity of our instruments or techniques. That is, substances that we do know we should be looking for may elude our detection in certain situations, yet still have ecological repercussions. The limit of detection for a given parameter often is a transient characteristic of the current level of our technology. Yet when a certain parameter is labeled "undetectable" after a given analysis, there may be a predisposition toward assuming that it cannot, therefore, represent an ecological hazard.

A somewhat controversial example of this point concerns the denitrification rate in nature. Denitrification is a process carried out by certain soil and water bacteria, in which nitrates are reduced to nitrous oxide or nitrogen. The net global flux of nitrous oxide into the stratosphere, which is almost entirely a result of denitrification, is a very poorly measured quantity, known only to order-of-magnitude accuracy. In the stratosphere, nitrous oxide is a major source of nitric oxide, which initiates a catalytic cycle leading to a natural ozone sink (98). A change in stratospheric ozone concentration could thus result from a change in the global denitrification rate. A change in the global denitrification rate could in turn result from anthropogenic activity if additional nitrates are rendered available to bacteria or the rate-constant for the bacterial process is altered. Industrial fertilization of crop land and acidic precipitation are examples of such activities. Because of the extraordinary difficulty in measuring the background denitrification rate, it is possible that a change in the global nitrous oxide flux into the atmosphere could go undetected until a dangerously increased level was attained in the stratosphere.

PATCHINESS For quite some time, ecology has been concerned with the detailed temporal changes undergone by various biological parameters, as well as the correlations and causal relations that can be deduced from these changes. In recent years, attention has focused to an increasing degree on the problem of spatial variation in parameters of ecological interest. This is especially true of aquatic ecology, where for many years there had been an unstated and incorrect assumption of large-scale uniformity in the plankton environment.

Spatial heterogeneity potentially is of much significance to ecosystems. It is often important to understand the spatial structure of ecosystem parameters not only for an estimate of the reliability of our sampling techniques, but also for understanding certain phenomena intrinsic to the functioning of ecosystems. In particular, spatial structure can influence the stability properties of coexisting and interacting populations (99), and it may figure significantly in the survival of populations that depend on patches of higher-than-average food concentrations in order to increase the combined efficiency of their searching and feeding processes. It is thought that the survival of the larvae of certain commercial fish species may depend in this manner on spatial heterogeneity (100).

By the same token, the spatial structure of the stresses on an ecosystem, in addition to their mean space-averaged value, must figure in the ecological responses to our energy development activities. In the case of phytoplankton, for example, it appears that for length scales less than 10^2 m the distribution of phytoplankton is controlled mostly by turbulence, while for scales greater than 10^2 m spatial variability in metabolic rates and community structure help determine algal distributions (101). An oil spill with structure at long wave lengths thus can have repercussions in the persistence of interacting plankton populations apart from toxic effects attributable to the averaged oil concentration.

The realization of this issue puts another terrible burden on our monitoring program. It may be necessary in certain circumstances to characterize the spatial structure of stresses, and to monitor in sufficient detail so that this can be done quantitatively by such means as spectral analysis (102). The spatial structure of impacts has been ignored primarily out of practical considerations: the monitoring effort could be unmanageable in many situations. Yet we should keep in mind the corollary that understanding ecological responses may be an unmanageable effort, and that we delude ourselves if we believe that this understanding is within our grasp.

ANTHROPOGENIC VERSUS NATURAL POLLUTANT SOURCES The stress or impact associated with an energy source often can be inseparable from identical types of stress arising from natural causes. Air pollution provides us with many examples (103). On a worldwide basis, anthropogenic carbon monoxide sources comprise only about 10% of the total. Most of the remainder (almost 80% of total) comes from the oxidation of methane and generation of methyl radicals. The methane, in turn, is a product of anaerobic digestion of organic material decomposing in, for example, swamps, estuaries, lake, and ocean sediments.

A similar situation exists for nitrogen oxides, about 90% coming from natural sources. The major natural source, in the form of nitrous and nitric oxide, is represented by bacterial activity in soil, sediment, and seawater. Nitrogen-containing organic compounds are decomposed to release ammonia; the ammonia is oxidized, and the oxidation products are denitrified to nitrogen oxides.

Particulates in the atmosphere follow the same pattern. Approximately 90% of atmospheric particulate matter emanates from natural sources, divided about equally between primary emissions directly into the atmosphere and secondary formation of particulates from natural gaseous emissions. The primary emissions are comprised almost entirely of sea salt and aerosols.

In the case of hydrocarbon emissions, about 55% of the total comes from the naturally occurring methane-producing bacteria. Another 30% consists of terpenes or hemiterpenes emitted by plants, particularly trees. Of all the main constituents of atmospheric contamination, sulfur oxides have the lowest proportion attributable to natural sources. Yet even for sulfur oxides, 55% arises from the oxidation of natural hydrogen sulfide emissions, which in turn are produced by the decay of dead organic matter.

Anthropogenic sources, of course, are concentrated, so that anthropogenic emissions locally can overwhelm natural emission rates. Over 95% of the carbon monoxide in urban areas, for example, is of human origin. Nonetheless, the variable nature of both natural and man-made emissions presents obvious difficulties in pinpointing the quantitative nature of stresses associated with certain energy sources.

DATA AVAILABILITY Our last point concerns the state of the data accumulated on the ecological stresses associated with energy development. Scientific problems of this magnitude and with this much social significance involve thousands of workers in government agencies, universities, and private commercial and industrial concerns. The data are obtained with divergent techniques, are made available to others through a variety of means, and are of enormous volume. Three problems quickly become obvious to anyone conducting research in the general area:

1. The lack of standardized analytical techniques for many parameters inhibits our ability to generalize from the available data. Researchers should strive to stay informed of the most widely accepted procedures in their field.
2. A plethora of anonymous publications on ecological consequences of energy technology is beginning to emerge, mostly from government and industrial organizations. The anonymity helps the authors of these publications to avoid responsibility for tenuous conclusions, and prevents the free exchanges of questions and criticism that underly advances in understanding.
3. The data are too voluminous and too scattered to be used to the fullest without a computerized data base system. A variety of agencies have responded to this need by creating their own individual data base system. Unfortunately, the number of data bases that now exist is so large that the volume problem has reappeared in a different guise. Increasing con-

solidation of these data bases would be welcome, including perhaps the scheduled publication of information overviews that survey the field in an intelligent and comprehensive way (e.g. on coal conversion (84)).

Problems of Prediction

The complexity of ecosystems poses enormous problems for those who require the ability to predict or generalize ecological responses. Our present level of energy use unfortunately has placed all of us in the category of those who require this ability. In this section we review the most important approaches that have been taken toward these problems. A crude distinction can be drawn between field studies, both observational and experimental; laboratory work, especially that involving microcosms; and mathematical modeling, including both simulation activities and theoretical work on fundamental properties of ecosystems. The distinction is a crude one because most researchers combine these approaches in an integral fashion to investigate their particular problems. Nonetheless, these three categories do represent separate activities, and we can examine the methodological advantages and disadvantages peculiar to each. It also should be noted that many aspects of the previous discussion on problems of measuring ecological stress apply equally to measuring ecological response; these aspects thus play a role in problems of prediction, but they are not elaborated on further in this section.

FIELD STUDIES Field research has been and always will be the major path by which we truly increase our understanding of ecosystems. Its fundamental role is self-evident and it provides the measuring stick against which accomplishments in the laboratory and in modeling are judged. Although laboratory research and modeling attempts can help to direct field work and explain field observations, their role is, of necessity, a secondary one.

Field research can take the form of pure measurement and observation, or it can involve experiments in which ecological parameters are manipulated intentionally and the in situ response of other parameters recorded. Actually, the distinction between pure observation and experimental manipulation in field work is not a clear one. Unintentional stresses from human or climatic sources are constantly being applied to ecosystems, and these may be, in fact, just the type of stresses one would choose to use in some intentional experimental manipulation. In any case, field observations alone provide us with at least a crude outline of the causal relationships underlying changes within an ecosystem and often yield quantitative correlations as well. (Field observations also, of course, are the means by which we identify and characterize ecological response. However, here we are concerned solely with the role of field research in predicting ecological response.)

The causal relationships and the correlations that are arrived at in this manner unquestionably are stimulating to experimental work in the field and laboratory as well as to the progress of computer simulation and to theoretical ecology. Unfortunately, though, the correlations that emerge from our observations sometimes assume an unmerited authority. A well-known example of this problem concerns the postulated positive correlation between the diversity of organisms in an ecosystem and the stability of the ecosystem. Depending on the proponent of the theory, the word "stability" could be intended to mean an absence of fluctuations in the ecosystem, or alternatively, the ability to resist external perturbations. The "stability-diversity hypothesis" was motivated originally by such observations as the low diversity and large fluctuations in polar regions, as opposed to the high diversity and supposed constancy of tropical ecosystems. This concept has penetrated the popular folklore of ecology rather thoroughly, although recent examinations of the hypothesis demonstrate it to be groundless (104).

The lesson to be learned is that correlations that emerge from field observations alone cannot be considered authoritative, unless the correlations are based on a large enough number of examples. What constitutes "large enough" is a more or less subjective matter, but the uniqueness of each ecosystem suggests that data from a huge array of ecosystems would be required as acceptable evidence. The field effort to obtain the required level of persuasiveness for a particular correlation would be large, but not necessarily unmanageable. The National Eutrophication Survey of the Environmental Protection Agency, for example, has investigated hundreds of inland water bodies in the United States, collecting a variety of physical, chemical, and biological data at different times of the year. Many persuasive empirical relationships have evolved from the study, connecting ecological stress (e.g. types of land use) with ecological response [e.g. nutrient levels in drainage waters (105)]. The ultimate purpose is to develop a predictive capability for the trophic state of a water body, given the land use in the drainage basin and the morphometric and hydrographic characteristics of the area. Real progress has been achieved along these lines, and the correlations that have been developed from these and similar studies are perhaps our best quantitative guidelines for dealing with eutrophication problems. It must not be forgotten, however, that a tremendous expenditure of money and manpower (including the National Guard in many states) was required to determine these persuasive correlations. It is doubtful that we can bear the costs of this approach for all of our environmental problems, and more efficient avenues are required in general.

One such approach involves a deliberate manipulation of the ecosystem, followed by careful monitoring of the ecological response. The manipulation may be a large-scale one that affects the energy flow and nutrient cycles of the entire system significantly, or it may be a small-scale one that alters only what is taken to be a representative segment of the system. An example of a large-scale manipulation is found in the work of Likens et al (106) at the Hubbard Brook Experimental Forest in New Hampshire. Deforestation of selected watershed ecosystems led to large increases in nutrient export from the watersheds and dramatically illustrated the importance of watershed vegetation to protecting downstream water quality. An additional example of an extremely rewarding large-scale manipulation is the series of fertilization experiments at the Shield Lakes in northern Canada (107). Selective additions of carbon, nitrogen, and phosphorus combinations to whole lake basins provided the essential evidence implicating phosphorus as the main culprit in cultural eutrophication.

Although experiments of this nature do involve disruption of otherwise valuable ecosystems, they have provided some of the most reliable generalizations accepted by ecologists, as well as the few principles available on which to base strategies for protecting and managing ecosystems. One obvious drawback to these experiments is their expense. However, by avoiding a commitment to detailed mathematical models with their often unverifiable conclusions and requirements for enormous quantities of data, these experiments can justify the cost. A survey of the literature on ecological impacts and responses suggests that, unfortunately, the ecosystem-level experiments are not capturing the funding that they deserve. In fact, an undue amount of attention appears to be garnered by analytical methods and instrumentation technology. It is the responsibility of both funding agencies and researchers to strive for a better balance between numbers of significant digits and true understanding of ecosystem processes. Ecological research has, by no means, been freed from the technological mystique that permeates our society.

The bulk of field experiments take place on a smaller scale, i.e. they concern themselves with well-defined portions of an ecosystem. If the ecosystem is considered to be more or less homogeneous, then the behavior of these portions will be extrapolated to the entire system. The advantages of experimental work on this smaller scale are obvious, including less expense, the ability to replicate, noninterference with the "natural" ecosystem, etc. Of course, the results are much more persuasive when there is empirical evidence that the ecosystem response does mirror the response in small enclosures. Occasionally this verification has been undertaken, as, for example, when Goldman (108) demonstrated that the response of an entire lake's primary productivity to trace metal input (molybdenum in this case) could be predicted successfully on the basis of the short-term response of 125-ml portions of lakewater. More recently, attention has favored experiments in larger enclosures, avoiding the problems of high surface area-to-volume ratios in small containers (109). Although never as convincing as the large-scale manipulations, the smaller-scale experiments enable a greater variety of approaches to be explored, and reflect funding policies that call for balanced distribution of research money among many institutions and geographical areas, i.e. that favor many small projects over fewer large ones.

LABORATORY RESEARCH In recent years there has been a resurgence of interest in laboratory microcosms as a means for predicting ecological response and numerous symposia have been organized to discuss current ideas in this area. When used in an ecological context, the word "microcosm" refers to a collection of chemicals and organisms within well-defined spatial boundaries, generally under controlled physical conditions, and in a volume convenient for laboratory study. When appropriate biotic complexity is present, the laboratory microcosm is thought of as a model ecosystem with a structure and behavior fundamentally resembling naturally occurring systems. There are numerous advantages to studying laboratory microcosms:

1. The small size permits replication;
2. Qualitatively different ecosystems can be created;
3. Spatial heterogeneity is less complicated;
4. Experimental manipulations can be accomplished with little effort and expense; and
5. The absence of uncontrolled environmental variability facilitates interpretation.

A number of studies have demonstrated similarities between the behavior of microcosms and of natural systems, including diel community metabolism (110), seasonal plankton variations (111) and response to trophic structure manipulations (112). A consensus is forming that laboratory microcosms may be the best way to screen the roughly 1000 new chemicals introduced each year for the commercial market, such as with the methods pioneered by Metcalfe (113) for delineating degradation pathways of organic compounds introduced into microcosms.

There are, however, inherent drawbacks in the use of microcosms, drawbacks that have not received the attention they deserve. Many of these disadvantages are related to the size of microcosms (114) and thus are not obviously susceptible to a technical solution. The three major problems of scale in aquatic microcosms have their origin, respectively, in (*a*) the shallow depths of most microcosms, (*b*) the relatively small volume, and (*c*) the high ratio of container surface area to volume.

These properties of small aquatic microcosms lead to distorted behavior. Shallow depth prevents the existence of a realistic thermal stratification of the type characterizing most temperate lakes in summer, and also results in a bottom zone which is not adequately light-screened. The relatively small volume of many microcosms prevents the presence of higher trophic levels, such as fish, except under conditions in which their survival and growth results in abnormal water quality characteristics (112) and in excessive excretion rates in proportion to nutrient flows associated with the lower trophic levels in the system (114). If higher trophic levels are desired, a minimum size of at least 10 m^3 appears to be necessary. Similar considerations apply with respect to the area of terrestrial microcosms. Finally, the relatively large surface-to-volume ratio of a small microcosm results in the excessive influence, relative to natural lakes, of algae attached to the sides and bottom. To avoid this problem in a small microcosm, either means of control must be found (e.g. mechanical scraping) or experiments must be confined to the period of several months between initiation of the system and the development of a heavy side and bottom growth.

In general, these arguments suggest that microcosms will have to be larger than they usually have been in the past if the microcosm technique is to play a reliable role in the prediction of ecological responses. A balance must be struck somewhere between increasing the microcosm volume and maintaining the advantages listed earlier in this section. Only further empirical evidence can pinpoint the appropriate size range, and research with larger "mesocosms," such as the dozen 13 m^2 systems at the University of Rhode Island (115), needs more emphasis.

MATHEMATICAL MODELING Attempts to construct mathematical models of ecosystems span the range of sophistication from simple linear regressions to systems of nonlinear partial differential equations with variable coefficients. Toward the end of the last decade and the beginning of the present one, a tremendous enthusiasm for the potential of more sophisticated models characterized the attitude of many ecologists, and one of the major emphases of the International Biological Programme was to explore this potential in some detail. The "systems approach" was vaunted as the means toward predicting ecological responses, and the complexity of natural systems was thought to be no barrier to prediction if matched by sufficient complexity in a "corresponding" set of equations. The basic approach consisted of a qualitative description of the trophic web; a quantitative formulation of each trophic interaction and its dependence on environmental factors; and a combination of the two kinds of information on the basis of mass conservation. Ironically the extreme reductionist path struck the fancy even of the environmental counter-culture, which managed to reconcile for itself the "systems approach" with the necessity of taking a "holistic view" of these same natural systems.

Although the construction of detailed mathematical models of ecosystems is by no means a thing of the past, the lack of any reliable results from the large number of well-funded projects in this area has created some needed skepticism. A more cautious approach to the possibilities of detailed models has evolved. Much of the caution reflects a realization that even the simplest trophic interactions evade exact characterization. Even with phytoplankton photosynthesis, where the behavioral options should be among the smallest in number, the quantitative responses to the important environmental factors have by no means been delineated (116). In a recent discussion of the barriers to deriving believable systems analyses when biological organisms are involved, Goodman (117) provides a useful list of ecosystem features that seem destined to frustrate the extreme reductionist approach. These include the large number of species present in any ecosystem; the "improbable" adaptations that distinguish one species from another, so that each species requires individual attention; and complex, homeostatic behavior that prevents simple extrapolation from short-term experiments. As Goodman also points out, the fact that some detailed models appear to successfully predict biological behavior in ecosystems has not been a counter-example to this argument. These models typically contain a number of undetermined variables whose values are chosen to provide an optimum fit to actual data. Considering how easy it is to fit an equation in several variables to seasonal variations of almost any organism, this approach must be considered unreliable as a predictive tool.

The detailed models can be criticized from a completely different perspective as well. Certain theoretical studies [for example that of Lorenz (118)], have demonstrated that there exist fundamental limitations to the degree of predictability that can be attained for noisy, nonlinear, dissipative thermodynamic systems. Most of this work addresses numerical forecasting models for large-scale meteorological features, but Platt et al (118a) have discussed how the same considerations apply to prediction in ecology. The basic difficulty begins with the fact that initial conditions cannot be specified exactly. Lorenz shows that two initial states differing by a small observational error can evolve, within finite time, into two states that are as dissimilar as would be two states chosen randomly from all possible states of the system. Platt et al (118a) demonstrate how these results severely restrict predictability in the ocean; for example, prediction is limited to three days in advance for scales of 10 km. The outlook for detailed systems models, accordingly, is a pessimistic one.

The models that we have discussed so far can be thought of as deterministic, mechanistic (or reductionist) models, i.e. models in which the values of the variables can be specified exactly and in which causal relationships are delineated explicitly. As we have seen, the major pitfalls in this type of model arise when we strive for too much detail, imposing an unbearable load of undetermined parameter values, as well as potential theoretical barriers once the equations reach a certain level of complexity. Simpler formulations need not be plagued by the same troubles, and a number of researchers have employed simple deterministic, mechanistic models to great advantage. The work of Vollenweider (119) is an outstanding example, and was a major impetus to the National Eutrophication Survey mentioned earlier. Vollenweider started with a simple mass-balance equation that expressed mean total phosphorus concentrations in a lake as a function of areal loading rate, mean lake depth, hydraulic retention time, and a sedimentation coefficient. Assuming that algal growth increases with total phosphorus concentrations, Vollenweider suggested that the trophic condition of a water body could be predicted from the four independent variables listed above. (Later work derived empirical expressions for sedimentation coefficients in terms of the other three variables.) This simple approach has been startlingly successful and serves as one of the few useful theoretical tools for managing biological water quality.

Another use of potential value for simple, deterministic, mechanistic models is the ability to generate testable hypotheses concerning the general features of ecological response. For example, suppose that we wish to find which features of an ecosystem, if any, might be correlated with the stability of certain biological populations, in the sense of their ability to resist external perturbations. One approach would be to hypothesize a simple system of equations; use mathematical techniques of stability analysis to derive some predictive indicator of stability; and gather evidence from theoretical work or computer simulations that the results are independent of the exact formulation of the model (120). Hypotheses not immediately forthcoming from ecological intuition can be arrived at in this manner, serving as a starting point for further experimental work with microcosms or in natural systems.

Finally, we should note the existence of stochastic, empirical models, in which the dependent variables are probability distributions and the equations essentially describe the available data without regard to the internal mechanisms of the system. The adoption of a stochastic formulation does not imply a conviction that the system is truly random; it often expresses our ignorance of the deterministic details. Simple linear regressions can be considered the most elementary form of this type of model, although the available mathematical tools now allow sophisticated elaboration of this technique within the context of time-series modeling (121). Typically this approach requires long time series of data, a requirement met only for a few ecological parameters to date. In many cases where we require information about a potential ecological stress, there is no prior empirical evidence from which to construct a time series model. Accordingly, these stochastic empirical models are unlikely to play an important role in assessing ecological responses to different energy alternatives.

Problems of Valuation

Assuming that it is possible to give a comprehensive list of ecological stresses and the corresponding ecological responses, on what basis can we value these responses in our individual lives? And can we always compare the value we attach to the response with someone else's reaction to this response? The discussion of these questions is clear-cut only for the few ecological changes with obvious monetary or medical repercussions. The totality of repercussions is so complicated, so subtle, and so often delayed in time that it would be enticing to have to deal only with the clearly quantifiable issues. At the same time we must ensure that the complexity that makes itself obvious to ecologists is shared with the public if all of us are to participate in policy decisions in a balanced manner. In this section, we first consider the general categories through which ecosystem structure and function is related to human welfare, followed by a brief survey of the difficult issues that confront us when we attempt to quantify these considerations.

ECOSYSTEM DEGRADATION AND HUMAN WELFARE Westman (3) makes a useful distinction between the "goods" and the "services" provided by various ecosystems for human use. Goods refers to the standing stock of material available and corresponds to ecosystem structure; services, on the other hand, corresponds to ecosystem function and represents the activities or dynamic behavior of ecosystems that directly benefits mankind. Ecosystem structure is immediately perceptible, and most goods offered by natural systems can be appreciated with little thought or experience. Ecosystem function is more refractory to direct observation and, correspondingly, has played a background role in considerations of environmental degradation and human welfare.

Among the more important benefits that can be classified as goods are:

1. Farm products from agricultural ecosystems;
2. Fish, invertebrates, and macroscopic algae from aquatic ecosystems;
3. Wood and specialty products from forest ecosystems;
4. Genetic diversity for the potential provision of new crop strains or animals for domestication;

5. Recreational settings for a number of pastimes, such as natural history, backpacking, fishing, hunting, etc;
6. Opportunities for unique aesthetic experiences, and
7. Opportunities for seclusion, especially near urban areas.

All of these can be considered as goods because they exist for our use at a given time independent of any dynamic activity of the ecosystem. On the other hand, there is an element of arbitrariness in this distinction because the continued availability of these goods depends on their constant conservation and renewal through ecosystem function.

The important services provided by ecosystems include:

1. Maintenance of the gas balance of the atmosphere through photosynthesis, respiration, nitrogen fixation, and denitrification;
2. Control of air quality by removal of atmospheric pollutants;
3. Control of water flow and distribution, especially local storage vs runoff;
4. Maintenance of water quality, both by watershed soil stabilization and self-purification processes; and
5. Checking of the rampant growth of potential pests and prevention of the extinction of rare valuable species.

Neither list is intended to be exhaustive. The point to be made is a familiar one. The many goods and services that can be attributed to the presence of ecosystems is not merely a fortuitous convenience for the human species. Rather, it reflects the coevolutionary quality of life on earth and the fact that our survival needs necessarily have corresponded to what ecosystems make available to us. Occasionally an argument has been made that less attention should be paid to the satisfaction of human needs by ecosystems and more to some intrinsic rights or value of nature, when we consider the consequences of ecological change from human activity (122). Certainly this approach would free us from the problems of reconciling our individual value judgments about ecosystem goods and services, and if completely embraced would signify the end of environmental degradation itself (as well as imply a drastic alteration in lifestyle). However, the efficacy of the argument depends on the adoption of a totally new mode of consciousness by a majority of people. Although we may believe that this is a desirable goal to work for, it does not provide much perspective for dealing with present conditions. The current situation demands at least a partial preoccupation with the specifics of goods and services, along with the formidable task of communicating the values we each attach to them.

Value of Ecosystem Goods and Services

In some cases the value of goods and services is easy to quantify on a common (e.g. monetary) basis, readily permitting a numerical ordering of the social consequences of certain aspects of energy choices. In other cases, the consequences may be quantifiable, but in terms of different units, so that comparison of consequences becomes a difficult matter. Finally, there are situations in which any type of quantification appears to be out of the question. Budnitz & Holdren (2) have discussed this distinction in some detail.

Even in those cases where consequences seem to lend themselves to some common valuation, there are vast complications in arriving at an actual valuation. The most obvious cases are those in which we express losses in terms of their current monetary value. For example, suppose that we assess the social costs of acid rain by computing annual financial losses from estimated decreases in forest productivity. The actual decrease in wood production, if on a large scale, itself influences the value of the financial loss, for it makes wood scarcer. And even without this feedback effect, are we naive enough to believe we can anticipate the monetary wealth of forest products 25 years from now? Similar complications apply to all the material goods provided by ecosystems that appear to have a present well-defined financial worth.

Valuation of ecosystem services introduces us to the additional problem of comparing consequences that do not appear to be quantifiable on a common basis. One of the most common approaches suggested as a solution is the concept of "shadow pricing," i.e. estimating the market value of services needed to retain or restore the benefit. For example, Westman (3) discusses the shadow price of ozone damage to pine trees in the San Bernardino Mountains near Los Angeles. Assuming that 50% of the trees in one 4000-hectare area soon will be replaced by grasses, the cost for sediment removal resulting from erosion losses alone is $27 million per year in 1973 dollars. The subtle costs of environmental degradation can be surprisingly large, and the advantage of shadow pricing is to bring to our attention the minimum financial loss involved.

However, because of the difficulty in anticipating how people will react to a particular loss, shadow pricing often will be of little relevance to the actual cost borne by various people. What if we choose not to replace the services lost by environmental degradation? More importantly, what if we do not have the technical means to replace the lost services? If either is the case, then the response to the loss can have ramifications that bear absolutely no resemblance to the shadow price. Suppose recreational sites are destroyed in the course of certain ecological responses and we establish a shadow price for transporting former users to the nearest equivalent place. What relationship does this price bear to the social costs of crime committed by those who would seek adventure in criminal activity rather than travel elsewhere for recreation?

Finally, we come to those characteristics for which any sort of quantification seems impossible. Primary among these are the aesthetic qualities of ecosystems, the opportunity for experiencing "wildness" or "naturalness," the opportunity for seclusion, etc. The concept of a common valuation is out of the question. For some people these opportunities completely outweigh most conveniences of a high-technology lifestyle, and they have expressed their choice in the place and manner that they now live. For others, the aesthetic and other opportunities play no role whatsoever. Our variable dedication to these characteristics depends to a large extent on our personal experience, our social milieu, and our source of employment. On any scale of perceived values, losing these ecosystem characteristics will be infinitely costly to some, of zero worth to others. The possibility of attributing a value beyond personal perception is unrealistic in our present society.

There is little point in belaboring these issues further. The point to be made is that the complexity of the valuation problem is beyond us and possibly beyond any analysis. Even in the simplest cases where it seems possible to assign monetary values, the true worth is dictated entirely by a future that we cannot predict. These simplest cases present the greatest danger, for at least in the case of "intangible" nonquantifiable values we are more inclined to accept the impossibility of a true valuation. At the same time, it is clear that we do lose a lot in the process of ecosystem degradation, and that it is important to delineate these losses as clearly as possible for policymakers. If we cannot actually attach a simple set of numbers to the costs of our energy choices, we still can work for a more balanced perspective by investigating the roles that ecosystems do play in our lives and by making the information available to the public in as clear a fashion as possible.

If there is any one conclusion that can be drawn from this entire discussion on problems with measurement, prediction, and valuation, it is that the present technical, theoretical, and psychological understanding of our culture is inadequate to deal with the challenges posed by what we perceive as our energy needs. The full consequences of our choices will remain inaccessible until they happen, and we should not delude ourselves otherwise. This very ignorance may be the most important factor to incorporate into our decisions. Above all, it underlines the extreme importance of energy conservation.

ARE SOFT ENERGY PATHS ECOLOGICALLY BENIGN?

In recent years there has been considerable questioning of the paths that industrialized society have traditionally pursued to supply its energy. Many people have called for a shift of emphasis in energy policy characterized by one or more of the following actions:

1. Dispersing, rather than geographically centralizing, energy production facilities.
2. Providing individuals with their own sources of energy rather than having public utilities or private corporations control supply. (Note that this "power to the people" idea goes beyond the issue of dispersed versus geographically centralized energy.)
3. Using renewable rather than exhaustible energy sources.
4. Matching rather than mismatching energy supply to end use (with respect to size, thermodynamic quality, etc).
5. Developing solar power rather than coal and nuclear power.
6. Aiming for technical simplicity rather than technical complexity.
7. Enhancing conservation of energy rather than enhancing supply of energy.
8. Using environmentally benign rather than disruptive energy technologies.

Lovins (123), who has produced a very readable synthesis of much of this questioning, has coined the terms "hard paths" and "soft paths" to describe, respectively, the historical and proposed new energy policies (see also the chapter by Lovins in this volume).

It is not unusual to find critics and proponents of established methods upset with each other, and discussions of energy policy provide no exception. The intensity of debate has led in some cases to a failure to think through and define carefully the exact source of disagreement. On the part of both critics and proponents of new ideas about energy, a blurring of distinctions among possible elements of a new energy policy has resulted. In many situations, when someone mentions one item in the above list, it is assumed that all items really are intended.

The last entry on the above list is the direct concern of this review. An energy policy that fulfills any or all of the first seven conditions will not necessarily fulfill the eighth. We look now at some considerations concerning the compatibility of the first seven characteristics of a soft energy path with the eighth. We review the salient issues and uncertainties and discuss some of the more clear-cut cases.

1. Geographic Distribution

In judging whether a given energy source is ecologically more benign in a dispersed or centralized distribution system, the following issues are pertinent:

1. Are there economies or diseconomies of scale that will affect the relative efficacy of pollution control (e.g. by selecting for or against better equipment)?

2. Is it better to concentrate or disperse ecological stresses such as pollution or habitat loss?
3. What ecological impacts are expected to result from the differing storage needs of dispersed and centralized systems?
4. How flexible is each type of system in responding either to new technological developments in pollution control or to new ecological findings that might warrant termination of use for a particular energy source?
5. The operation of dispersed and centralized systems leads to different needs for quantity of, and transportation of, raw materials (e.g. fossil fuels, nuclear fuels, and water) and energy products (e.g. heat, electricity, and synfuels). Construction and operation can lead to different needs for allocation of human resources (e.g. boomtowns). What are the ecological implications of these differences?

The answers to these questions of course are dependent upon the energy source under consideration. Some energy sources, such as solar heating and cooling for buildings appear ideally suited to a dispersed approach. All centralized energy sources for heating and cooling that we are aware of, solar or nonsolar, are more ecologically destructive than either passive or decentralized active solar.

In some other cases, dispersal entails serious drawbacks. For example, a large number of small backyard, neighborhood, or even community-sized coal gasification or liquefaction plants would probably be ecologically more harmful than a centralized facility with the same total output of synfuel. It is doubtful that as stringent a level of water treatment would be possible in the dispersed systems. And even if the dispersed plants dispose of the same total quantity of pollutants into aquatic systems as the centralized plants, it is likely that a greater reach of river habitat would be affected. Moreover, the damage is not likely to be significantly more diluted by dispersal than by centralization: much smaller bodies of water generally would receive the waste. All of these considerations are speculative; we urge that more attention and research be given to questions such as these before geographical distribution and plant size become rigidly determined by other considerations.

Wind energy is an interesting source to consider because it is relatively benign ecologically on any scale of application, but does pose certain issues relevant to geographic distribution. Aesthetic damage is probably lessened by dispersal. If windmills were located on farmland scattered over the entire countryside, and connected to an existing grid system, probably few would find them offensive. A centralized wind system would necessitate a new transmission system and create a massive, centralized, visual scar.

The use of wind energy is likely to require auxillary storage systems or some back-up supply of energy. The back-up source generally will be more ecologically damaging than the wind source itself. The storage facility also could pose serious ecological risks if, for example, pumped storage is employed. The storage needs of centralized and dispersed wind systems will depend upon the statistical distribution of wind speed at a given centralized site and upon the correlations of wind speed across a variety of dispersed sites. An appropriate analysis of meteorological data to determine relative storage needs is required before a judgment can be made on the relative ecological impacts of the two approaches.

Hydroelectric power can be dispersed by using either a large number of low-head dams or in-stream generators. Problems that can result from a dispersed approach are numerous and appear no less serious, per kilowatt generated, than those from centralized hydropower. Among the factors to consider in making a comparison are the reach of river habitat affected by the interruption of water flow, barriers to animal movement in the water, water loss from evaporation, wilderness quality of the sacrificed portion of river, and the amount of access road needed. With smaller dams, storage is an increasingly important problem and could lead to the necessity for constructing more low-head systems than anticipated. Considerably more study of the putative advantages of low-head and in-stream systems is needed lest society unthinkingly embrace what could well turn out to be an ecologically worse alternative to what is already an environmentally destructive technology.

Bioconversion is a technology that may well have ecological advantages if deployed in a dispersed manner. Centralized bioconversion schemes, in which large quantities of biomass are grown plantation-style will have serious ecological repercussions stemming from the quantities of land, water, and fertilizer needed. On the other hand, human and agricultural wastes could provide a relatively small but important source of energy that, even on a per-unit-energy basis, is likely to be relatively benign ecologically. Human and agricultural wastes for bioconversion are, of necessity, a dispersed energy source. The net impact of their use on water resources could even be a positive one if, for instance, waste water treatment is enhanced in combined water treatment and fuel production operations, or if feedlot wastes are converted to synfuels before they have an opportunity to wash into streams and lakes and accelerate eutrophication.

2. *Individual Energy Self-Sufficiency*

The issues here are basically the same as in the last section above. The problems of storage and of economies of scale in pollution abatement are particularly acute. Contrast, for instance, a dispersed wind system in which each family or neighborhood has its own set of windmills, with a dispersed system in which produced power is fed into a large regional or national grid. Clearly the storage problems are less severe in the latter case, and therefore ecological impacts generally will be less severe. On the other hand, an important potential advantage with locally owned energy systems is that they can, in principle, take into account local conditions. The ecosystems that communities most care about can be the ones most respected by choice of site, design, and operation of the facilities. It is not clear that this advantage will materialize in practice.

3. Renewables versus Nonrenewables

Hydroelectric power is, without a doubt, a counterexample to the notion that the renewable energy sources are ecologically preferable to the nonrenewables. Large scale bioconversion plantations to provide a renewable source of fuel from biomass do have the advantage over fossil fuels that they would not contribute to the carbon dioxide problem to any great extent. On the other hand, they would pose great threats to land and water resources. Other renewable solar technologies appear generally preferable to the nonrenewables. Of the geothermal sources, those that would last the longest, such as hot dry rock, likely would be the ones with the least impact. There is no consensus as to whether the breeder reactor is more environmentally benign than its less renewable counterpart in the conventional reactor, but there is general agreement that fusion could provide a more environmentally benign source of energy than the other, less renewable, nuclear sources.

4. End-Use Matching

Thermodynamic matching of energy supply to energy end-use means, for example, avoiding the use of electricity for resistance heating, or the use, for low-temperature purposes, of sources that can supply high-temperature heat. There is one a priori argument suggesting that ecological considerations should lead us to the same energy policy as would thermodynamic considerations: the more efficient our energy supply, the less primary energy raw material (fossil fuel, sunlight, etc) needed to satisfy a given level of end use. But ecological impacts quite often are as dependent upon consumption of secondary raw materials such as water used in energy production, and upon toxic effluents, as they are upon the consumption of primary energy inputs. And there is no a priori reason why these causes of impact should be diminished simply because thermodynamic efficiency is enhanced. The more efficient technology may require a fuel that is more ecologically destructive to mine.

In its strongest form, the argument for end-use matching has led some to the conclusion that electricity should only be used for lighting purposes and to run small motors. Consider, however, the case of transportation. When petroleum is no longer available as a source of motive power, it is possible for society to replace this source with synthetic liquid fuels derived from biomass, oil shales, or coal. But the ecological impacts of these alternative synfuel paths are likely to be extremely high. These impacts arise in the production stages where air pollution problems that are qualitatively similar to those associated with present day transportation can occur. It is very likely that electric automobiles, with flywheel coupling, could be developed to be more efficient, in the second law sense, than internal combustion automobiles. In that case, both ecological and thermodynamic considerations would point to their use. But even if the second law efficiency of electric transportation proves inferior, it still may be a preferable choice for ecological reasons. This quite clearly would be the case if the source of electricity were wind or photovoltaic conversion while the source of liquid synfuels were oil shales, coal, or bioconversion plantations. On the other hand, if human and agricultural wastes were the source of liquid fuels and the source of electricity was hydroelectric or fossil, then the choice likely would be reversed.

As another example of the subtleties at play in the subject of end-use matching, suppose that coal is to be a primary energy source for home heating. Should it be burned directly in the home, should it be converted to synthetic liquid or gaseous fuels that could be burned in the home, or should it be converted to electricity that could then be used for heat pump or resistive home heating? There are at least two environmental considerations that suggest the electric pathway is preferable. One is that it appears to lead to less water consumption and water pollution (45). The second is that, of the three choices, it minimizes the problem of indoor air pollution. Until the health effects of indoor air pollution, centralized power plant air pollution, and water pollution from coal conversion plants are better understood and compared, it may be difficult to weigh properly this last consideration. Determination of the optimum fraction of energy use to be supplied by electricity cannot be made by consideration of only one dimension of the problem.

5. Solar Power

There is ambiguity here also. Although some of the proposed solar technologies appear to be ecologically superior to alternative sources of energy, exceptions, such as bioconversion plantations, exist and are discussed in the overview section of this review.

6. *Technological Simplicity*

The most ecologically benign technologies do seem to be the simplest—passive or active solar heating and cooling of buildings, and wind-generated electricity are examples. On the other hand, not all simple technologies are ecologically benign—hydropower is a prime example.

7. *Conservation*

There is little ambiguity here. On environmental grounds, this particular soft path is the most beneficial of all.

Conclusion

Nothing automatically guarantees that an energy technology possessing one or more of the characteristics of a soft technology will be ecologically preferable to one that does not. Numerous examples to the contrary support this conclusion. There are some technologies, however, that do satisfy all or nearly all of the first seven characteristics of the soft path listed above and are notably benign ecologically. Active or passive solar space heating and cooling, conservation, and grid-connected dispersed wind generation of electricity are the best examples. An insistence on minimum use of electricity may be justified on thermodynamic grounds, but with a serious gaseous and liquid fuels problem facing the world, and with the possibility of water scarcity severely constraining US energy policy, both ecological and human health criteria may well point to the opposite conclusion. On the narrow basis of dollar cost, a technology such as dispersed, low-head, or in-stream hydroelectric generation may appear economically attractive and it may satisfy some of the soft-path criteria. Yet, use of such technology could well prove to be extremely hazardous ecologically.

Soft-path technologies have much to offer in many respects—environmental considerations will strengthen the case for some and weaken it for others. Careful analysis in a particular situation of the questions posed broadly here will enable the benign technologies to be identified.

SUMMARY

The various energy sources and technologies differ greatly in the type and degree of ecological risk they pose to nature and to society. The solar technologies, with some important exceptions, are relatively benign. Others such as oil shale and coal conversion to synthetic fuels and hydroelectric power can generate quite serious impacts on ecosystems. Among the energy problems faced by the world is that of finding alternatives to dwindling supplies of gaseous and liquid fuels. Suggested strategies for solving this problem pose especially grave threats to ecosystems and we urge that a

detailed examination of environmental issues precede a commitment on the part of society to any one of them. Whatever mix of energy sources is chosen by society, intense energy conservation is of paramount importance to the future viability of ecosystems.

Much of the ecological damage from energy activities is not readily measured in terms of direct death or injury to plants and animals. Rather it is first manifest as habitat loss. The effects of habitat loss are poorly understood and hard to quantify. Habitat loss often escapes attention when it occurs in piecemeal fashion. In other, more visible cases, such as wild river destruction, whole habitat types are in danger of extinction in large regions of the United States. Of the types of ecosystems at risk from future energy activities, freshwater lakes and rivers and the estuaries into which they feed stand out as the most threatened. Guidelines for habitat protection are sorely needed to prevent damage to wildlife, habitat extinction, and to prevent inaccessibility of open spaces to urban dwellers. This last item is especially critical: wildlife conservation in the future will be strengthened to the extent that opportunities for enjoyment of nature are available to many today.

Much of the effort at ecological impact assessment has been directed at quantifying environmental stresses such as pollutant levels or rates of land and water consumption. More effort is needed now to assess the ecological responses and the human consequences of these responses. While valuable insight has been obtained from studies on the effects of toxic substances on individual organisms, more ecological research should be directed toward effects at the community level. Experimental study of whole ecosystems so far has provided the greatest insight and should be emphasized.

The effort to assess the human consequences of ecosystem degradation is at a primitive stage. Goods and services provided by natural systems are recognized occasionally as being of vital importance to the survival of our species. But our knowledge of the linkages between disruption of ecosystems and disruption of the goods and services they provide is scanty.

A nearly intractable problem is that of valuation of the amenities provided by undisturbed ecosystems. Neither relegation of their importance to mystical appreciation alone nor insistence on an economic measure of the benefits of environmental goods and services, will result in a proper valuation of the role natural environmental systems play in our lives. We cannot suggest a proper valuation scheme here. But we do suggest that society will be in a better position to properly value environmental goods and services and to incorporate these values into policy decisions when environmental amenities are better understood within the disciplines of natural and human history, and when the results of such understanding are widely and forthrightly disseminated.

The soft energy technologies have much to commend them. Yet they, too, vary tremendously with respect to the ecological impacts they will generate. Many of the most benign energy technologies such as conservation, active or passive solar space heating and cooling, and dispersed wind generation of electricity, are also soft technologies. But it cannot be assumed that merely because a technology is simple, or thermodynamically optimum, or renewable, or inexpensive, or dispersed, or antiestablishment, that it is therefore preferable ecologically.

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