WORKING PAPER

NATURAL RESOURCES AND ENERGY SYSTEMS: A STRATEGIC PERSPECTIVE

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IIASA
International Institute for Applied Systems Analysis

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1. INTRODUCTION

- Oil price falls to below ten dollars a barrel!
- US synfuel program cancelled after billions of dollars are invested!
- Tennessee Valley Authority tries to sell unfinished nuclear plants to China!
- Completed nuclear plant stands idle in Austria!
- Canadians seek uses for excess power from Candu plants!

How do these facts characteristic of today's situation compare against the constructs of energy planning of the 1970s? Why have so many multibillion dollar energy projects of the last decade been either abandoned or mothballed?

Simply stated, the terms of the energy debate have changed dramatically over the past decade. Whereas the size of the fossil fuel resource base was the overriding concern of the 1970s, we are now faced with a totally new set of distresses – a glut of cheap oil, a general excess of operating nuclear capacity, an ever growing number of mothballed or not quite completed non-operating nuclear plants, to give but a few prominent examples. Today the formidable challenge is to use abundant energy sources in ways that support social and economic development and protect the environment.

In this paper we seek to provide a strategic perspective on how to meet this challenge. Toward this end, we explore the misconceptions of the past that led to costly errors in energy planning. The issue here is to dispel the myth of resource depletion as the driving force for the shift from one energy source to another. To gain insight into the actual basis for energy substitution, we turn our attention to energy patterns, viewing these in retrospect and prospect. This review of energy development provides an opportunity to consider some of the environmental implications of the expanded use of energy resources. These findings are then drawn together in an attempt to highlight certain R&D options that we believe offer a sound basis for strategic energy management. Finally, we underscore the importance of international cooperation in dealing with the truly global issue of energy development.

2. THE MYTH OF "RUNNING OUT OF RESOURCES"

Recent work at IIASA and elsewhere has seriously challenged the hypothesis that whatever is the most desirable and necessary resource will eventually "run out". This "running out" hypothesis – the modern mineral version of the old Malthusian food supply myth – has pervaded the bureaucratic, business, and scientific communities for decades. It has served as a basis for national policy, industrial policy, investment policy, and research policy. We shall use the case of energy to dispel the myth of resource depletion as the driving force for resource substitution. Our studies of nonfuel minerals have led to a similar conclusion (Tilton 1984; Tilton and Landsberg 1984).

The resource base of fossil fuels is large, particularly of coal and natural gas. Along such lines it is useful to consider the estimates given in Table 1 for nonrenewable fossil energy resources. The data are not intended to be definitive, but rather to show that the world is in no imminent danger of running out of energy sources.

Moreover, recent technological advances in resource exploration are leading to upwardly revised estimates of both conventional and unconventional gas resources. Until recently, natural gas was extracted mainly as an unwelcomed byproduct of crude oil production, and was either reinjected or flared. Even today on a real-time basis, there is more associated gas flared around the world than is consumed in Europe. Admittedly, this is a crude estimate. It is crude in the sense that there has been no systematic attempt to meter or report the volume of flared

Table 1. Fossil Energy Resources and Primary Energy Consumption, 1984.

	Coal (10^9 tce*)	Oil (10^9 toe*)	Shale (10^9 toe)	Gas (10^{12} cm)	Fossil (10^9 toe)
World	5241	352	428	438	4572
% of total	(74)	(8)	(9)	(8)	100
Cons '84 (10^9) toe	3.35	2.84	—	1.79	7.20
% of resource	(0.06)	(0.81)	—	(0.39)	(0.16)

*tons of coal equivalent (tce); tons of oil equivalent (toe); cubic meter (cm). Numbers may not total due to rounding.

Based on data from BP Statistical Review of World Energy 1983 (1984), Delahaye and Grenon (1983), Häfele (1981) and World Energy Conference (1983).

associated gas. Flaring has occurred in order to release high volumes of gas and thus facilitate the production of associated oil or because it has been too expensive and/or dangerous to seal the well and "kill" the flare.

Additionally, there is growing evidence that abiogenic methane resources may be abundant in the earth's crust (Gold 1984, 1985; Gold and Soter 1982; Wakita 1985; Wakita and Sano 1983; Marsden and Kawai 1965; Sano and Wakita 1985). This implies that not only methane deposits but even some petroleum and other carbon compounds may be of abiogenic origin from the deeper strata in the crust. Over millenia, primordial methane has been continuously outgassing from the earth. The volume trapped within the upper strata of the crust may have contributed a significant, if not the major, part to known resources of methane and other carbon compounds. If it is true that much of the methane, and indeed much of the petroleum and coal deposits, are of abiogenic origin, then the potential amount of hydrocarbon resources not yet discovered would be enormous.

Later in Section 5 we examine the issue of exploiting the vast potential for methane resources. At this point we argue against the notion of "running out" as the basis for energy substitution. To support this belief, we briefly review energy developments and what these reveal about the behavior of energy systems.

3. ENERGY DEVELOPMENT: IN RETROSPECT AND PROSPECT

For centuries fuelwood, together with animal and farm waste and animal and human muscle power, were the mainstays of energy supply. Compared with contemporary energy consumption patterns, these traditional energy forms were used at low absolute levels and low densities of generation and end use. Essentially, their exploitation was not dependent on infrastructures for transformation and transport.

These patterns were altered with the emergence and intensification of the industrial revolution of the 19th century. As Figure 1 indicates, fuelwood was replaced by coal during the last half of the 19th century, with fuelwood's share declining from some 70 percent in 1860 to about 20 percent around the early 1900s and concomitantly that of coal increasing from 30 percent to almost 80 percent. Fuelwood was abandoned, not because of the threat of resource depletion, but because coal mining and coal end-use technologies had provided an energy source that could do what fuelwood did – but better. Although it was possible (and still is) to operate trains and ships with fuelwood and to use fuelwood for shaft-power and electricity, coal technology advances made it increasingly easier, more efficient, and cheaper to do so with coal.

However, by 1910 coal's rapid growth had ceased, with its share of the primary market peaking some ten years later and declining in relative shares thereafter in a pattern that is almost symmetrical with that of fuelwood fifty years earlier. By the early 1960s, coal had been displaced by crude oil as the dominant fuel on the primary market both in market shares and on an absolute basis. A similar substitution pattern can be observed. Coal resources were (and still are) abundant. But with the discovery of oil drilling around 1860, a set of oil-related technologies began a development process that eventually led to the large-scale and efficient refining of crude oil into a broad range of products and chemical feedstocks. This opened up the energy market for oil. On the end-use side, refined oil products proved to be far superior to coal for powering trains, automobiles and aircraft, for generating electricity, and for providing residential and commercial heating. All but one of these end-use applications had been achieved first by coal. The primary new application opened up by the use of oil was, of course, aviation, now a large consumer of refined oil products. Nonetheless, around 1980 crude oil peaked on the world primary market both in terms of shares and on an absolute basis, and began to decline thereafter. As Figure 1 also shows, natural gas and nuclear energy have been steadily gaining market shares against crude oil – natural gas since around 1920 and nuclear energy since around 1970.

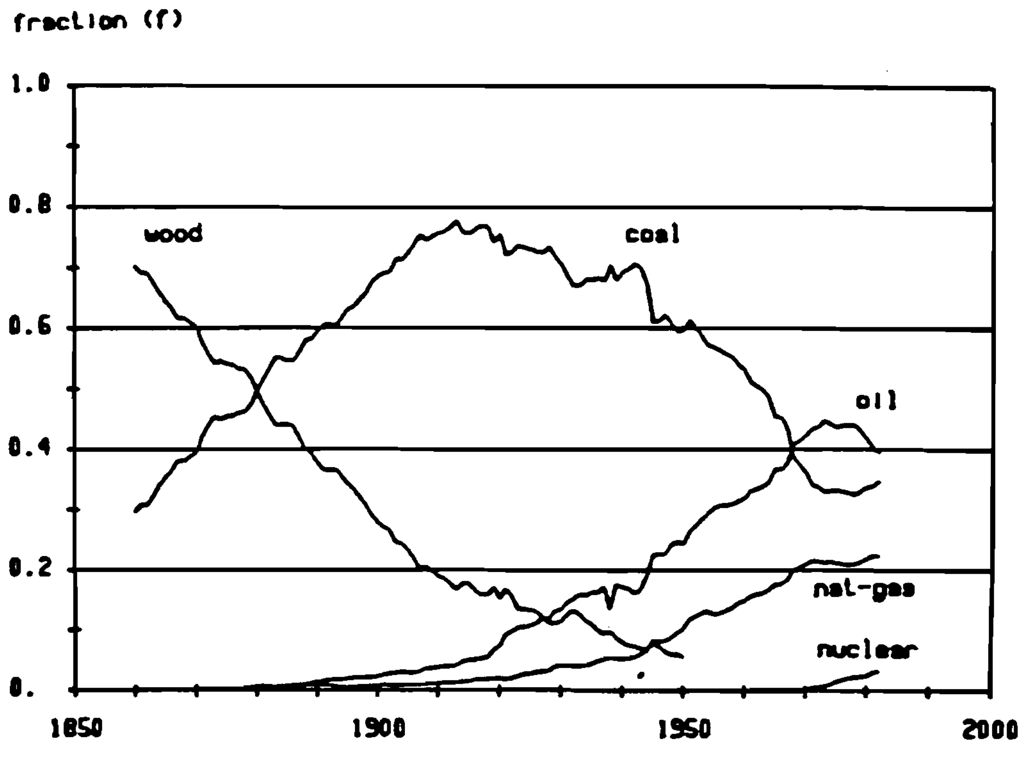

Figure 1: Fractional Shares of Major Primary Energy Sources, World (Nakicenovic 1984).

Thus from the historical perspective, energy substitution has been driven by the availability of a set of new technologies that enabled an alternative energy source to better satisfy the end-use demands of society.

This reasoning led IIASA to forecast – more than a decade ago – that natural gas and nuclear energy would be the dominant growth fuels over the next few decades. At that time, these predictions were a highly controversial and emotional issue. They have, however, stood the test of time. An understanding of the analytic basis of these predictions is considered useful for our discussions. We therefore briefly describe the work of Cesare Marchetti and Nebosja Nakicenovic at IIASA on the dynamics of market substitution and what this reveals about the system behavior (Marchetti 1979; Marchetti and Nakicenovic 1979; Nakicenovic 1979, 1984).

The evolution of primary energy consumption emerges as a regular and predictable substitution process when it is assumed that energy sources are clusters of technologies that compete in a Darwinian manner to conquer the market — or, in ecological terms, to fill a niche. Figure 2 shows the results of applying the logistic substitution process to the competition on the global primary energy market and the projected paths to the year 2050. The picture emerging is that of natural gas progressively capturing the market from crude oil, achieving a maximum penetration (ca. 70 percent) around the year 2025 and declining in market shares thereafter. Another interesting feature of this chart is that, at the world level, nuclear energy has begun a steady penetration of the market and is therefore well-positioned to replace natural gas as the dominant primary energy source sometime around the middle of the next century.

The market penetration of natural gas can also be viewed through the lens of the hydrogen–carbon (H/C) ratio (Figure 3). Over the past one hundred years, the global primary energy system has moved progressively toward hydrogen-rich quality fuels: the H/C ratio of fuelwood is roughly 0.1; of coal, 1.0; of oil, 2.0; and of natural gas, 4.0.

This phenomenological approach has been applied to over 400 cases involving energy systems and to some 500 cases involving social and economic systems, demonstrating the capacity of the Volterra method for both backcasting and forecasting. These applications also show that there are time constants for the societal acceptance of technologies. In the case of energy, the time constant involved was several decades; thus, energy substitution is an evolutionary process. Failure to recognize these characteristics and the "running-out" myth could have well been responsible for the failure of many multibillion dollar projects. Indeed, the existence of regular patterns of evolution would have far-reaching implications for strategic energy management. We explore this issue later in Section 5.

The findings of the IIASA global energy study, ***Energy in a Finite World***, also point to an increasingly larger role for natural gas and nuclear energy in the global energy system (Häfele 1981). The logistic substitution analysis was, in fact, an integral part of the global analysis that examined, among other things, constraints on resource supply, environmental implications, and energy supply and demand balances. The IIASA study, conducted during the energy crises of the 1970s, explored not only post-oil systems but also post-fossil fuels systems and how the world might successfully negotiate the transition to such systems. It concluded that resources and technologies are available or in hand to meet a projected two- to threefold increase in global primary energy consumption by 2030. The next 50 years would mark a transition to a world primary system based on the expanded use of fossil fuels and increasing contributions from nuclear energy. The contribution of renewable energy sources, albeit important, would remain at a relatively low level globally. Constraints on the buildup of large-scale solar facilities would not allow this primary source to contribute significantly at the global level before the end of the next century. At the end-use side, the structure of demand would not change significantly, with liquid fuels, electricity, and process district heat remaining the preferred energy forms over the next few decades.

Recently, IIASA exploited these findings to determine the technical and economic feasibility of an expanded gas market in both Eastern and Western Europe and what this would imply for the development of a viable international gas market. Industry was an active partner in this effort, which realistically examined how environmental issues, government policies on import-export quotas, prices, and other related issues may affect the ability of natural gas to compete on European markets against its main rival oil and, to a lesser extent, coal. (Rogner *et al.* 1985; Sinyak 1984).

In sum, the IIASA gas study indicates substantial growth prospects for natural gas ***after*** the turn of this century, ***provided*** government policies and capital investments along the entire energy chain (from extraction to end use) are put in place now to support the expansion of natural gas into the electricity and the heat generation markets. The picture over the next 15 years is less sanguine: although natural gas consumption will increase in the process and space heat market, the market itself is expected to remain relatively stable over this period. As Figure 4 suggests, natural gas consumption would be relatively insensitive to price alterations up to the year 2000; however, over the longer term (up to 2030) a 20 percent reduction of gas prices could lead to a roughly 50 percent increase in gas consumption. Not surprisingly, the study also found natural gas consumption to be highly sensitive to environmental issues.

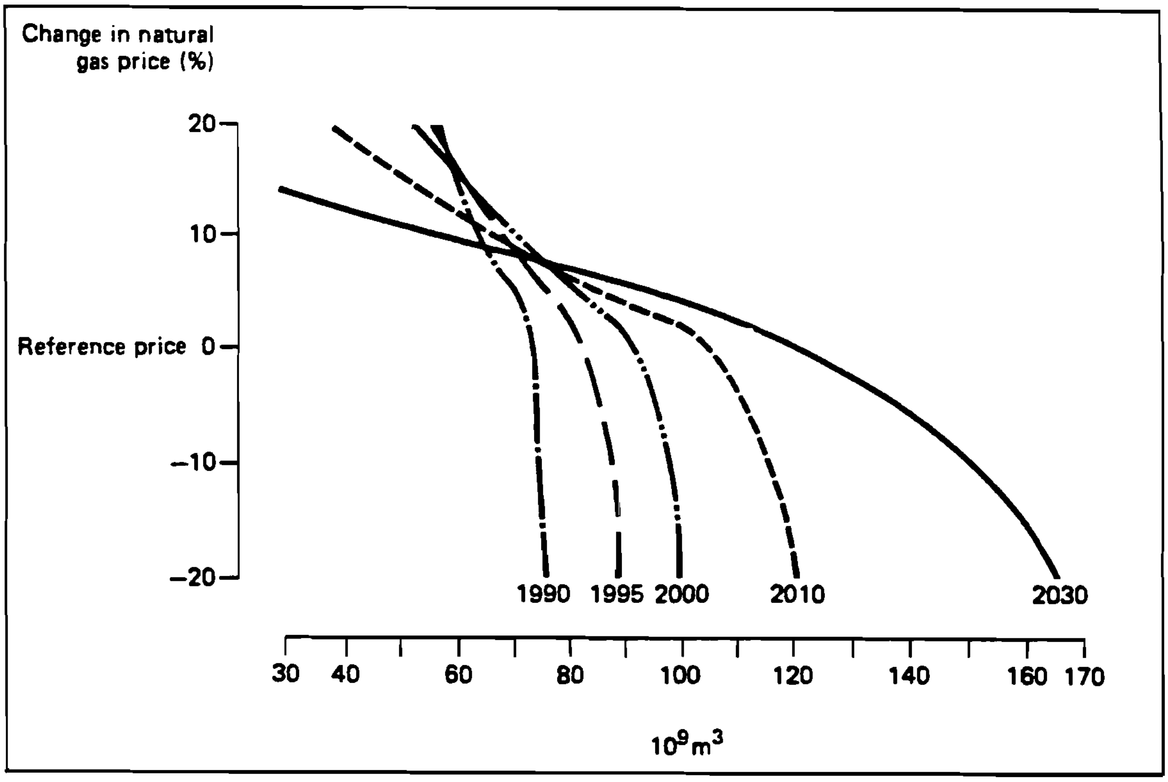

Figure 4. Natural Gas Price Elasticities, Central Europe (Industrial Sector), 1990–2030 (Rogner *et al.* 1985).

Before ending our review of energy trends, we comment briefly on the prospects for nuclear energy. All the bad news about the current situation, particularly in the United States, has been covered many times over in the media. A negative picture has emerged that clouds the reality. Straightforwardly speaking, despite all reported cancellations – myriad troubles, delays, cost overruns – the net nuclear additions and cumulative nuclear electricity production are not only logistic but are penetrating much faster than was forecasted more than a decade ago on the basis of business-as-usual (Marchetti 1985a). A similar dynamic is reflected in the median estimates for the 1985 poll of the International Energy Workshop: nuclear energy is the fastest growing primary energy source on a worldwide basis, with an annual growth rate of 7 percent over the period 1980-2000. This corresponds to a some fourfold increase in the use of nuclear energy in the industrialized world as a whole and a twelvefold increase in the case of the developing world outside the OPEC countries (Manne *et al.* 1985).

Recall that we are discussing growth prospects for nuclear energy at the global primary scale. Up to now, this rapid growth may be attributed to the fact that nuclear energy has found a ready-made distribution network in the electrical grid. But, as recent analyses suggest, nuclear's share of the electricity generation sector may be approaching saturation in several countries (e.g., France, Sweden, the FRG). It is not our intent to discuss these findings, which are well documented (see, for example, Häfele 1985; Marchetti 1985a). Later in Section 5 we consider system possibilities for so-called second generation nuclear technologies that could support the market penetration of nuclear energy along the lines described above.

Armed with these insights on dominant trends in energy development, we focus our attention on the environmental implications of expanded energy use. A common thread running throughout these energy analyses is the increasing interdependence of human development activities and the environment.

4. ENVIRONMENTAL IMPLICATIONS OF EXPANDED ENERGY USE

We have entered an era of increasingly complex patterns of environmental and human development interdependences, characterized by time and spatial scales transcending those of most contemporary political and regulatory institutions. What were once local incidents of pollution shared through a common watershed or air basin now involve many nations – witness the concern for acid deposition in Europe and North America. What were once straightforward questions of conservation versus development now reflect complex linkages – witness the global feedbacks among energy and crop production, deforestation, and climatic change that are evident in studies of atmospheric "greenhouse effects". As a result, planners are faced with tradeoffs in the face of significant scientific uncertainty and minimal social consensus.

The major features of the interaction of human development and the global environment were sketched in a recent report of the International Council of Scientific Union's Committee on Problems of the Environment (SCOPE). They are reported here as background to our discussion:

- "Man's activities on earth today induce fluxes of carbon, nitrogen, phosphorus and sulfur that are of similar magnitude to those associated with the natural global cycles of these elements; in limited areas man's influence dominates the cycles. The likely increase of man's activities during the remainder of this and during the next century will undoubtedly mean significant disturbances of the global ecosystem.
- The most important ways whereby man is interfering with the global ecosystem are:
  - fossil fuel burning which may (a) double the atmospheric CO_2 concentration by the middle of the next century; (b) further increase the emission of oxides of sulfur and nitrogen very significantly;
  - expanding agriculture and forestry and the associated use of fertilizers (nitrogen and phosphorus) significantly alter the natural circulation of these nutrients;
  - increase exploitation of the fresh water system both for irrigation in agriculture and industry and for waste disposal.
- According to our present understanding, the most important impacts of these changes in the long-term perspective are:
  - a gradual change toward a warmer climate, the details and implications of which we know very little about;
  - the concentration of ozone will decrease in the stratosphere, due to the increased release of N_20 and chlorine compounds and increase in the troposphere, due to the increased release of NO_x, and hydrocarbons;
  - an increase of the areas affected by lake and stream acidification in mid-latitudes and possibly also in the tropics; the ion balance of the soils may be significantly disturbed, as is now being found with regard to aluminum;
  - a decrease of the extent of tropical forests, which will enhance the rate of increase in atmospheric CO_2 concentration and release other minor constituents to the atmosphere; this may also contribute to soil degradation;
  - due to loss of organic matter and nutrients, soil deterioration will occur and this implies a reduced possibility for the vegetation to return to pristine conditions...;
  - a trend toward the eutrophication of estuarine and coastal marine areas;

- more frequent development of anoxic conditions of fresh-water and marine systems and sediments.

• The long-term implications of exploiting the natural resources of the earth are not well understood, nor do we understand what is permissible in order to guarantee that present or future (possibly higher) levels of productivity will not later decline..." (Bolin and Cook 1983).

The modern world described by the SCOPE report supports three times the human population and one hundred times the industrial activity than it did a century ago. As the report suggests, today's environment is not just modified by human action; it is fundamentally transformed.

To learn more about these transformations, IIASA recently began a study of the increasing interaction of human activities and the environment. The aim is to identify the technological, institutional, and research strategies that if adopted over the next decades could improve the management of these interactions. The effort involves collaboration with institutions in Canada, the Federal Republic of Germany, Hungary, the Netherlands, Poland, Sweden, the Soviet Union, and the United States, as well as with regional and international agencies. (For perspective on the program see Clark in press; background essays appear in Clark and Munn in press.)

For our discussion here we draw heavily on the insights emerging from this research as they apply to the role played by energy development in these environmental transformations. We focus primarily on the long-term, large-scale carbon dioxide (CO_2) implications of fossil fuel burning. However, this is not to imply that we consider fossil-fuel based emissions of sulfur, nitrogen, and other gases and particles insignificant. Quite simply, the CO_2 issue has received the most analytic attention from the global perspective. It is only recently that researchers have begun to assess the impacts of fossil fuel burning via pathways of sulfur oxides, nitrogen oxides and radiated trace gases. There is growing evidence that the impact of these trace gases on atmospheric greenhouse effects may exceed that of

CO_2 alone (Dickinson and Cicerone 1986; Ramanathan *et al.* 1985). The situation is complex and not well-defined.

CO_2 Implications of Fossil Energy Use

We again start with a look at history, in order to discern persistent background trends against which future interactions of energy development and the environment can be assessed. Unfortunately, global histories of the environmental consequences of energy consumption are only now beginning to be assembled (Jäger 1983; Darmstadter in press; Richards in press). Moreover, the pictures emerging from these studies are incomplete, particularly with regard to the environmental implications of energy consumption based on fuelwood, hydropower, and nuclear fission. Figure 5 shows the results of attempts to reconstruct global fossil fuel consumption that extend back to the middle of the last century. The production of CO_2 can be observed to grow exponentially, with a slowing down in the global production rate occurring around 1973.

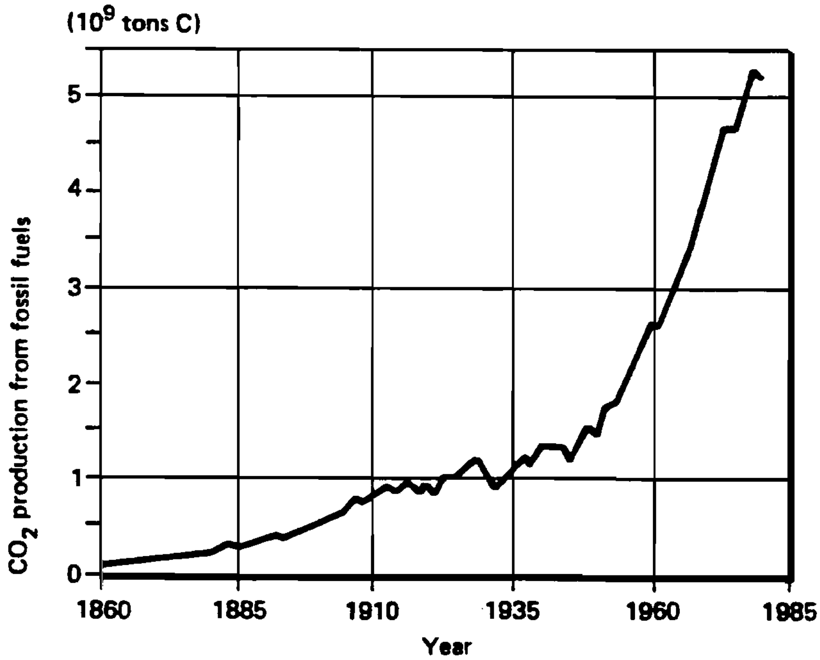

Figure 5. History of World Fossil Fuel Energy Consumption as Reflected in Carbon Emissions. Data from R. Rotty published in Clark (1982).

As to present and projected trends, there are a number of long-term, global-scale energy studies that in varying degrees have considered environmental issues. However, the merits of these studies are hotly debated (see, for example, Ausubel and Nordhaus 1983). One reason given for these shortcomings is that all of these studies make convenient, but unrealistic "surprise free" assumptions regarding future developments in the institutional, technological, and knowledge spheres (Brooks in press). Recently IIASA critically reviewed major global forecasts of energy in terms of their usefulness in addressing environmental transformations (Ygdrassil *et al.* 1985). We comment briefly on the findings of three studies which IIASA is exploiting to develop a more realistic perspective on human development and environmental interactions.

As mentioned earlier, the IIASA global energy analysis concluded that fossil fuels and nuclear power have the potential for meeting a large fraction of the world's primary energy demand over the next 50 years. From this basis, the study examined the possible climatic impacts of substantial increases in the atmospheric concentration of CO_2 and other gases and particles, as well as of large-scale waste-heat releases, particularly when they are concentrated in certain areas. The results suggest that the CO_2 buildup caused by fossil fuel combustion over the next 50 years is probably the most severe climate issue, possibly leading to global average temperature increases of from 1° to 4° C by 2030. In terms of the global energy demand levels estimated in the two IIASA scenarios (equivalent to a two- or threefold increase over the current level) waste-heat releases would probably not perturb the global average climate state in the foreseeable future (Häfele 1981). Recently the IIASA low scenario served as a basis for exploring energy-based emissions of sulfur, nitrogen, and trace gases and their deposition patterns on regional levels. The analysis provides a useful framework for ordering the knowns and unknowns with respect to environmental-energy interactions. (Häfele, *et al.*

1986).

The long-term, regionalized energy model developed by J. Edmonds and J.A. Reilly of the Institute for Energy Analysis of the Oak Ridge Associated Universities has been used extensively in the United States since 1982 (Edmonds and Reilly 1983, 1985). Essentially they explored the sensitivity of CO_2 releases to assumed rates of growth in total energy consumption and to interfuel use patterns. The results suggest that the CO_2 implications of growth in energy consumption will not be a pressing issue throughout this century (influenced to a considerable extent by nuclear energy's gain in market shares); however, they expect the situation to change dramatically in the next century when (as assumed) energy systems shift to a heavy reliance on coal and shale oil. On this basis they predict a doubling of CO_2 concentration sometime around 2080.

William Nordhaus and Gary Yohe's study of alternative energy futures and the CO_2 implications was carried out within the framework of the National Research Council report on climate change (Nordhaus and Yohe 1983). Their time horizon extends to 2100, during which they envisage a decrease in the level of carbon emissions and buildup relative to that of conventional estimates. They attribute this to a slowdown in the growth of the world energy and to the higher prices for fossil energy. A key feature of their study is the systematic treatment of uncertainty, which leads them to underscore the need to take this specifically into account in designing energy management strategies. Nevertheless, they identify a one-in-four probability of a doubling of atmospheric CO_2 concentration before 2050 and even odds for this event to occur during 2050–2100.

Notwithstanding the differences among these and related studies, three major points emerge. First, fossil fuel combustion for energy seems likely to be the largest anthropogenic source of CO_2 at present and for any future in which the carbon dioxide question might be of concern to society (Clark 1982; National Research

Council 1983a). Second, there is a high probability of a significant rise in global CO_2 concentration by the middle of the 21st century. Third, there is need simultaneously for more research to narrow the uncertainty range with respect to all energy-based emissions and for more flexible energy management strategies to avoid serious, possibly irreversible, damage to not only the climate system but to all ecosystems.

Sulfur and Nitrogen Emissions: The Case of Acid Deposition

The pressure on government and industry to act in the face of much scientific uncertainty is also evident in the escalating debate on acid deposition. Decision makers are hard pressed to decide whether to install additional controls on power plants and other potential sources of pollution; to take steps to mitigate possible effects of acid deposition (e.g., liming of lakes and soils, development of resistant species of biota); or to wait perhaps five or ten years until there is more conclusive scientific information about emissions, atmospheric transformation and transport, deposition and ecological effects. Consequently, control policies are being advanced that often have only a tenuous link with scientific knowledge. For example, in Europe a common policy being implemented for acidification control is a 30 percent reduction in sulfur emission by 1993 relative to the 1980 level.

Research aimed at improving scientific understanding of the acidification problem has increased dramatically over the past few years. (See, for example, OECD 1979; National Research Council 1983b; Netherlands Ministry of Housing, Physical Planning and Environment 1985; HAPRO 1985; Izrael *et al.* 1983; Royal Society of Canada 1984.) At IIASA, we are developing a conceptual framework for an integrated assessment of the acidification problem in Europe. The work is being done in close collaboration with the United Nations Economic Commission for Europe (ECE), which oversees the European joint efforts to abate the effects of acidification (the Geneva Convention on Long Range Transboundary Air Pollution).

(See, for example, Hordijk, in press; Hordijk 1985; Alcamo *et al.* 1985; Alcamo *et al.* in press).

Figure 6 illustrates the results of applying the IIASA-built RAINS (Regional Acidification Information and Simulation) model to an analysis of energy-use patterns and total sulfur deposition in Europe in the year 2010. This is viewed from the perspective of two scenarios, both based on energy forecasts by the International Energy Agency (IEA). The first scenario involves no controls for SO_2 emissions, with the bold lines encapsulating the area where deposition is above a moderate level (defined here as 5 $g/m^2/yr$). For the second scenario, extensive SO_2 emission controls were assumed (i.e., flue gas desulfurization units at power plants and industrial boilers, and the use of low sulfur fuels for domestic and transport sectors). The shaded area on the graph indicates where sulfur deposition is above moderate level. As the results suggest, the use of emission controls would drastically reduce the area in Central Europe affected by sulfur deposition.

Relative to sulfur emissions, the inventories for nitrogen oxides and related nitrogen compounds are much less advanced. IIASA is working with the Federal Republic of Germany–Netherlands PHOXA project, the Nuclear Research Center Karlsruhe (FRG), and the OECD to develop a NO_x emission model for integration in RAINS.

Controlling Emissions

Most of the discussion of management responses to the question of energy emissions have centered on measures to alter the production of carbon, sulfur, nitrogen, and related emissions. Basically these fall into three classes (Clark 1985a; 1985b). The first and more general concerns the total use rate of energy. Given the large share of fossil fuels in the total energy budget, energy conservation and slower growth in energy consumption (say, from more efficient uses of

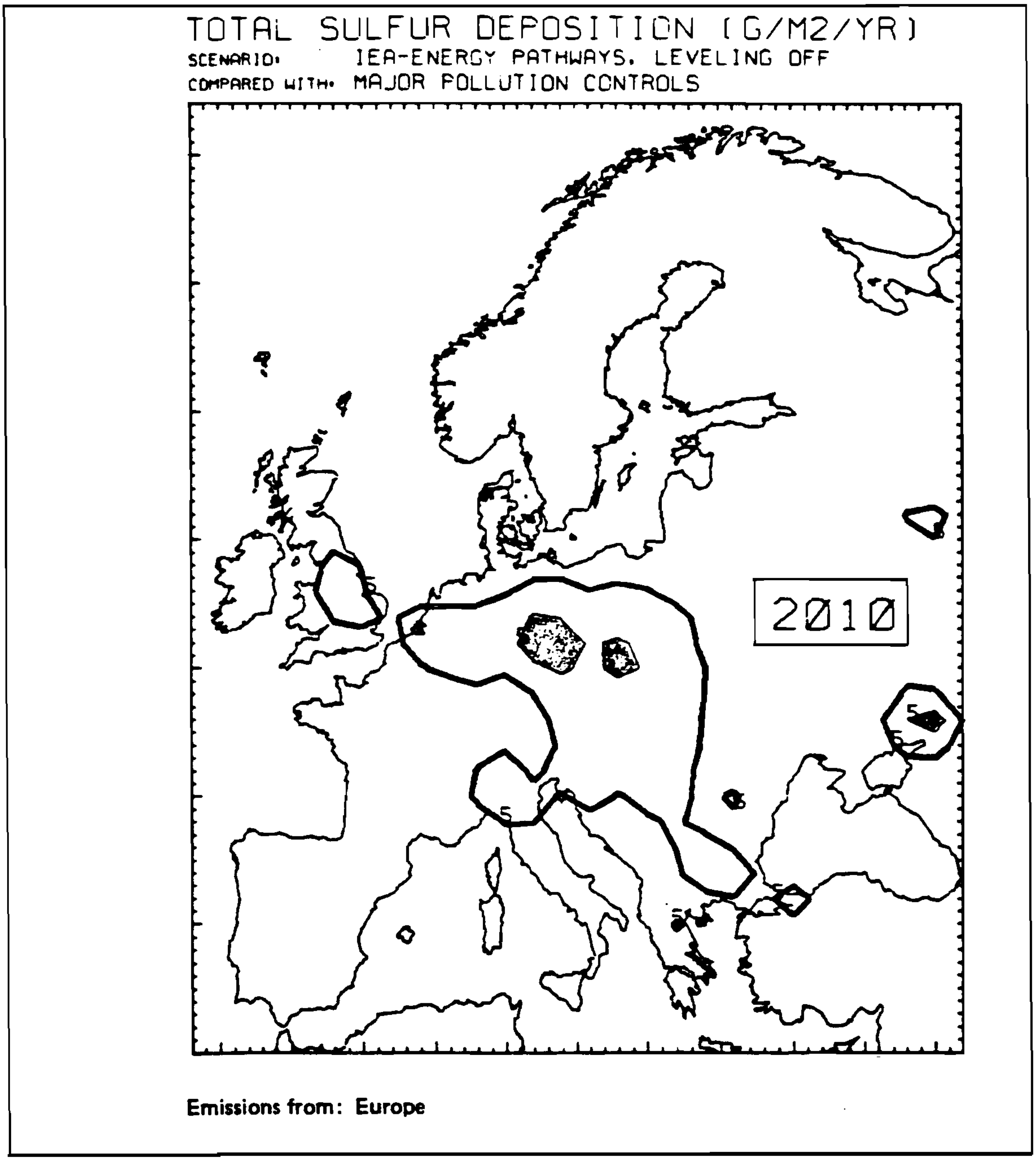

Figure 6. Computer Generated Schematic Map of Europe Showing Areas With Moderate Sulfur Deposition Levels (5 $g/m^2/yr$) Resulting From Energy Emissions, 2010.

energy) are almost certain to reduce emissions. The ways in which changes in energy use rates would alter CO_2 emissions have been explored in numerous studies. (See, for example, Edmonds and Reilly, 1983, 1985; Ausubel and Nordhaus, 1983; Perry *et al.*, 1982.)

The second energy management option concerns the share of fossil fuels in the total energy budget. Replacing fossil fuels by solar, nuclear, sustained yield biomass, or exotic forms of noncarbon energy will all limit emission releases to the atmosphere. Both the Edmonds–Reilly and Nordhaus–Yohe studies referred to above provide perspectives on the impact this would have on the CO_2 problem.

The third energy management option concerns the share of various fossil fuels in the total fossil fuel budget. In the case of CO_2, natural gas and oil produce about 60 and 80 percent, respectively, as much CO_2 as coal. Synthetic fuels derived from coal require energy expenditure in their production and therefore yield around 150 percent as much CO_2 as coal (Marland 1982), unless the processing energy is derived from nonfossil sources. Natural gas combustion produces essentially no sulfur emissions and from that viewpoint is considered environmentally more attractive than oil and coal.

A fourth class of responses to emission control involves abatement measures for the post-combustion process. As Thomas Schelling (1983:563) puts it... "If we cannot help producing too much, can we remove some?" Several technologies (e.g., scrubbers) are now available, restricted mainly to use on large-scale fuel combustion systems like electrical power utilities. While such techniques can reduce the level of energy-based emissions, they cannot eliminate them. Moreover, there are enormous costs associated with such measures, particularly when a high level of reduced emissions is required. The case of lignite use for electricity generation in the Federal Republic of Germany, following the establishment of stringent SO_2 emission standards, underscores the difficulties one can expect with such practices (Der Bundesminister des Inneren 1983). The concept of integrated energy systems has been advanced as a technical option that, in principle, can eliminate sulfur and nitrogen emissions and keep the problem of CO_2 emissions in focus (Häfele and Nakicenovic 1984, Häfele *et al.* in press). We will discuss this novel approach to environmentally benign energy systems in the next section, when we take up the issue of strategic energy management.

5. R&D STRATEGIES FOR ENERGY MANAGEMENT

Throughout our discussions we have stressed that the process of energy substitution is essentially a competitive process whereby a successful energy technology is able to comply with end-use demands for increasingly more efficient, cleaner, and flexible forms of energy. We have indicated the strong probability of an increasing reliance on fossil fuels and nuclear energy over the next few decades. We now explore two broad R&D strategies that could help governments and industries to exploit these energy forms in line with these consumer demands.

Technology Life-Cycles: The Case of Methane Technologies

It is well known that many industries and resource production sectors are plagued by overcapacity problems. World steel mills, automobile plants, steam turbine/generator factories, heavy construction equipment factories, and home appliance plants are prominent examples of industries troubled by overcapacity of a factor of two to five. Recent phenomenological evidence suggests that overcapacity and industry maturity occur almost simultaneously (Marchetti 1980, 1983a, 1983b; Nakicenovic 1986; Nakicenovic in press).

Why do managers flagrantly overbuild plants at the end of an industry's growth cycle? The roots of the problem appear to lie in the lack of perception of the phase of saturation in the so-called life-cycle of technology and business. Here we briefly describe a new research effort at IIASA that could yield valuable insights about measuring and controlling the life-cycle process and appropriate management responses.

Technology and business are assumed to undergo three distinct life-cycle phases (Figure 7). The first phase is embryonic, characterized by chaotic competition among numerous experimental technologies that are struggling to emerge the winner. Once beyond this high-risk phase, the successful technology enters a phase of exponential growth in which generally it competes with an older technology to provide a similar service or product. The learning curve becomes a valuable tool for analyzing this growth phase, which typically involves decreasing costs and improved performance. Maturity defines the final phase, during which improvements are incremental and costly and demand eventually saturates. A mature technology is seriously challenged by new competitors that are entering their own exponential phase of steady growth prospects.

We have a number of case studies underway of technologies at various stages in the life-cycle, ranging from mature technologies (e.g., coal extraction and Bessemer steel), to those in the growth phase (e.g., automobiles and aircraft), to emerging technologies. Methane-related technologies are a prime example of an emerging technology cluster that has a high potential for success. IIASA energy specialist Ed Schmidt considers the situation for methane-related technologies to be analogous to that of aircraft engineering and the aviation industry in the 1930s: since the middle of the 1930s until today, aviation technology has improved roughly by a factor of one hundred. Specifically, the Boeing 747 is about 100 times more productive than the DC-3, measured in terms of ton-kilometers per hour and operating over comparative routes. Operating over "non-comparative" routes, i.e., intercontinental routes, the 747 is infinitely more productive. The DC-3 simply cannot operate from New York to London, or Tokyo to Frankfurt. If one were to have used the performance of the DC-3 in the 1940s as the basis for predicting

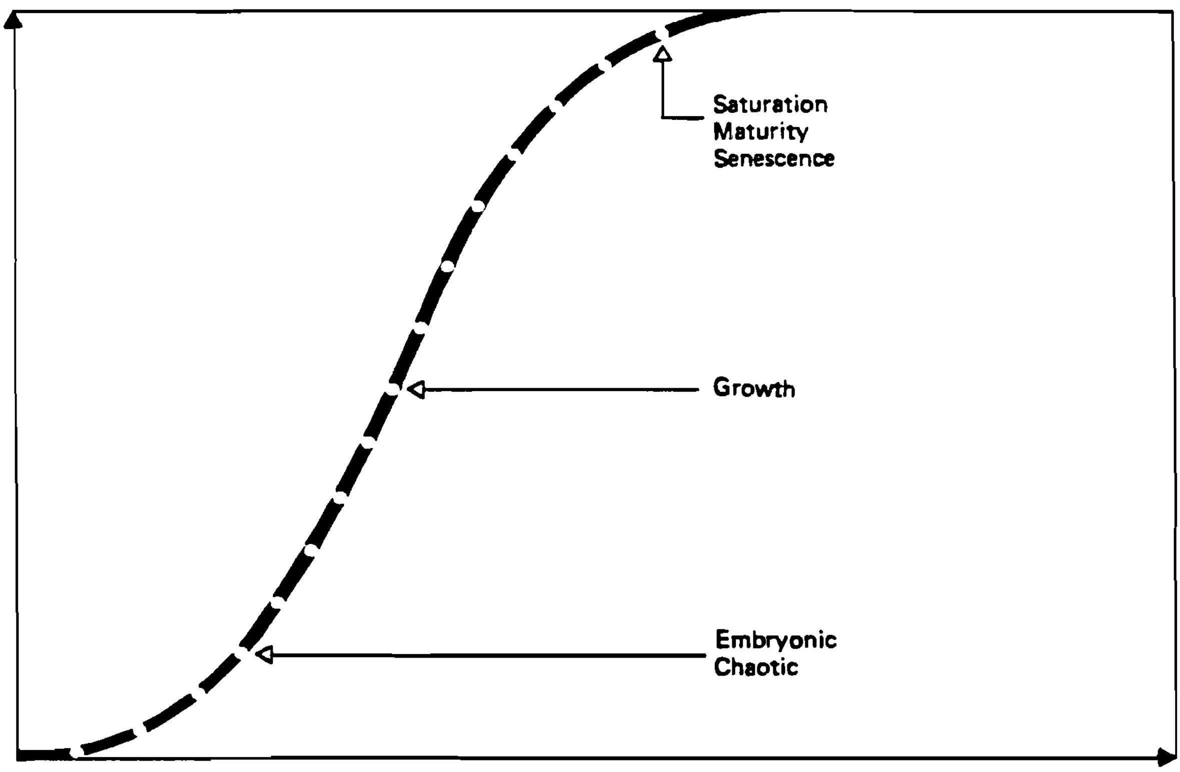

Figure 7. Technology Life-Cycles.

the future of commercial aviation, undoubtedly the answer would have been wrong.

There is increasing evidence that at the point where a technology is on its life-cycle there also exist other interdependent phenomena. These include technical performance, price, cost, market share, industry structure, spatial shift of leadership position, management and investment issues. If IIASA's forecasts about the growing importance of methane is to be realized, the set of methane-related technologies will have to move along the life-cycle rapidly in the decades to come.

The problems associated with the expanded use of natural gas on a global scale have been defined. For example, natural gas is more difficult to transport over transcontinental distances, than, say, crude oil and its refined products. The main reason is that methane is gaseous at ambient pressures and temperatures. As a result, natural gas is invariably associated with the need for elaborate infrastructures for long distance transport, storage, and distribution. In its gaseous form, natural gas cannot be stored in compact reservoirs, constraining its use currently to stationary devices with direct communications to grid systems. Thus primary applications of natural gas have been in the industrial, residential, and commerical sectors, with very little natural gas being used for the transport sector. On the supply side, natural gas is transported by two technologies – pipelines, generally for continental links, and LNG (liquefied natural gas) vessels, mainly for intercontinental links. Pipelines, LNG vessels and facilities, as well as distribution grids are highly capital intensive; once installed they represent a commitment during the lifetime of the plant which is in the order of 15 to 20 years or more.

Will these obstacles be overcome as methane-related technologies evolve and progress along the life-cycle curve? We are exploring this issue, analyzing a group of methane-related technologies from the dynamic perspective. Among the technologies being studied are search and exploration techniques, such as geophysical and geochemical methods, high-speed drilling with continuous coring, the use of downhole motors with electronic guidance packages and direct communication with the surface via the MWD (measurement-while-drilling) techniques; more efficient technologies for transport via pipelines, LNG vessels; and conversion and end-use technologies, such as catalytic conversion of methane into clean liquid fuels at ambient temperatures and high-performance combined cycle gas turbines for electricity generation.

This represents a formidable task that necessarily involves close working relations with industry and researchers around the world. For example, we are collaborating with the Gas Research Institute (GRI) in the United States that recently began research on technologies for finding and producing nonassociated methane and for exploring the possible locations of abiogenic methane. Similar work is underway at the University of Tokyo. Indeed, the prime example of scientifically confirmed production of nonassociated methane is that from the Niigata Basin on the West Coast of Japan. Close contacts are also being maintained with Thomas Gold of Cornell University concerning new theories of methane formation and location. IIASA's Ed Schmidt and Professor Gold visited the Siljan Crater in Sweden, the site of an experimental drilling effort to produce abiogenic methane from a 350 million year old meteor impact crater in the Baltic Shield; production drilling will begin in summer. Other research groups include the University of Southern California in the United States and the University of Trondheim in Norway, both of which have major R&D efforts underway for the direct catalytic conversion of methane into room temperature liquid fuels. As to conversion technologies, we are working with the Massachusetts Institute of Technology (MIT) that has a major effort underway with the General Electric Company and the Electric Power Research Institute (EPRI) to analyze the technology growth patterns and resulting market impact for combined cycle gas turbines. The findings of their analysis (the so-called EGEAS study) suggest that, even at today's energy prices and with existing technology, in most parts of the United States the use of methane for electricity generation in combined cycle systems would be more economic than is the case for either oil- or nuclear-based electricity generation systems (Tabors and Flagg 1985). Moreover, with the use of the advanced technology in combined cycle systems, the results are even more dramatic. In the Soviet Union, IIASA's partners include the Siberian Energy Institute, the Presidium of the USSR Academy of Sciences, and V/O Soyuzgazexport. In May, IIASA will hold an international meeting in Hungary on methane-related technologies. The Hungarian Committee for Applied Systems Analysis is helping to sponsor the event, which is expected to add considerable momentum to our work.

Integrated Energy Systems

We now consider a novel approach to an energy system that, in principle, can ultimately achieve the goals of zero emissions and enhanced system efficiency and flexibility. The concept of integrated energy systems (IES) has been developed over the past four years by the Kernforschungsanlage Jülich (KFA) in the FRG, and MIT in an effort to identify a whole set of energy sources that can support a smooth transition to the so-called second generation of fossil fuels and nuclear energy technologies. In this way, the IES is evolutionary and able to take into account the inherent uncertainty of accurately predicting which fuels will dominate future energy systems. The basic idea behind such a system is to use varying inputs of different primary energy sources to provide a flexible range of clean fuels, industrial gases, process heat, and electricity. One of the important features is the carefully controlled and environmentally acceptable upgrading of "dirty" (low hydrogen content) fossil fuels into "clean" (hydrogen rich) fuels. The idea is captured in Figure 8, and has been discussed in detail in several publications. (See, for example, Häfele *et al.* in press; Häfele and Nakicenovic 1984; Lee 1983; Lee *et al.* 1983.)

There are a whole set of technologies associated with the IES concept that are either well advanced or in hand. These include the following:

- Steam reforming for fuel decomposition (see, for example, Singh *et al.* 1984)
- High temperature reactors for process heat generation (see, for example, Barnert *et al.* 1984; Singh *et al.* 1984; Nickel *et al.* 1983; Lee *et al.* 1983)
- High performace gas turbines (see, for example, Tabors and Flagg 1985; Smith and El-Masri 1981; Magnusson 1982)
- Air separation systems
- Separation systems for synthesis gas (CO from H_2)
- Ammonia production

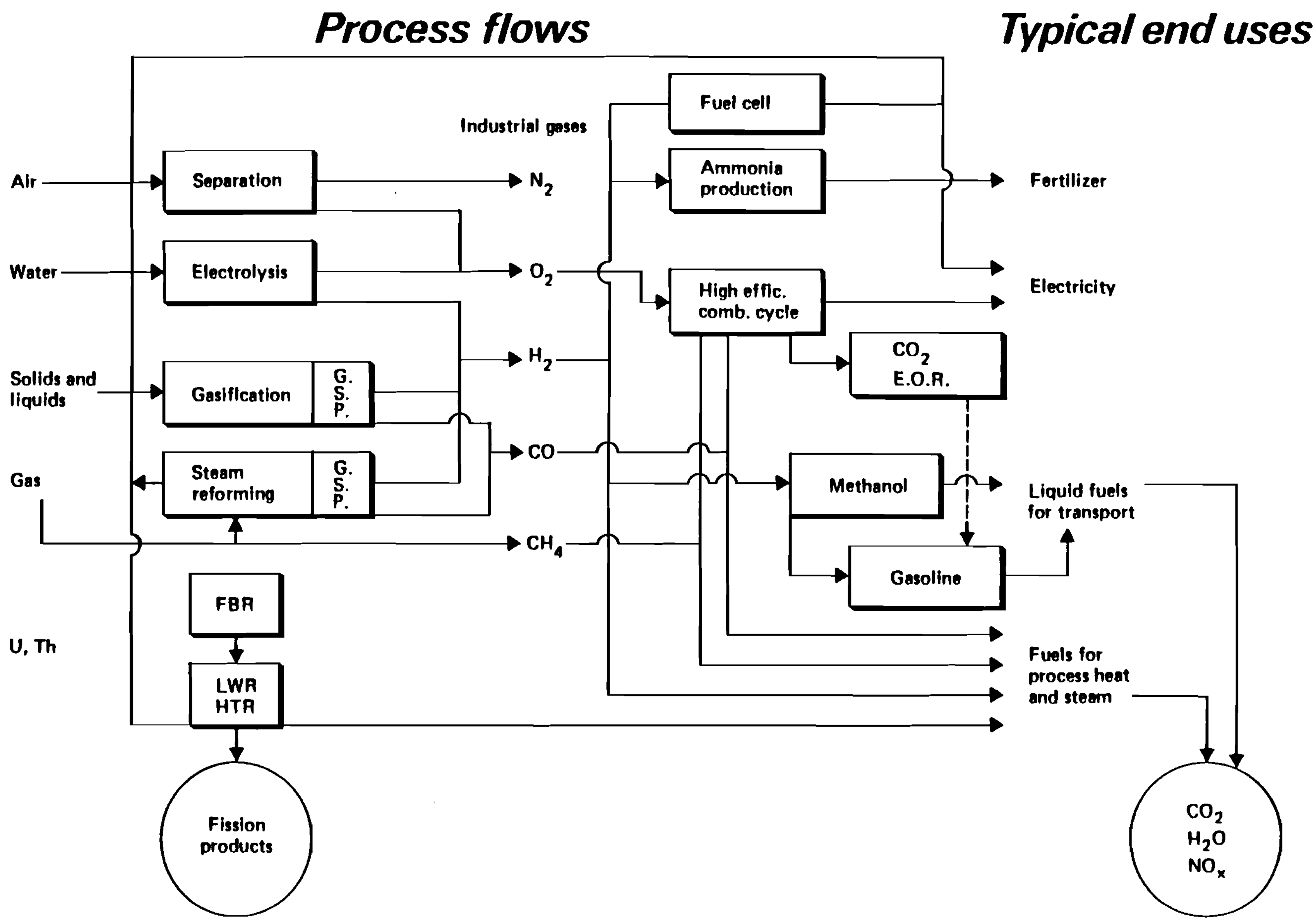

Figure 8. Concept of Integrated Energy Systems (Lee *et al.* 1983).

- High temperature electrolysis for splitting water (see, for example, Nürnberg *et al.* 1983; Dönitz *et al.* 1980)
- Steam coal gasification (see, for example, von Bogdandy 1983; Kirchhoff *et al.* 1984)
- Hydrogen coal gasification (see, for example, Scharf *et al.* 1984)
- Molten iron bath (see, for example, Klöckner-Werke-AG 1983; KHD Humboldt Wedag 1985)
- Texaco process of converting hard coal to fuel gas and methanol (see, for example, Guy *et al.* 1980)
- Enhanced oil recovery with CO_2 and other techniques for CO_2 disposal
- Fuel cells

The technical feasibility of the IES concept is not in doubt. Advances in technology are expected to expand system applicability. Starting with today's most popular IES-type system – co-generation – one can trace a number of evolutionary technical scenarios that can lead ultimately to zero emission systems (e.g., high temperature electrolysis and hydrogen-fed fuel cells). Moreover, the economic feasibility of the IES is not a basic issue. For example, combined cycle and co-generation systems as well as combined ammonia production and CO_2 enhanced recovery systems are established commercial technologies. Essentially the IES concept provides a systematic way of describing dominant trends in energy systems. But by viewing energy developments through the lens of this concept, we gain a perspective on strategies for R&D planning and for overcoming possible shortsighted institutional and social barriers that could impede the gradual introduction of an energy system that can satisfy society's demand for cleaner, more efficient and flexible energy sources.

Toward this end, IIASA is working with an increasing network of institutions that includes the Kernforschungsanlage-Jülich; MIT; the Siberian Energy Institute, Soviet Union; the Energy and Mines Research Organization, Taiwan; the Atomic Energy Research Institute, Japan; and the University of Oklahoma, United States. Work recently began on a three-stage analysis of system aspects and performance, institutional and organizational factors associated with the development of the IES concept, and case studies of specific features of introducing the system concept in both market and planned economies.

6. CONCLUSIONS

IIASA, as an international institute, has necessarily devoted a significant fraction of its resources for studying the global issue of energy development. More than seven years have passed since the completion of IIASA's global energy analysis (*Energy in a Finite World*), and it seemed appropriate to look back at some of the findings of this pioneering effort and what these suggest about future pathways.

In sum, we have seen that energy substitution is essentially technology substitution – an evolutionary process operating within a time frame. As energy systems evolve over the next few decades, there will be an increasing role for methane and nuclear energy, as well as a heavier reliance on low-grade fossil fuels. Given the environmental risks associated with the expanded use of fossil fuels, strategies need to be put in place now to advance environmentally benign energy systems.

We believe that the challenges posed by these developments can be met. Specifically, it is possible to move in an evolutionary way toward energy systems that satisfy societal demands for cleaner, safer, and more productive energy sources. This belief is reflected in IIASA's commitment to environmental research, to the newly launched studies of technology dynamics and life-cycles, and to our active involvement in advancing the concept of integrated energy systems.

There is yet another dimension to the global issue of energy that we believe has not yet received sufficient attention. In the past, international exchanges in the field of energy have centered mainly on trade – be it crude oil exports from the Middle East and North Africa, or coal resource shipments from Australia, the Soviet Union, and the United States. But with the spread of technology advances in many countries, we have entered a period of greater interdependence that offers vast opportunities to combine national strengths for global well-being. There are many possibilities for the world's leaders in energy technologies to work more closely together – be it on drilling technologies in the Soviet Union and the United States, on combined cycle systems in Japan and the United States, on coal gasification schemes in Japan, the FRG, Sweden and the United States, or on methane conservation techniques in Norway and the United States. Indeed, no one country can claim intellectual exclusivity, nor can or should the benefits of technology be confined within national boundaries.

It is in this spirit that we have sought to provide a strategic perspective on how natural resources and energy systems could contribute to a more peaceful world.

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