A Global End-Use Energy Strategy

Robert H. Williams[a]
Amulya K.N. Reddy[b]
Thomas B. Johansson[c]
Jose Goldemberg[d]
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[a] Senior Research Scientist, Center for Energy and Environmental Studies
Princeton University

[b] Professor of Inorganic and Physical Chemistry
Indian Institute of Science
Bangalore, India
(Visiting Senior Research Scientist, Center for Energy
and Environmental Studies, Princeton University,
during the preparation of this paper.)

[c] Professor of Energy Systems Analysis
Department of Physics and Environmental Studies Program
University of Lund
Lund, Sweden

[d] President, Companhia Energetica de Sao Paulo (CESP)
Sao Paulo, Brazil

[e] Research Associate, Center for Energy and Environmental Studies
Princeton University

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Center for Energy and Environmental Studies
Engineering Quadrangle
Princeton University
Princeton, N.J. 08544

SUMMARY

If the energy problem is approached not as the challenge of expanding supplies but as one of providing energy services in the most cost-effective ways, it is possible to identify a long term global energy strategy consistent with and supportive of solutions to other important global problems with strong links to energy -- the most pressing of which include the global economic crisis, North/South conflicts, widespread poverty in developing countries, population growth, food scarcity, the risk of global nuclear war, nuclear weapons proliferation, man's role in changing global climate, and deforestation and desertification.

Despite the fact that the world is now moving into an era of more costly and scarcer energy supplies, the availability of energy need be a constraint neither on the development of developing countries nor on the continued prosperity of already industrialized countries, because it appears to be both technically and economically feasible to evolve a much more prosperous world over the next several decades with about the same level of global energy use as today. This is possible because of ongoing structural shifts in industrial economies to less energy-intensive activities and because of major opportunities in industrialized and developing countries alike for making make more efficient use of energy. Much flexibility in energy supply planning is gained when demand is not growing; it thereby becomes possible to avoid many serious problems posed by heavy dependence on oil, fossil fuels generally, and nuclear power, and by the present nonrenewable use of bioenergy resources.

1 INTRODUCTION

At the present rate of consumption, the world's remaining oil resources that can be ultimately recovered are generally believed to amount to less than a 100 year supply. Two thirds of these resources are located in Middle East/North African (ME/NAf) countries and in countries with centrally planned economies (1.A). The amount left in the rest of the world is about a 40 year supply at the present rate of consumption there (1.A). These numbers indicate the ephemeral nature of the present oil glut and highlight the need to begin the global transition from oil.

The half of the world's people who are dispersed in rural areas of developing countries are also caught up in an energy crisis, even though oil plays only a minor role in their lives. Here people are largely dependent for energy on biomass -- mainly fuelwood used for cooking. A "fuelwood crisis" has arisen because in many areas increased fuelwood demand associated with population growth is exceeding the rate of fuelwood regeneration via photosynthesis. It has been estimated by the FAO that about 100 million human beings now suffer "acute scarcity" of fuelwood; and about 1 billion a "deficit" (Forestry Department, FAO, 1981). Fuelwood-gathering involves many hours of drudgery each day, particularly by women and children. The ecological effects of deforestation created by excessive fuelwood use are amplifying this human toil.

These oil and fuelwood supply issues show clearly that energy is a major global problem. But energy is only one of several important global problems, the most pressing of which include the global economic crisis, North/South conflicts, widespread poverty in developing countries, population growth, food scarcity, the risk of global nuclear war, nuclear weapons proliferation, man's role in changing the global climate, and deforestation and desertification. If mankind is to achieve a sustainable world society for the long term, each of these problems must be resolved. All these problems have strong links to energy. If solutions to the energy problem are pursued without consideration of the relationships to these other problems, the other problems could be aggravated.

The present analysis explicitly recognizes these links and seeks to identify a long term global energy strategy which supports, or at least does not conflict with, solutions of other important global problems. More generally, our analysis seeks to articulate the dimensions of a long run energy strategy that is compatible with considerations of equity, economic efficiency, environmental soundness, human welfare in the long term, self-reliance, and peace -- the key features of a sustainable world society.

2 THE ROLE OF ENERGY IN SOLVING OTHER GLOBAL PROBLEMS

To begin the analysis, the links to energy of the above mentioned problems are identified and potential contributions to their resolution from energy planning are indicated.

The Economic Crisis: The last decade has been a period of rampant inflation, major global recessions, widespread unemployment, soaring real interest rates, and an associated international debt crisis which could lead to collapse of the global financial system if hard-pressed debtors of the developing world fail to discharge their debts.

Costly energy has been a major contributing factor to these problems. The oil price shocks of the 1970s were directly responsible for slowing economic growth, spurring general inflation, and sending the oil import bills of many developing countries soaring to the point where imports now account for 50% or more of export earnings. Also, new energy supplies are generally far more costly to develop than energy supplies now being used: for example, between 1972 and 1982 capital expenditures on energy supply in the US rose from 25% to nearly 40% of all new plant and equipment expenditures. Committing so much capital to energy supply makes capital scarcer for other economic activities.

Energy planning can contribute to improved economic efficiency and well-being if energy costs can be brought under control. This can be accomplished if energy planning is focussed on ways to provide energy services (for space conditioning, lighting, mechanical work, mobility, etc.) at the least total social cost. The direct monetary costs of providing such services can often be reduced by investments in energy efficiency improvement (T. B. Johansson and R. H. Williams, 1985). This can also mean a lower world oil price, if world oil demand remains sufficiently low that tight world market conditions can be avoided (see Figure 1)*. Prices would be lower for other energy forms as well, to the extent that costly new energy sources are not needed.

North/South Conflicts: Poor countries of the "South" account for 3/4 of the world's population but have per capita incomes which are on average only 1/10 as large as in the rich countries of the "North." This income disparity is a crucial factor responsible for the grave and worsening

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* A distinction should be made between the world oil price and the price the consumer sees for oil products. It may be desirable to impose a tariff on imported oil or taxes on oil products that would have the effect of making consumer prices constant or slowly rising over time in real terms, as an alternative to the bumpy oil price trend of the last decade.

crisis characterizing the world economy. Problems such as deteriorating commodity prices, Northern protectionist barriers against the emerging manufacturing industries of the South, and the vulnerability of Southern debtors to rising interest rates because of their dependence on variable rate loans have put developing countries at a disadvantage in the global marketplace.

The solution to North/South conflicts is to work toward eradicatation of the disparities that give rise to the conflicts, by means of policies that foster the development of developing countries -- including policies that would help make affordable the energy needed to meet development goals.

Poverty in Developing Countries: Not only are "North/South" disparities large, but within developing countries there are enormous disparities between the the elites, which typically account for 10% of the population and 1/3 to 1/2 of all income, and the rest of the population who live in abject poverty. The traditional approach to tackling this problem of widespread poverty by maximizing economic growth and expecting the benefits of growth to "trickle down" to help the poor has failed.

A policy targeting the satisfaction of basic human needs (BHN) for food, shelter, sanitary services, health care, education, and providing meaningful employment is more promising. Satisfying these needs requires energy services. Providing these services must be a goal of development efforts.

Population Growth: The population explosion is closely linked to the problem of poverty, since the economics of large families tend to be favorable for the poor (The World Bank, 1984). Thus efforts to solve the population problem will be assisted by targetting the satisfaction of the

BHN of the poor.

Food Scarcity: Whatever success is achieved in slowing population growth, the problem of feeding an expanding population will remain a major global challenge for decades. Modernization of agriculture and the associated increased energy inputs are key to meeting increased food production goals. The FAO has estimated that food production in developing countries must double by 2000, for which extra energy equivalent to 2.8 million barrels of oil per day is required (FAO, 1981). As this is less than the amount of oil saved by the US alone between 1978 and 1982, it is clear that the challenge has less to do with the quantity of energy required than it does with ensuring that supplies are available for meeting agricultural needs.

The Risk of Nuclear War: That conflict in the Middle East can draw in the superpowers and threaten nuclear war is indicated by the experience of October 1973, when the Soviet Union threatened to intervene in the Arab-Israeli War, and the US, in response, raised the alert status of its nuclear forces (B.M. Blechman and D.M. Hart, 1982). The creation of the US Rapid Deployment Force to assure continued access of the industrialized market economies to Persian Gulf oil and the presence of mobile Soviet forces in the region indicate the continuing potential for US/Soviet conflict arising from Middle East turmoil. The potential for superpower conflict can be reduced if the industrialized market economies become less dependent on Persian Gulf oil.

Nuclear Weapons Proliferation: In 1964 the US, the USSR, France, and Great Britain were the only nuclear weapons states in the world. Since then, China and India have acquired nuclear weapons, and several other countries either have already gained or soon will have the capability to produce nuclear weapons. In the coming decades many more countries could join the "nuclear club" -- particularly if nuclear power comes to be a major energy resource.

An indissoluble link between nuclear weapons and nuclear power arises from the fact that plutonium, a nuclear weapons-usable material, is produced in substantial quantities in nuclear power reactors. There is no technical fix for eliminating this link.

The proliferation risk increases enormously if plutonium is recovered from spent reactor fuel and is recycled in fresh fuel. If a non-nuclear weapons state acquires plutonium recycle technology, it thereby obtains nearly all the technology and materials needed to make nuclear weapons quickly, <u>without ever having to make an explicit decision to acquire nuclear weapons.</u> This route to nuclear weapons, which has come to be called "latent proliferation" (H.A. Feiveson, 1978), is a particularly dangerous route to proliferation, involving low risk to the would-be proliferator.

The risk of proliferation can be greatly reduced if nuclear fuel cycles which involve the reprocessing of spent reactor fuel and the recycle of the recovered plutonium are avoided. Such fuel cycles must be avoided in all countries, as any two-class system which discriminates against countries judged to be proliferation-prone would prove ultimately to be unstable (H.A. Feiveson and J. Goldemberg, 1980).

Reprocessing and plutonium recycle can be avoided for many decades even with considerable expansion of nuclear power, because these activities offer no significant economic advantage until the uranium price is several-fold larger than at present (R.O. Sandberg and C. Braun, 1984), and because large world uranium resources are available at uranium prices competitive with plutonium recycle (W.H. Donnelly <u>et al.,</u> 1984).

Avoiding reprocessing would greatly reduce but would not eliminate the proliferation risk. A country determined to acquire nuclear weapons could do so by various means, and "once through" fuel cycles offer access to large quantities of plutonium in the spent fuel discharge -- e.g, a 1000 Mw(e) pressurized water reactor discharges in its spent fuel each year about 140 kg of fissile plutonium, enough to make some 20 nuclear weapons. This plutonium could be recovered in clandestine or quickly constructed fuel reprocessing facilities. For this reason, it would be safer still if nuclear power did not become too widely used in the world -- i.e., if nuclear power were regarded as an energy technology of last resort.

Technological constraints on the scope and character of nuclear power programs must be complemented by measures to reduce the political motivation of countries to acquire nuclear weapons. As long as the superpowers continue to feel that their security is enhanced by having nuclear weapons, other nations will want nuclear weapons as well. The only way to avoid a world in which nuclear weapons are widely proliferated is to couple the avoidance of dangerous nuclear power technologies with superpower efforts to move away from dependence for their security on weapons of mass destruction (H.A. Feiveson and J. Goldemberg, 1980).

Global Climatic Change: In a matter of decades man could bring about major changes in the global climate because of activities leading to the build-up in the atmosphere of carbon dioxide and the resulting "greenhouse effect." The problem is closely related to energy because the major source of this build-up is the burning of fossil fuels. Already in 1979 the atmospheric

CO2 level was 1.15 times the pre-industrial level or 334 ppm. Climatologists believe that with a doubling of the CO2 level there would be an increase in the global temperature of 3 ± 1.5 °C and perhaps a two- to three-fold greater warming at the poles; the slowdown of the "atmospheric heat engine" associated with the differential equatorial/polar heating rates is expected to lead to significant changes in global weather patterns (Carbon Dioxide Assessment Committee, 1983).

There appear to be no feasible technical fixes for the CO2 problem (W.W. Kellogg and R. Schware, 1981). The magnitude of the prospective climatic change can best be reduced by not being too dependent on fossil fuels.

Deforestation and Desertification: Between 1952 and 1972 the world's forests were lost at an annual average rate of some 30 million hectares per year (B. Bolin *et al.,* 1979), while cropland and rangeland losses to desertification averaged 6 million hectares per year (M.R. Biswas, 1978). Deforestation is associated in part with the nonrenewable harvesting of fuelwood; desertification in large part with the overuse of marginal lands for agricultural purposes, especially the grazing of livestock. Efforts are needed to reverse these trends -- for both environmental and economic reasons. Fuelwood resources could be used renewably if demand levels where maintained below the regeneration rate via more efficient use of biomass and via increased production through better forest management. The trend toward desertification could be eased if agricultural production, including the grazing of livestock, were shifted from marginal to better lands, via use of modern energy-intensive agricultural techniques -- a hopeful prospect since only about 1/3 of all cropland is farmed with heavy farm machinery and since, on average, fertilizer usage per hectare in developing countries is just 40% as great as in industrialized countries (D. Pimentel *et al.*, 1985).

The Treatment of These Problems in Other Global Energy Analyses:

Traditionally, analysts who have dealt with the long term global energy problem have not sought to identify energy strategies compatible with the solutions of these other important global problems. Although some recent analyses have explored the impacts of particular energy supply constraints on the long term future of energy (2.A), the energy problem has usually been viewed as the rather narrow engineering challenge of bringing forth enough new energy supplies in ways energy suppliers know best, to meet estimates of future energy needs based on extrapolations of crude historical correlations of levels of energy use and human welfare. Long range projections of future global energy requirements made in recent global energy studies by the World Energy Conference (WEC) (J. -R. Frisch, 1982), and the International Institute for Advanced Systems Analysis (IIASA) (Wolf Haefele *et al.*, 1981), are based on this conventional approach to energy. The supply orientation of these studies is evident in that these studies indicate that energy requirements will increase some 2- to 3 -fold in the period 1980 to 2020. These projections present a view of the global energy future which involves major shifts to coal and nuclear power, an emphasis which takes advantage of the abundance of coal and nuclear fuels. But in a world where these projections would be realized, other important global problems would be exacerbated.

The projections for future fossil fuel use made in the WEC and IIASA studies imply that the atmospheric carbon dioxide level would double in the latter half of the 20th century. The nuclear power projections in these studies imply a serious nuclear weapons proliferation risk; for example, the IIASA nuclear projections imply that by 2020 there would be some 1.8 to 3.0 million kg of plutonium recovered from spent reactor fuel and circulated each year in global commerce; for comparison some 5-10 kg is required to make a nuclear weapon.

These analyses also fail to give adequate attention to the unique problems of developing countries. While the centralized energy technologies emphasized in conventional energy planning may be applicable to certain urban situations, solving the energy problem of rural areas will require quite different strategies. More decentralized solutions, involving energy supplies suitable for widely dispersed industries, are needed for rural areas, as the cities are increasingly unable to accommodate with jobs and public services the large numbers of people now migrating to cities.

3 THE END-USE APPROACH TO THE GLOBAL ENERGY PROBLEM

In an ongoing global energy project an attempt is being made to develop a long term energy strategy that is both technically and economically feasible and consistent with the achievement of a sustainable world society, for both industrialized and developing countries (J. Goldemberg, T.B. Johansson, A.K.N. Reddy, and R.H. Williams, 1985). The present paper explores global aspects of this energy strategy.

We have found that to identify such an energy strategy it is necessary to shift the focus of energy analysis from supply to demand, and to give attention instead to energy services. The "end-use approach" helps in understanding the extent to which the energy services needed to satisy BHN are being met (J. Goldemberg, T.B. Johansson, A.K.N. Reddy, and R.H. Williams, 1985) and the implications for energy services requirements of ongoing structural changes in the economy (T.B. Johansson and R.H. Williams, 1985). Moreover, understanding better the details of how energy is used, by whom and why, can lead to the discovery of opportunities for cost-saving improvements in end-use technologies (T.B. Johansson and R.H. Williams, 1985). The end-use approach makes it possible to identify the least costly mix of energy supplies and investments in efficiency improvements for providing a given level of energy services.

If the opportunities for energy demand reduction identified this way are exploited, flexibility is gained in energy supply planning to choose an energy supply mix that mitigates the externalities posed by overdependence on oil, fossil fuels, and nuclear power, and by nonrenewable use of biomass, because the lower the overall level of energy demand, the greater the number of energy supply options. At high demand levels (as in the WEC and IIASA projections for the period beyond the turn of the century) essentially all available supply options must be pursued to the limits.

A comprehensive global perspective on energy demand/supply based on the end-use approach should be developed as an evolutionary process, "from the bottom up." The analysis should begin with country studies that examine the ways energy is used and provided today and possible future patterns of demand for energy services, taking into account factors such as climate, demography, the mix of economic activity, social aspirations, etc. Then opportunities for deploying alternative end-use technologies and alternative energy supplies for meeting future needs for energy services should be described. Such studies could provide the basis for formulating long term energy strategies for countries that are consistent with long term social goals. Individual country strategies should then be aggregated into regional strategies, which in turn should be aggregated into a global strategy.

While it is not yet possible to put together a global energy strategy according to this idealized prescription, since detailed country studies and country strategies have been developed via the end-use approach for only a few countries, it is nevertheless feasible to formulate a preliminary global energy perspective based on extrapolating to the global situation what is known for a few countries.

4 A BASE CASE ENERGY DEMAND/SUPPLY SCENARIO

We shall now construct a base case global energy demand/supply scenario to illustrate our finding that there are energy futures that are both technically and economically feasible which lie far outside the range of outcomes forecast in conventional global energy studies, yet are both compatible with economic aspirations and responsive to concerns about a broad range of other global problems that would be exacerbated by conventional energy strategies.

Our scenario should be viewed not as a forecast of what the global energy future will be but rather as an argument that it is feasible to evolve an energy future compatible with the achievement of a sustainable world society. The scenario we describe is by no means unique in this regard. Rather it involves a set of plausible assumptions showing what can be accomplished via energy demand and supply technologies which are already proven or are in an advanced state of development. With this analysis we hope to provide a more informed basis for the decision-making process relating to energy planning, by articulating important but largely unfamiliar choices for the energy future, and by showing that <u>the future of energy demand/supply is more a matter of choice than of prediction.</u>

On the demand side our global scenario involves extrapolating: to all industrialized countries the results of our analyses for Sweden and the US; to all developing countries the results of our analysis for an hypothetical developing country, as described below. On the supply side this scenario attempts to avoid or mitigate the serious energy supply-linked global problems described above.

In our energy scenario we focus on the year 2020. This date is sufficiently far in the future that there would be ample time to carry out programs aimed at the satisfaction of basic human needs in developing countries and to achieve considerable improvements in living standards beyond the satisfaction of basic human needs. There would also be ample time for the widespread adoption of the kinds of energy-using technologies emphasized in this book. It is also a time by which the world should be well into the transition to the Post-Petroleum Era, and by which the carbon dioxide problem associated with continued reliance on fossil fuels and the nuclear weapons proliferation problem associated with large-scale expansion of nuclear power would reach critical proportions if conventional energy strategies were pursued. Yet the date is sufficiently close that it has an important bearing on long range energy planning today.

Our analysis is but a first step toward determining how a supply mix compatible with our global goals at the projected energy demand levels might be put together. Because the energy demand/supply balances associated with this exercise are highly aggregated at the global level, our analysis necessarily neglects regional variations in energy demand and supply availability, and thus sheds no light on the problems of how particular energy resources concentrated in particular locations might be made more widely available geographically. Detailed country and regional studies are needed to provide a basis for dealing with such problems.

4.1 Energy Demand

Future Per Capita Energy Demand in Industrialized Countries: Major responsibility for the global risks associated with conventional energy supplies described above lies with the industrialized countries, on account of their heavy appetite for energy. With only 1/4 of the world's population, today these countries account for 2/3 of world energy use.

Fortunately, however, it is feasible to bring about a large reduction in the energy intensity of economic activity in the industrialized world. One important factor bearing on future energy demand is the phenomenon that the industrialized world is making a transition to the Post-Industrial Era, which is characterized by growth activities which are inherently less energy-intensive than economic activities of the Industrial Era. Superimposed on this changing demand structure is the potential for radically improving the efficiency of energy use, as shown in (T.B. Johansson and R.H. Williams, 1985).

We now present a base case energy demand scenario for the industrialized world which takes into account such considerations, extrapolated from the results we have obtained for two countries: Sweden

(T.B. Johansson, P. Steen, E. Bogren, and R. Fredricksson, 1983) and the United States (R.H. Williams, 1985).

First, our findings for Sweden. While per capita GDP in Sweden is comparable to that in the US, final energy use per capita is only about 3/5 as large -- averaging 5.4 kw per capita in 1975. Indeed, Sweden is generally looked to as a model "energy-conserving" society. Yet our analysis for Sweden shows major opportunities for energy savings. The methodology used for the Swedish study involved showing the impact of improved energy-using technology on the demand for energy at various levels of consumption of goods and services. Two different levels of technological improvement were considered: best available technology (that which is judged to be economic today) and advanced technology (for which some success is assumed in ongoing R&D efforts to improve energy efficiency, and for which expected costs are in the range of interest). The results of the analysis for Sweden are that per capita final energy use would be reduced to about 3.5 kw (4.2 kw) for a 50% (100%) increase in the consumption of goods and services using best available technology; using advanced technology, which may be more appropriate when looking as far ahead as 2020, per capita consumption would be reduced to 2.7 kw (3.3 kw) instead, for the same increases in the consumption of goods and services.

Our United States country study is also based on the wide use of cost-effective energy-using technologies. For the US case, projections were made to the year 2020, by which time we showed that it would be feasible to reduce per capita final energy use to 4.0 kW (4.4 kW), from 9.0 kW in 1980, associated with a 50% (100%) increase in the per capita consumption of goods and services. Because US energy use is presently so high, the projected reduction in aggregate US energy use between 1980 and 2020 is very large (some 0.71 to 0.87 TW) -- equal to 25-30% of all energy use in developing countries in 1980.

In light of these results for Sweden and the US and the broad applicability of the technologies involved in these analyses, it is reasonable to expect that a 50% average reduction in per capita final energy use could be achieved via energy efficiency improvements, along with continuing improvements in standard of living in all industrialized countries between 1980 and 2020, reducing per capita final energy use there from 4.9 kw to 2.5 kw, to a level which is comparable to what could be realized in Sweden with "advanced technology" and a 50% increase relative to 1975 in the per capita consumption of goods and services there*. Since in 1975 per capita GDP in Sweden was some 75% higher than the average for all industrialized countries in that year (4.A), an energy demand level of 2.5 kW could be associated with an increase in the average per capita GDP for all industrialized countries which is considerably greater than 50%.

Although this level of future per capita energy demand in industrialized countries is radically different from that envisaged in previous major global energy studies, this scenario, on the basis of what has emerged from the US and Sweden case studies, would appear to be both technically feasible and economical -- i.e., no more costly and perhaps

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* The reduction in per capita energy demand could vary from country to country and could be quite small for low income industrialized countries, without affecting very much the overall average level of future energy demand in industrialized countries. To illustrate this point suppose that for the 6 industrialized countries with the lowest per capita energy use (Greece, Ireland, Portugal, Spain, Albania, and Hungary) average per capita energy use in 2020 were at the 1980 level (2.2 kW). Then in 2020 the average level of per capita energy use for all industrialized countries would be 2.58 kW instead of 2.5 kW.

less costly than an equivalent amount of energy supply expansion.

While this scenario appears to be feasible, it is not likely that it would evolve without public policies which would facilitate the exploitation of opportunities for energy efficiency improvement. The needed measures include, inter alia, elimination of subsidies for energy supply expansion, marginal cost pricing for energy, and shifting energy utilities from being purveyors of energy supplies to energy services.

A major uncertainty concerning this scenario is the extent to which opportunities for energy efficiency improvement, which have been identified largely in OECD countries, would be seized upon and pursued in CMEA countries, which to date have made little headway in adopting energy efficiency improvements (see Figure 2).

In Section 5 we shall describe the implications for global energy supply of per capita energy demand levels for industrialized countries in 2020 which are higher than 2.5 kW.

Future Per Capita Energy Demand in Developing Countries: The energy demand situation is completely different for the three-quarters of humanity who live in developing countries and today account for only 1/3 of world energy use.

At present, per capita energy use in developing countries averages about 0.9 kw per capita, of which some 0.4 kw per capita is non-commercial energy consumed largely by the two-thirds of the population who live in rural areas, for the most part isolated from market economies.

The challenge for energy planning in developing countries is to assure that the needed energy services are available -- for satisfying the basic human needs of the poor; for providing food for a growing population; and for generally bringing about a much higher standard of living for the population as a whole -- in environmentally sound and sustainable ways that promote self-reliance and peace.

How much energy is needed in developing countries in the decades ahead to meet these goals? One would think that since per capita final energy use in developing countries presently averages only 0.9 kW, less than 1/5 of that in industrialized countries, substantial increases in energy use would be required to meet development goals.

This is not necessarily so, however. Because the bulk of energy is used for cooking and because this energy is used so inefficiently in developing countries, it is possible to provide marked improvements in standard of living there without changing much the overall level of energy use.

High-efficiency, low-cost wood cooking stoves that have recently become available make it possible to achieve near-term fuel savings in cooking of at least a factor of two (S. Baldwin, G.S. Dutt, H.S. Geller, and N.H. Ravindranath, December 1984), along with the attendant benefits associated with the reduced time and labor required for fuelwood gathering.

To give an indication of what might be achieved in the longer term, we have developed an energy budget for an hypothetical country with a mix of energy-using activities similar to that for Western Europe in the 1970s (excluding space heating, which is not needed in most developing countries) and with the activity levels matched to energy intensities corresponding, in energy performance, to best available technologies on the market today or to advanced technologies that could be commercialized over a period of about a decade. Remarkably, total final energy use per capita for this scenario would be only about 1 kW, or only slightly more than at present (4.B).

Part of the explanation of how it is possible to achieve such large improvements in living standards without increasing energy use is simply that without even taking into account new opportunities for efficiency improvement, there would be enormous increases in energy efficiency simply by shifting from traditional, inefficiently used, non-commercial fuels to modern energy carriers. This is evident from the fact that in 1975 per capita GDP in the WE/JANZ region was 10 times that of developing countries, even though per capita final energy use for purposes other than space heating was only 2.3 kW, about 2 1/2 times the final energy use level in developing countries today.

The significance of the shift to modern energy carriers is vivid for cooking. The majority of the population in developing countries now uses biomass for cooking at a per capita rate of 1/2 to 1 tonne of fuelwood per year -- equivalent to an average energy use rate of 250 to 500 Watts. Shifting to a high quality gaseous fuel (like LPG or biogas), would cut fuel use for cooking to some 50 Watts (which is typical in houses using LPG in Brazil and India), because gas stoves are so much more efficient than traditional wood stoves.

In addition to the savings associated with the shift to modern energy carriers, considerable further savings can be gained by adopting new, more energy-efficient technologies that have recently become available. For a wide range of such technologies, it would generally be less costly to provide a given level of energy services with the more energy-efficient end-use technology than with conventional end-use technologies and more energy supplies. This has been shown for industrialized countries in (T.B. Johansson and R.H. Williams, 1985) and for the case of Brazil in (H.S. Geller, February 1984). The folowing examples are indicative of the magnitude of the energy savings opportunities: recently developed gas stoves are 70% efficient and less polluting than conventional stoves, which have efficiencies around 50% (K.C. Shukla and J.R. Hurley, July 1983); a new 315 l refrigerator/freezer with the energy performance of the most energy efficient unit available in 1982 requires just 475 kWh per year -- or less than 1/3 of the electricity required by the average refrigerator/freezer in use in the US; new compact fluorescent light bulbs that can be screwed into ordinary incandescent sockets use just 1/4 as much electricity as incandescents.

While most of the technologies we have assumed for this 1 kW scenario are commercially available today, a few are still in an advanced state of development -- for example the Swedish Plasmasmelt and Elred processes for steel-making. With these steel-making technologies only half as much energy is required to produce a tonne of steel as with the average Swedish technology in use in 1976 (T.B. Johansson and R.H. Williams, 1985).

The WE/JANZ activity levels in this 1 kW scenario should not necessarily be taken as "targets" for developing countries. In the first place, because technology is continually changing, it would be foolish to target for the future of developing countries a state achieved in the past in industrialized countries. At present the same or higher levels of amenities can be achieved not only with less inputs of energy than in the past but also with less inputs of basic materials generally. Higher energy costs usually translate into higher costs for basic materials. The rising costs of basic materials in recent years has fostered a wave of innovation in industrialized countries that is leading to the introduction of lighter weight products, longer lasting durable goods, substitutions of less costly materials in product manufacture, and less wasteful practices for using non-durable goods -- a trend that is expected to continue for years to come (E. Larson, R.H. Williams, and D. Bienkowski, 1984). This means that future rates of materials consumption (e.g., per capita consumption rates for steel, paper, ammonia, etc.) considerably lower than those assumed for the 1 kW scenario would be adequate to provide the same level of amenities as for the WE/JANZ region in the 1970s.

Moreover, instead of adopting copy-cat development strategies, long term development goals should reflect the resource constraints, the comparative advantages, and the unique social needs of developing regions. One alternative pattern of development to that followed in Western Europe, which emphasizes instead decentralized industry and local self-reliance would tend to require much less in the way of energy-intensive activities than a development style which continues to emphasize urbanization (e.g., because there would be less need for long distance transport, packaging, and storage of foodstuffs and industrial goods) -- see, for example (U. Colombo and O. Bernardini, July 1979). With a strong emphasis on energy efficiency improvement, this alternative development path could probably be supported with less than 1 kW by 2020; or, with less emphasis on energy efficiency, energy requirements could be about 1 kW.

Even though the activity levels for our 1 kW scenario should not be blindly adopted as goals for developing countries, the 1 kW analysis shows clearly that living standards ranging all the way from the present up to those of the WE/JANZ region today can be achieved without increasing per capita energy use.

On the basis of such considerations we assume an average level of per capita energy use of 1 kW for developing countries in 2020 -- a level which, with emphasis on energy efficiency improvement and modern energy carriers, would be adequate both to ensure that BHN are satisfied and to allow for considerable further improvements in living standards.

That development goals can be achieved with little change in the overall per capita level of energy use should not obscure the difficulties of bringing this about. As in the case of development generally, large amounts of capital would be required to bring about a shift to modern energy carriers and to efficient end-use technology. Nevertheless, this analysis suggests that there should be no fundamental energy constraint on development, as our energy supply analysis will show more clearly.

In Section 5 we shall explore the implications for the energy supply problem of future per capita energy demand levels in developing countries which are greater than 1.0 kW.

The Demographic Context: In conventional energy demand projections it is customary to treat population as a "given" that is not affected by energy policy. In this study we have taken a different approach, arguing the importance of identifying energy strategies that are consistent with the solution of the global population problem. And if the pressures of population growth can be eased, the energy problem would in turn be significantly easier to solve. This can be appreciated by comparing the energy requirements for the alternative UN population projections for the year 2020 (4.C). Even though a relatively small range is projected (± 10% of the medium variant projection of 7.8 billion), the absolute population level is so large by 2020 that small relative changes can have significant impacts on the energy problem. For example, at the present level of per capita energy use, the difference between the high and low UN population variants corresponds to an extra energy supply in 2020 equivalent to nearly the present level of world oil production!

We have stressed the importance of pursuing a development strategy that targets the satisfaction of basic human needs as part of the overall effort needed to deal with the population problem. Because this emphasis on satisfying basic human needs is central to our overall energy strategy, we shall assume for our base case scenario that such efforts would be reflected in slower population growth than would otherwise be the case. Since it is not possible at this time to quantify the impact of a BHN policy on population growth, we instead simply adopt the low UN population variant for our base case energy demand scenario: 1.24 and 5.71 billion for industrialized and developing countries respectively in 2020, up from 1.11 billion and 3.32 billion in 1980.

In Section 5 we explore via sensitivity analysis the significance for the energy problem of higher population growth rates.

Global Energy Demand: Assuming for industrialized countries a 50% reduction in per capita final energy use, 1980-2020, and the low UN population variant for the year 2020, total final energy use by industrialized countries would be reduced from 5.5 TW in 1980 to 2.9 TW in 2020 (4.D). Assuming for developing countries a per capita final energy use level of

1.0 kW, total final energy use there would nearly double, 1980-2020, with the low UN population variant of (4.D).

Global final energy demand, however, would be about the same in 2020 as in 1980, and the developing country share would increase from 1/3 to 2/3 of the total (4.D). Figure 3 shows the global energy demand level for 2020 and the distribution of demand between developing and industrialized countries in terms of primary energy (which includes the energy conversion, transmission and distribution losses for the assumed supply mix): for our base case scenario, for the alternative WEC and IIASA scenarios, and for 1980. It is clear from this figure that as far as the projected energy demand levels are concerned, the major difference between our base case scenario and the energy scenarios presented in the 1982 WEC energy study and the 1981 IIASA energy study lies in the treatment of the industrialized countries. The primary demand level for developing countries in our base case scenario is 1.3 kW per capita, which is the same as the average value for the WEC high and low scenarios and is only slightly less than the average of 1.5 kW for the IIASA high and low scenarios. In light of the much greater emphasis given here to energy efficiency improvement, however, the 1.3 kW of primary energy in our base case scenario corresponds to a much higher living standard.

While the global level of energy demand would not change much, 1980-2020, in our base case sceanrio, we expect there would be a marked shift to higher quality energy carriers. In particular we assume a continuation of the ongoing "electrification" of the global energy economy, so that the electricity share of final demand would increase from 10% in 1980 to 18% in 2020 (4.D). This increase in the share of electricity in final demand implies a doubling of electricity production, 1980-2020.

4.2 Energy Supply

When energy demand is not too great there is flexibility in the choice of energy supplies. We now explore the extent of this flexibility for dealing with the energy supply problems which tend to be aggravated by conventional energy strategies.

Instead of speculating on the possibilities for making radical shifts in the energy supply mix, we explore the prospects for dealing with these problems by making only relatively minor shifts from the present situation.

In this spirit we begin by assuming that the total fossil fuel supply that would provide this demand is the same in 2020 as in 1980. We shall subsequently adjust the mix of coal, oil, and natural gas in the overall fossil fuel supply to reflect considerations of the atmospheric carbon dioxide build-up from the burning of fossil fuels, global security and the world oil price, and the relative abundances of the remaining fossil fuels. While assuming that only the mix of fossil fuels changes, 1980-2020, represents a relatively modest change relative to the present situation, the change is quite dramatic relative to the future customarily envisaged for fossil fuels. As shown in Figure 4, the WEC and IIASA scenarios project that fossil fuel use will approximately double between 1980 and 2020.

Atmospheric Carbon Dioxide and the Burning of Fossil Fuels: The prospect that the atmospheric carbon dioxide level would double in the latter half of the next century and give rise to major changes in the global climate in this period, as a result of fossil fuel expansion scenarios such as those of the WEC and IIASA studies, has led to a rapidly growing literature on accommodation strategies for dealing with the carbon dioxide problem; for example, one of the major recommendations of the 1983 US Environmental Protection Agency report on the carbon dioxide problem is to accelerate and expand research on improving our ability to adapt to a warmer climate (S. Seidel and D. Keyes, September 1983).

Pursuing an end-use oriented energy strategy provides a basis for dealing with the carbon dioxide problem that instead involves much less dependence on fossil fuels than is usually forecast.

Our base case scenario assumption that overall growth in fossil fuel use would be curtailed would slow the atmospheric build-up of carbon dioxide and reduce the climatic changes that this build-up would give rise to. In addition, however, consideration should be given to adjusting the mix of fossil fuels. The mix is important first because the carbon dioxide emissions differ from one fossil fuel to another -- with coal being more problematical than either natural gas or oil: per unit of fossil fuel energy released, coal generates 1.2 times as much carbon dioxide as oil and 1.8 times as much as natural gas (4.E). Second, the vastly greater remaining coal resources indicate that coal should be given focused attention: whereas using up all the remaining ultimately recoverable oil and gas resources (with no further use of coal) would lead to an atmospheric carbon dioxide level only 1.5 times the pre-industrial level (440 ppm), using up half of the coal left in the ground would increase the CO2 level to 4 times the pre-industrial level (4.E). Finally, in an energy-conserving world it may prove to be easier during the transition to the "Post-Petroleum Era" to "make do" with less coal, a dirty, relatively difficult-to-use fuel, than either oil or natural gas, which are clean, easy to transport, and convenient to use.

To relate future levels of fossil fuel use to constraints on the ultimate level of carbon dioxide in the atmosphere, we assume that: (i) half of the released carbon dioxide remains in the atmosphere; (ii) all estimated ultimately recoverable oil and gas resources are eventually used up, so that concerns about carbon dioxide are reflected as constraints on coal production; and (iii) coal production falls exponentially over time.

With these assumptions the rate of decline of coal use in the future depends on the CO2 ceiling level [see (4.F) and Figure 5)]. If the ultimate ceiling were as low as 1.5 times the pre-industrial level, coal must be phased out very rapidly, falling to 1/2 the present level before the turn of the century -- which is not a practical target. On the other hand if the allowable level were 2.0 times the preindustrial level, then coal production would fall extremely slowly, to half the 1980 level only after 230 years.

While major climatic changes are expected if the atmospheric CO2 level doubles, it is impossible to say what an "acceptable" CO2 ceiling should be. For the purposes of the present analysis we arbitrarily select a ceiling of 1.7 times the pre-industrial level (490 ppm) for the base case scenario -- which implies that coal use would fall to half its present level only after 100 years, and that coal use would decline by 20% between 1980 and 2020.

While coal use would be reduced from the present level by a relatively modest amount in the base case scenario, the level of coal use would be only 20 to 40% as high in 2020 as in the WEC and IIASA scenarios (see

Figure 6), and emissions of carbon dioxide in 2020 from the burning of all fossil fuels would be only 40 to 60% as large as in the IIASA and WEC scenarios. By 2020 the atmospheric carbon dioxide level would be about 1.3 times the pre-industrial level (380 ppm) with our base case scenario.

Despite the slow rate of coal phase-out implicit in this scenario, the notion of controlling the atmospheric carbon dioxide buildup by restricting coal use poses major economic challenges. The CO2 ceiling we have assumed would require limiting coal use in the long run to about 1/4 of the amount of coal available at prices less than 1/2 the world oil price in 1982 (4.G). Nevertheless, with this constraint coal would remain a major energy resource for a long time to come; the cumulative allowable production is equivalent to a 150 year supply at the present rate of usage. Moreover, the fact that almost 90% of the coal left in the ground is concentrated in just three countries [the USSR, the US, and China -- see (4.E)] makes the prospect of control easier than would be the case if the resources were distributed widely throughout the world, since agreement among just these countries may lead to a solution of the problem.

In Section 5 we shall explore the implications for alternative energy supplies of imposing alternative ceilings on the atmospheric carbon dioxide level.

The World Oil Problem: Most global energy studies envisage that future oil demand will be so high that the balance of oil market power must again shift back to the Persian Gulf in the time period of interest here. This is illustrated in Figure 7, which shows that in the IIASA energy scenarios and in the WEC high scenario the ME/NAf region in 2020 would be required to produce oil at or near capacity levels -- a situation similar to that in 1979, when world oil supplies were so tight that the Iranian revolution triggered the second oil price shock (4.H).

It appears to be possible to avoid this tight oil supply situation for the entire period out to 2020 by pursuing end-use energy strategies, in conjunction with efforts to shift the mix of oil and gas use to give greater emphasis to natural gas.

There is about as much natural gas as oil left in the world. But the gas resource is much greater in relation to current consumption. The amount of remaining gas judged ultimately recoverable at the global level is about a 200 year supply, compared to a 100 year supply for oil; that outside the ME/NAf region and countries with centrally planned economies about a 100 year supply, compared to 40 for oil, at the current consumption rate there (4.I). Thus one strategy for dealing with the global oil problem would be to give more emphasis to gas. Natural gas can be readily substituted for oil not only in stationary applications but in mobile vehicles as well (4.J).

We assume that by 2020 gas and oil production rates become equal (see Figure 4). Together with our assumptions about overall fossil fuel use and coal use, this implies a 1.85-fold increase in gas use but a reduction in global oil use from 59 to 45 million barrels per day, 1980-2020. At this lower level of world oil demand there would probably be adequate oil supplies available outside the ME/NAf region at production costs lower than $30 per barrel (in 1982 $) to sustain dependence on the ME/NAf region at the 1983 "world oil glut level" of 15 million barrels of oil per day (4.K). Such a scenario implies much greater global security and far lower oil prices than in the WEC and IIASA scenarios -- and perhaps even stable oil prices for the entire period out to 2020. The prospect of more secure oil supplies and stable oil prices means that oil would be a more dependable and affordable energy source during the transition to the Post-Petroleum Era, and -- in particular, would be much more available for essential development purposes in developing countries during this critical transition period.

In Section 5 we shall explore the implications of higher levels of dependence on oil in 2020.

Nuclear Weapons Proliferation and Nuclear Power: Regarding the nuclear power/nuclear weapons connection, it is widely believed that the "genie is out of the bottle," so that we must learn to live with the risks of a proliferated world. It would indeed be true that the genie would be out of the bottle if the WEC or IIASA projections were borne out -- projections that nuclear power will grow to levels 10 to 30 times as high as in 1980 (see Figure 8). But these projections are not necessarily destiny. Here again, the pursuit of end-use oriented energy strategies, together with the poor economic prospects of those nuclear power technologies which offer the greatest proliferation risk, provides a basis for a less grim outlook.

We have argued that by avoiding nuclear power technologies involving the reprocessing of spent nuclear fuel, the risk of nuclear weapons proliferation could be reduced and, in particular, the risk of latent proliferation could be greatly reduced. We argued further that since even a ban on reprocessing technologies would not prevent proliferation via the recovery of plutonium or other weapons usable material from spent fuel --

the risk of which increases with the extent of world-wide nuclear power development -- nuclear power should be regarded as an energy technology of last resort, limited to those situations where viable alternative energy technologies are not available.

Our base case global energy scenario reflects this perspective on nuclear power. For the year 2020 this scenario involves nuclear power production amounting to 0.3 TW *, which represents official judgments of the early 1980s as to the worldwide production level for nuclear power by the year 2000 (4.L). While this would be a 4-fold increase in nuclear power production over the 1980 level, it implies essentially no net nuclear capacity increment beyond what is already planned for the year 2000, so that beyond the turn of the century the only new nuclear power plants that would be built are those that would replace retired units.

At this level of nuclear power development (and even considerably higher levels) there would be an abundance of low-cost uranium in the world for a long time. The economics of nuclear fuel reprocessing are not favorable today and would be only marginally favorable at very high uranium prices (4.M). It has been shown that even with rapid growth in nuclear power in the US (such that US nuclear power output would grow to 0.4 TW by 2020 and then would level off), US uranium resources would be adequate to make reprocessing and the breeder reactor uneconomical for a period of the order of 100 years, at least (H.A. Feiveson, F. von Hippel, and R.H. Williams, 1979). The same analysis showed that even uranium-poor nations could afford to forego reprocessing and the breeder reactor and could

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* Assuming an average capacity factor of 65%, this corresponds to an installed nuclear capacity of 460 GW (e).

achieve uranium supply security simply by stockpiling uranium; because uranium (unlike oil) is very cheap, the cost of stock-piling is very low (on the order of 1% of the cost of producing electricity). Thus economics would work in support of policies that seek to avoid reprocessing out of proliferation concerns.

Similarly, the more favorable economics of investments in energy efficiency improvement relative to investments in energy supply expansion generally [see (T.B. Johansson and R.H. Williams, 1985)] work in support of efforts to make nuclear fission power more generally the energy technology of last resort.

In Section 5 we explore the implications for energy supply planning of alternative nuclear power levels for the year 2020.

Roles for Renewable Resources: One way to cope with the global risks posed by dependence on oil, fossil fuels generally, and nuclear power, is to shift to greater dependence on less troublesome renewable energy sources. However, the prospects for major shifts to renewable resources are far more speculative at the present time than the prospects for reduced dependence on conventional energy sources via the use of much more efficient energy end-use technology. Moreover, large scale development of some renewable energy resources, if not done carefully, can also pose land use and other conflicts with other societal objectives. For example, as we have pointed out, the present patterns of non-renewable biomass use for energy and other purposes is a major contributing factor to the problem of deforestation.

Nevertheless, renewables can play an important role in the overall global energy budget. Hydropower, wind and photovoltaic energy, and bioenergy in particular, are among the more promising renewable energy sources which, with careful planning, could be significant energy sources that are less troublesome than conventional energy sources [see (J. Goldemberg, T.B. Johansson, A.K.N. Reddy, and R.H. Williams, 1985)].

For our base case scenario, we assume that these sources meet energy requirements in excess of what can be provided with conventional energy sources, in light of the constraints we have assumed to limit the use of fossil and nuclear energy sources.

We do not suggest that the level of renewable energy use or the mix of renewable sources we have chosen for 2020 in our base case scenario [see Figure 4 and (4.N) and (4.O)] is optimal. Rather we have chosen a level and a mix which we feel are plausible and which would not obviously be significantly constrained by any of the potential land use conflicts and other limitations on these resources.

HYDROPOWER Among renewable power generation sources, hydropower is fully proven and is especially promising in developing countries, where only 7% of economical reserves have been developed to date. Development of hydro power, which is often much less costly to develop than thermal power, provides the opportunity for many developing countries to become more self-reliant in energy.

We assume that the hydro share of total electricity increases from 20% in 1980 to 25% in 2020, by which time about 40% of the economic hydro potential (or 20% of the technically usable potential) would be developed (4.N). The level of hydro development we assume for our base case scenario is sufficiently far from the technical limit of the resource that it need not involve sites that would be particulary disruptive ecologically.

Moreover, the pace of hydro expansion is sufficiently modest (2% average annual growth) that hydro development could be carried out so that its planning is carefully integrated into the overall development process, taking into account the range of social and ecological concerns that have been raised about hydro development.

WIND and PHOTOVOLTAICS   Wind power is also a potentially important renewable power source, for which large, mass-produced wind machines would be appear to be competitive in windy areas with conventional sources of electric power [see (J. Goldemberg, T.B. Johansson, A.K.N. Reddy, and R.H. Williams, 1985)]. The most promising wind regimes lie are in industrialized countries, in several of which commercial wind energy sytems are currently being built. To achieve a high level of wind energy development would probably require emphasizing large (2 to 3 MW) windmills that are integrated into the utility grid system in ways that would improve the reliability of wind electricity. There are many promising ways to do this, but the present prospects for large scale wind development are still uncertain.

While not yet commercially established, photovoltaic technology (especially involving innovations such as amorphous silicon solar cells) holds forth great promise as a power generating source applicable in a wide range of circumstances [see (E.A. Demeo and R.W. Taylor, 1984)]. Owing to the commercial uncertainties surrounding photovoltaics, however, we make no separate estimate of the level of use of this technology but instead consider wind and photovoltaic technologies together and assume that these sources together account for 5% of total electricity use in 2020.

In the event that photovoltaics technology is not commercialized, all of this electricity would be provided by wind. For this case the required level of wind energy development would be a tiny fraction of estimates which have been made of the wind energy potential (4.N). On the other hand, if the promise of photovoltaic technology is realized, the photovoltaic contribution could be considerable, with perhaps less emphasis on wind.

FUEL-FIRED THERMAL POWER PLANTS We assume that electricity requirements in excess of what is provided by nuclear power, hydropower, wind and photovoltaics, would be provided via fuel-fired thermal power plants -- either cogeneration plants or conventional central station thermal power plants. Assuming that 15% of the electrical demand could be met by cogeneration (a percentage which reflects our analysis of the industrial cogeneration potential in the US), this implies that the amount of electricity required from fuel-fired central station thermal power plants would be the same in 2020 as in 1980, despite a doubling of the overall use of electricity (4.N).

BIOMASS ENERGY SOURCES Biomass is widely regarded as "poor people's energy" -- an energy source unfit for a modern society. Indeed the industrialized world made a transition a century ago from wood to coal and other fossil fuels. These facts make it difficult for many people to take seriously any notions of giving greater emphasis to bioenergy sources. Yet bioenergy sources have many attractive aspects.

Used directly, biomass is a fuel that is usually less costly than oil and is often competitive with coal. And for the production of synthetic gaseous or liquid fuels biomass is in many ways superior to coal: it has much less sulfur than coal, little ash, and, because of its looser molecular structure, it can be gasified at a lower temperature than coal.

An important advantage of biofuels from the societal perspective is that, grown on a renewable basis, biomass becomes a source of chemical fuels, the production and use of which leads to no net increase in the atmospheric carbon dioxide level.

The production of modern gaseous and liquid energy carriers from biomass sources also enables fossil fuel-poor but biomass-rich countries to become more self-reliant. Moreover, there is already a rapidly growing interest in modern biomass-derived fuels in several countries, as an alternative to continued reliance on oil imports. For example, in a very short period of time Brazil was able to establish a large scale ethanol program based on sugar cane, and recently it has taken the world lead in its decision to build the world's first wood-based methanol production facility. While sugar cane-based ethanol may be relevant only to a few parts of the world where fertile land is abundantly available, methanol production can be based on wood grown on land poorly suited for food production in many parts of the world.

For our base case scenario we assume that 1/2 of all cogenerated electricity (e.g., cogeneration in the forest products and agricultural processing industries) is based on biomass -- requiring some 0.2 TW of primary biomass energy (4.0). A much larger role for biomass would involve providing direct fuel needs in 2020 that could not be met with fossil fuels, owing to our assumed constraint on the overall fossil fuel supply. For direct use applications some 1 TW (1/8 of all direct fuel use) of solids, liquids and gases would be required from biomass sources [see (4.D) and (4.O)]. Assuming that biomass feedstocks are converted to useful solid, liquid, and gaseous energy carriers at an average conversion efficiency of 70% *, some 1.4 TW of primary biomass energy would be required to make these fuels, bringing the total primary biomass energy requirements for our base case scenario to 1.6 TW, which is only slightly higher than the use of bioenergy sources in 1980 [see Figure 4 and (4.O)].

We assume here that attempts would be made to utilize bioenergy on a renewal basis, so as to reverse the ongoing process of deforestation associated with the current harvesting of biomass. Toward this end we give focussed attention here to two biomass sources, the careful use of which could support efforts to reverse the ongoing process of deforestation: organic wastes and biomass grown for energy purposes.

The global level of production of organic wastes (forest product industry wastes, crop residues, manure, and urban refuse) is enormous, amounting in 1980 to about 2.8 TW -- which is some 2/3 as large as world oil production! Assuming that the production of organic wastes increases simply in proportion to population, it would reach 4.1 TW by 2020 (4.P). Because of competition for these wastes for other purposes (4.Q), however, we assume here that only about 0.8 TW (1/5 of the total) of wastes is recovered for energy purposes in our base case scenario. With this level of organic waste utilization, an equal amount of biomass would have to be provided by growing biomass for energy purposes.

Because of the relatively low productivities of existing forests, we explore here the potential for managed biomass production for energy use or

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* This is the approximate average conversion efficiency which would result if the mix of energy carriers were 1/2 biogas and methanol and 1/2 synthesis gas and solid fuel.

for multiple purposes via bioenergy "plantations" or "farms" or "woodlots". With managed biomass production productivities can be much higher than in natural forests. In what follows we shall speak of "plantations" in describing such managed production -- whether on a small-, medium-, or large-scale basis.

To provide 0.8 TW of biomass for energy purposes requires the annual production of some 1.4 billion tonnes of dry biomass per year. How much land would be required to grow this much biomass? It depends on the biomass productivity. For the purposes of the present analysis we assume that the mean recoverable biomass productivity is 10 dry tonnes per hectare per year. While this is far less than what has been achieved under very favorable circumstances, there is not enough good long term data available upon which to indicate reliably much higher productivities (4.R). Such a productivity implies that the plantation land area required by 2020 would be some 140 million hectares, which is of the order of 4% of the world's forest area.

In the cases of both organic waste utilization and bioenergy from plantations it is clear that the demands on the biomass system are rather modest and would not seem to be limited by any significant land-use or other constraints.

Overview of Energy Supply for the Base Case Scenario: The primary energy supply for the base case scenario is shown in Figure 4 in relation to the actual supply of 1980 and the supplies for the WEC and IIASA scenarios. We have made no attempt to put together an energy supply mix that is optimal in an economic sense. Rather the supply mix for our base case scenario is a plausible one which satisfies the condition that it would be compatible with efforts to solve other important global problems having strong links to energy.

What is perhaps most striking in a comparision of the supply levels and mixes for our base case scenario and the WEC and IIASA scenarios is that while our finding, that it appears to be both technically and economically feasible to find energy strategies compatible with and supportive of the solutions to other important global problems, is a "radical result," it is the WEC and IIASA energy supply scenarios which are radically different from the present situation and which would pose formidable economic and institutional challenges to bring about. Our base case scenario involves no major changes from the present situation -- the overall level of fossil fuel use is unchanged, the renewable share is up only modestly (from 16% in 1980 to 19% in 2020), and no exotic energy surces would be required. The energy supply problem would be a quite managable in the base case energy scenario.

5 SENSITIVITY ANALYSIS

Our analysis has shown that for the assumptions underlying our base case scenario a plausible energy future can be described which is compatible with and supportive of the solutions of other important global problems. But how dependent is this outcome on the various assumptions?

To address this issue we now present sensitivity analysis relating to the most important parameters underlying our base case scenario, considering in turn biomass and then oil and natural gas as "swing energy sources" -- meaning that the levels of these energy supplies for the year 2020 would be adjusted to bring energy supply and demand into balance as variations are made in the scenario assumptions.

5.1 Biomass as the Swing Energy Source

Biomass is a potentially important swing energy source because: its use on a renewable basis would not aggravate the global carbon dioxide problem; it is a widely available renewable energy source that can be readily utilized with technologies at hand or which can be brought to commercialization with little developmental effort; and the planting and careful management of biomass for energy purposes would be an important part of a global effort of afforestation.

The two sources of biomass we consider for this purpose are organic wastes and the managed production of biomass for energy purposes on energy woodlots, farms, or plantations.

Because of the uncertainties surrounding the degree to which it will be possible to utilize organic wastes for energy purposes, we shall assume in the sensitivity analysis that the use of organic wastes for energy in

2020 cannot exceed 1.0 TW or 1/4 of the total organic waste generation rate (4.P). We further assume that plantations and organic wastes make equal contributions to the total biomass supply until the organic waste utilization level reaches 1.0 TW and that beyond this level all extra biomass must be biomass grown for energy purposes.

An index which illustrates in a graphic way the needed biomass production effort is the average rate of starting new plantations (in million hectares per year) needed to assure that enough biomass is available for harvesting in 2020 to meet the required biomass supply level. We shall refer to this index as the plantation expansion rate or PER *. For our base case scenario this rate would be 4.6 million hectares per year -- which is comparable to the present PER in developing countries (5.A).

We now discuss in turn the impacts of changes in each of several important assumptions underlying our analysis on the demand for biomass **.

POPULATION We have already pointed out that total energy supply requirements in 2020 are a sensitive function of the population. With plantation energy as the "swing" energy source, the PER is even more sensitive to population, as indicated in Figure 9: the PER increases from less than 5 to 14 million (22 million) hectares per year as the

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* Here it is assumed that the average period of rotation for the plantations is 5 years, so that the planting for supplies to be harvested in 2020 must be carried out in the period 1985 to 2015.

** In all the alternatives to the base case scenario we assume that: (i) electricity accounts for 18% of final energy demand; (ii) hydro (wind and photovoltaics) accounts for 25% (5%) of electricity production; (iii) cogeneration accounts for 15% of electricity production, with a 50/50 mix of fossil fuels and biomass; (iv) the nuclear electricity level is fixed @ 0.3 TW unless specified otherwise; (iv) the remainder of electricity production is by fossil fuels in central station plants.

population increases from the low to the medium (high) UN variant for 2020.

The biomass effort clearly becomes much more challenging at the higher population growth rates, and this calculation underscores the importance of solving the population problem as means of dealing with global resource management problems generally. But even these more ambitious bioenergy development efforts may be feasible or desirable. The PER value associated with the medium population variant is comparable to the 11 million hectares per year expansion rate for agriculture in the period 1950-1975 (B. Bolin *et al.,* 1979). Moreover, even with the high population variant the required PER is still low in relation to the global deforestation rate. A substantial reforestation effort may be needed to reverse the ongoing process of deforestation. According to FAO statistics the world's forest area decreased from 4400 million hectares in 1952 to 3800 million hectares in 1972, or at an annual rate of 30 million hectares per year in this period (B. Bolin *et al.,* 1979).

Of course at the higher PER values the issue of competition between bioenergy and food production must be dealt with carefully. However, the best use of land may be to pursue complementary rather than competitive strategies for bioenergy and food production. It may be both feasible and desirable to restrict agricultural production to the better lands and increase productivity there with inputs of energy (via tractors, fertilizers, irrigation, etc.) and to grow biomass for energy purposes on the more marginal lands -- using some of the energy produced this way to support more modern, more energy-intensive agricultural methods. Tree farms with rotations of 5-10 years or more would probably be a more sustainable use of marginal lands than attempts at agricultural production.

PER CAPITA ENERGY USE Figure 9 illustrates the impacts on the PER of alternative per capita energy demand levels -- specifically the impacts of alternative combinations (A,B), where

A = per capita final energy use rate (in kW) for developing countries (DC),

B = per capita energy use rate for industrialized countries (IC)

For developing countries we consider as an alternative to the base case rate of 1.0 kW, a case involving a 50% increase in per capita final energy use, 1980-2020, to 1.3 kW. This rate of final energy use corresponds to a primary energy use rate of about 1.7 kW, which is near the high end of the WEC and IIASA projections for 2020. [The per capita primary energy use rate for the WEC (IIASA) scenarios in 2020 is in the range 1.1 to 1.6 kW (1.2 to 1.9 kW)]. This alternative energy use rate implies only modest improvements in the efficiency of energy-using technologies in developing countries, and certainly no significant "technological leap-frogging" to energy-efficient, advanced energy-intensive processes.

For industrialized countries we consider as alternatives to the base case final energy use rate of 2.5 kW, levels of 3.3 kW and 4.9 kW per capita, representing considerably less ambitious conservation efforts than that which characterizes our base case scenario.

The 3.3 kW case involves per capita final energy use in 2020 which is 1/3 less than in 1980 and is equal to the 1980 final energy use level for the WE/JANZ region. In the 4.9 kW case energy efficiency would improve, 1980 to 2020, just enough to offset economic growth. An indication of the modesty of the conservation effort that would be involved in this case is provided by a comparison with OECD economic and energy performance, 1973 to 1982. In this period real per capita GDP increased 12%, while per capita primary energy use declined 10%. (Because electrification increased in this period, per capita final energy use declined even more rapidly than primary energy use.)

Figure 9 illustrates the impacts of alternative assumptions about per capita energy demand on the requirements for bioenergy development, assuming that biomass is the swing fuel. This figure shows that the (1.0, 3.3) scenario would involve a PER comparable to the average rate of cropland expansion, 1950 - 1975, while the (1.3, 2.5), (1.3, 3.3) and (1.0, 4.9) scenarios would require PER values in the range 20 to 30 million hectares per year, some 2 to 3 times the average rate of cropland expansion -- a formidable undertaking.

THE ATMOSPHERIC CO2 LEVEL The ultimate level of carbon dioxide buildup in the atmosphere could be varied by speeding up or slowing down the rate of coal phase-out via substituting biomass for coal, or vice versa. Figure 9 shows how variations in the ultimate carbon dioxide ceiling in the range 1.5 to 2.0 times the preindustrial level would affect biomass plantation requirements. This figure shows that the PER is relatively insensitive to the atmospheric carbon dioxide ceiling for ceilings in the range 1.6 to 2.0. To reduce the ceiling to 1.5, however, requires a PER more than triple that for the base case.

The major impediment to realizing a 1.5 ceiling level is probably not so much its implications for biomass production as the prospect of major dislocations in the coal industry that would arise from the rapid coal phase-out: in this case coal use would have to decline @ a very rapid rate of 4% per year to a level by 2020 which is just 1/5 of that in 1980.

So far we have assumed in the carbon dioxide analysis that eventually all oil and gas supplies would be used up. But there are conceivable circumstances where this assumption could be relaxed. One of the most promising energy supply technologies in the offing involves the use of amorphous silicon solar cells (perhaps laid out flat on the deserts on simple support structures) to produce hydrogen via electrolysis. Our preliminary analysis indicates that if present industry expectations regarding the costs of amorphous silicon solar cell panels are realized, it may be feasible to produce hydrogen at costs competitive with the costs of oil and natural gas [see (J. Goldemberg, T.B. Johansson, A.K.N. Reddy, and R.H. Williams, 1985)].

Let us suppose that this technology is successfully developed and that it proves to be feasible to substitute the produced hydrogen for all fossil fuels in the period 2020 to 2050. The result is that the ultimate level of atmospheric carbon dioxide could be limited to 1.4 times the pre-industrial level or 400 ppm (5.B). The land area required for solar cells would be of the order of half the state of Texas or about 2% of the world's warm deserts (5.C).

NUCLEAR POWER We consider two alternative nuclear power levels consistent with our philosophy that nuclear power should be the energy source of last resort: 0 TW and 0.5 TW, compared to 0.3 TW in the base case scenario. The former is a nuclear phase-out scenario, in which no more nuclear plants would be built beyond those now under construction. Our "high" nuclear power scenario involves the same rate of nuclear power expansion in the period 2000-2020 as in the period 1980-2000; in this scenario new plants would be built, 2000-2020, at a rate of 36 plants (of 1 GW(e) average capacity) per year (5.D), with installed nuclear generating capacity reaching nearly 800 GW(e) by the year 2020.

What is noteworthy about these alternative scenarios is the small impact these changes make on the PER [from 5 million hectares per year in the base case to 3 (10) million hectares if the nuclear power use rate changes from 0.3 TW to 0.5 (0.0) TW (see Figure 9)].

Nuclear power would not have a major impact on the overall global energy picture unless it were widely used throughout the world at levels several times higher than the maximum we have assumed in this analysis, and under such circumstances the risks of proliferation would be large as well.

5.2 Oil and Natural Gas as the Swing Fuels When Energy Demand is High

In the above sensitivity analysis we have shown that at the higher energy demand levels considered it would be a major challenge to provide the extra energy required with biomass sources alone. Limiting the marginal energy supply options to biomass, however, is probably unnecessarily constraining. In particular our assumed levels of oil and gas production for the base case scenario are lower than what has been projected in other global energy studies (see Figure 4) and may be lower than is necessary to keep to reasonable levels the world oil price and to make the rest of the world reasonably invulnerable to disruptions of oil supplies that could otherwise arise if dependence on Middle East oil were too great.

To examine this issue we describe a "high energy demand scenario" in which the aggregate final energy demand is the highest we considered above -- 1.0 kW per capita in DCs and 4.9 kW per capita in ICs [see (5.E)]. For the supply mix we assume the same conditions as for the cases in which biomass is the swing fuel, except that:

- The biomass supply is limited to 3 TW or twice the 1980 level -- 1/3 of which would come from organic wastes (1/4 of all organic wastes) and 2/3 from plantations, corresponding to a PER of 12 million hectares per year, 1985-2015, approximately the rate of cropland expansion, 1950-1975.
- The extra demand not met by biomass is met instead via increased oil and natural gas production, the levels of which are assumed to be equal by 2020.
- Oil production outside the ME/NAf region is again assumed to be increased enough to limit the need for oil from the ME/NAf region to the 1983 glut level of 15 million barrels per day [see (5.F)].

The detailed energy supply features of this alternative scenario are described in (5.G) and (5.H). Here we note some of the highlights:

- Primary energy demand would increase from 10 TW in 2020 to 15 TW in 2010, a level which is still only about 2/3 as large as in the WEC and IIASA scenarios [see Figure 4 and (5.G)].
- Electricity demand would still grow at less than half the 5 percent per year average growth rate of the 1970s [see (5.H)].
- While oil use would be about the same as in 1980, the assumed expansion in natural gas production implies that the sum of oil and gas use would increase from 6 TW in 1980 to 9 TW in 2020 [see (5.G)], compared to 9 and 10 TW in the WEC and IIASA scenarios, respectively (see Figure 4).
- It may still be feasible under this scenario to maintain the world oil price at or near the present level through 2020, since the requirements for oil production outside the ME/NAf region are comparable to the estimated remaining supplies of oil outside the ME/Af region with production costs less than $30 per barrel [see (5.I)].
- The ultimate level of carbon dioxide in the atmosphere would be the same as in the base case scenario, since only the rate of using up oil and gas resources would be increased. Moreover, total fossil fuel emissions in 2020 would still be only 60% as large as in the WEC and IIASA scenarios in 2020 (5.J).

- The level of nuclear power development would be the same as in the base case, so that proliferation concerns would not be exacerbated.
- The level of hydropower development for 2020 would amount to only about half of the 1976 WEC estimate of the extent of hydro resources that can be economically developed.

It would seem from these numbers that most of our concerns relating to energy supply that motivated the base case scenario could be dealt with in the high demand scenario as well. Therefore a critical policy issue arises: Why should energy planners seek to attain the energy demand levels associated with base case scenario, which invovlves a much higher level of energy efficiency improvement, if largely the same objectives could be realized at the higher demand level?

There are two reasons to strive for the lower demand level. First, as we have repeatedly stressed, it is probably cheaper at today's energy prices to provide energy services with the higher efficiency end-use technologies that would characterize the lower demand scenario, than to provide the same energy services with less efficient end-use technologies but with more energy suppplies. In addition, it is desirable to seek the lower level for planning purposes to provide a significant margin for error in planning. Flexibility to contend with planning errors decreases, the higher the energy demand level.

The possibility of maintaining a relatively stable world oil price till 2020 with the demand levels of the high demand scenario depends on the assumptions that: (i) natural gas production can be expanded 2 1/2-fold, 1980-2020, to a level comparable to that projected in the WEC and IIASA high scenarios -- an endeavor that is probably feasible but nonetheless challenging; and (ii) low cost oil resources outside the ME/NAf region are indeed as large as estimated in the IIASA study, so that production of such resources would be effective in maintaining dependence on the ME/NAf oil producers at the relatively low level of the post-1980 oil glut (5.F). Moreover, if world oil demand were higher than the level assumed for this scenario, it is very likely that most of the extra demand would have to be met by ME/NAf producers. If world oil demand were just 1/4 higher than in the high demand scenario (corresponding to a mere 7% increase in world energy use) and if this incremental demand had to be met via increased ME/NAf production, that region would have to produce at near capacity levels -- a condition that would undoubtedly mean a much higher oil price (5.K) and greatly reduced global security.

The incremental energy demand associated with the high demand scenario could of course be met by expanding coal and nuclear power use instead, but the incremental supplies needed from these sources in order to provide reasonable assurances of a secure oil supply situation would require major compromises relating to the atmospheric carbon dioxide problem and nuclear weapons proliferation.

Of course the commercial success of new technologies such a amorphous silicon solar cells might enable expanded energy demand without jeopardizing the global goals we have established, but such technologies cannot be counted on at this time.

6 CONCLUSION

Drawing on the analysis of previous chapters we have shown that it appears to be both technically and economically feasible: (i) to meet basic human needs and to improve living standards considerably beyond the satisfaction of basic human needs without increasing per capita energy use levels in developing countries above the present average level, by taking advantage of opportunities to make much more efficient use of energy in both the modern and traditional sectors of developing countries; and (ii) to provide a continuing improvement in living standards in industrialized countries at the same time per capita energy use is reduced in half over the period 1980-2020 -- a possibility that arises as a consequence of both the ongoing structural changes in the economies of industrialized countries as well as the many opportunities for making more efficient use of energy.

From the global perspective these findings mean that it is feasible to meet ambitious economic goals in the period 1980-2020 without increasing the overall level of primary energy requirements. What would be required, however, is a continuing shift to higher quality energy carriers. For developing countries this would mean a major transition from the present situation -- where nearly half of primary energy requirements are provided by fuelwood, used largely for cooking -- to wide use of modern solid, liquid, and gasous fuels. For developing and industrialized countries alike it would mean a much greater degree of electrification of the world energy economy.

Our analysis also shows that as long as global energy demand is not too large, there can be considerable flexibility in the choice of energy supplies, the mix of which can be adjusted so as to develop a long run energy strategy which is consistent with the solutions of other major global problems: dependence on Persian Gulf oil can be reduced, so as to reduce the upward pressure on world oil prices and improve global security; expansion of fossil fuel use can be avoided, so as to reduce the risks of climatic change associated with the atmospheric buildup of carbon dioxide; and growth of nuclear power can be curbed, so as to reduce the risks of nuclear weapons proliferation.

We have not shown that the global energy balances we have arrived at are consistent with what can be achieved on a regional or country basis; that exercise remains to be carried out. As we have repeatedly stressed, a comprehensive global perspective on the energy problem must evolve as an integration of perspectives on individual countries and regions. But our analysis does suggest that there are no obvious significant global constraints to an energy future that is consistent with the solutions to other important global problems, and it thus provides a motivation for pursuing detailed country and regional analyses along these lines -- analyses that could subsequently be used to refine the global perspective as to what is achievable by pursuing end-use energy strategies.

Our sensitivity analysis shows further that a strong emphasis on energy-efficiency improvement is a robust approach to the problems we have posed -- i.e., the identification of an energy strategy consistent with the global goals we have established would not require that energy demand levels reach precisely the levels of the base case scenario. There would be a comfortable margin for planning error.

But this analysis has also shown that there would be little room to maneuver if demand were in the neighborhood of that for our high demand scenario. Our analysis thus highlights the importance of trying to pursue a global energy course in which total global energy use changes little over the next several decades. In such a course the pursuit of energy efficiency improvements would offset the expanded use of energy services that would arise from population and economic growth.

This course would require new policies that would facilitate the development of new energy service industries, along the lines suggested in (J. Goldemberg, T.B. Johansson, A.K.N. Reddy, and R.H. Williams, 1985). These new industries would be made up in part of existing companies (e.g., some utilities) converted from being purveyors of energy supplies into being purveyors of energy services as well. And it would be made up in part of entirely new institutions that deal exclusively in the marketing of energy efficient equipment and services for businesses and individual energy consumers (e.g., the energy management firms that are now emerging in the US to serve commercial and industrial businesses).

Bringing about a fundamental reordering of the energy problem from preoccupation with supply expansion to concern for the most effective ways to provide energy services would not be easy. But no other energy course for the future would be be easy either. The energy supply approach to the energy problem is foundering. The last several years have witnessed some of the most costly dry holes in the history of petroleum exploration. At the same time the falling world oil price brought on by the world oil glut beginning in 1980 has stymied efforts to develop supply alternatives to oil; in the US the massive attempts to launch a synthetic fuels industry have collapsed. The very survival of the nuclear power industry is threatened in many parts of the world. In relation to such problems, the challenge of creating an effective energy service industry does not seem to be so formidable.

If the end-use approach really catches on, it may actually prove to be easier to pursue than is indicated by our analysis. Our analysis has been restricted to technologies that are either already commerialized or are in such an advanced state of development that energy performance characteristics can be described fairly well. We have made no attempt to "guess" wholly new end-use technologies or to try to identify technological limits for future improvements in energy efficiency. Yet it is clear that there is room for much more innovation than what we have described. The technologies we have focussed on generally have energy performances that are still far from thermodynamic limits. For perspective it must be remembered that the era of concern for high-cost energy is only a decade old, and we are only now beginning to see the fruits of R&D efforts on end-use technologies that were initiated in the aftermath of the first oil crisis.

To sum up, the end-use strategy we have described, which involves emphasis on energy efficiency improvements in industrialized and developing countries alike, is not dependent on technological breakthroughs. It is economically feasible in the sense that investments in energy-efficiency often involve direct costs that are less than or equal to the costs of investments in the equivalent amount of energy supply. The major impediment to an end-use energy strategy is the present inadequate industrial infrastructure for marketing energy services.

It would seem to us that it is worth the challenge to public policy to see that the needed infrastructure is established, in light of the clear advantage of this approach to energy, which permits a broad menu of energy supply choice and thereby facilitates the formulation of an energy strategy consistent with and supportive of the achievement of a sustainable world.

Mahatma Gandhi would have understood clearly the desirablity of pursuing the end-use approach to energy. He knew that:

> The earth has enough for every man's need,
> But not for every man's greed.

Figure 1

OPEC pricing behavior: the percentage change in the real world oil price from the previous year vs. percent of OPEC production capacity used. The percentage of capacity utilization is equal to the crude oil production divided by the maximum sustainable production for that year. Source: (Energy Information Administration, US Dept. of Energy, May 1984).

OPEC PRICING BEHAVIOR (PERCENTAGE REAL PRICE CHANGE FROM PREVIOUS YEAR vs. PERCENT OF CAPACITY UTILIZED)

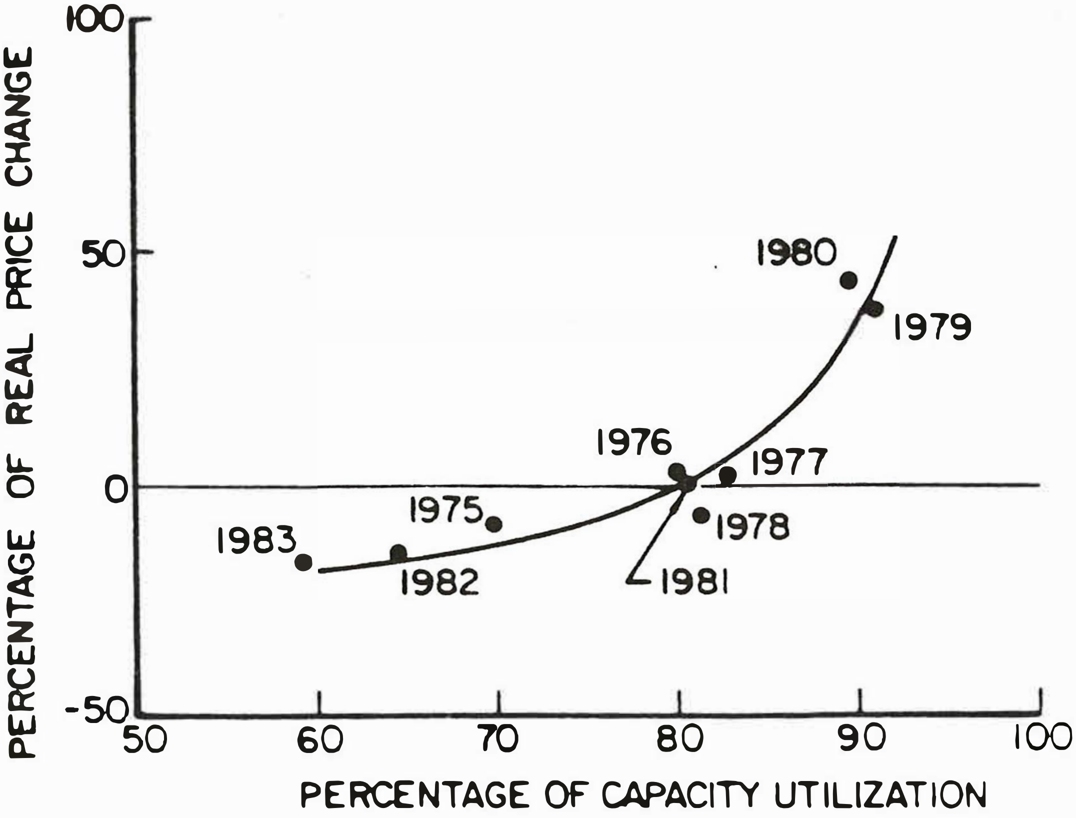
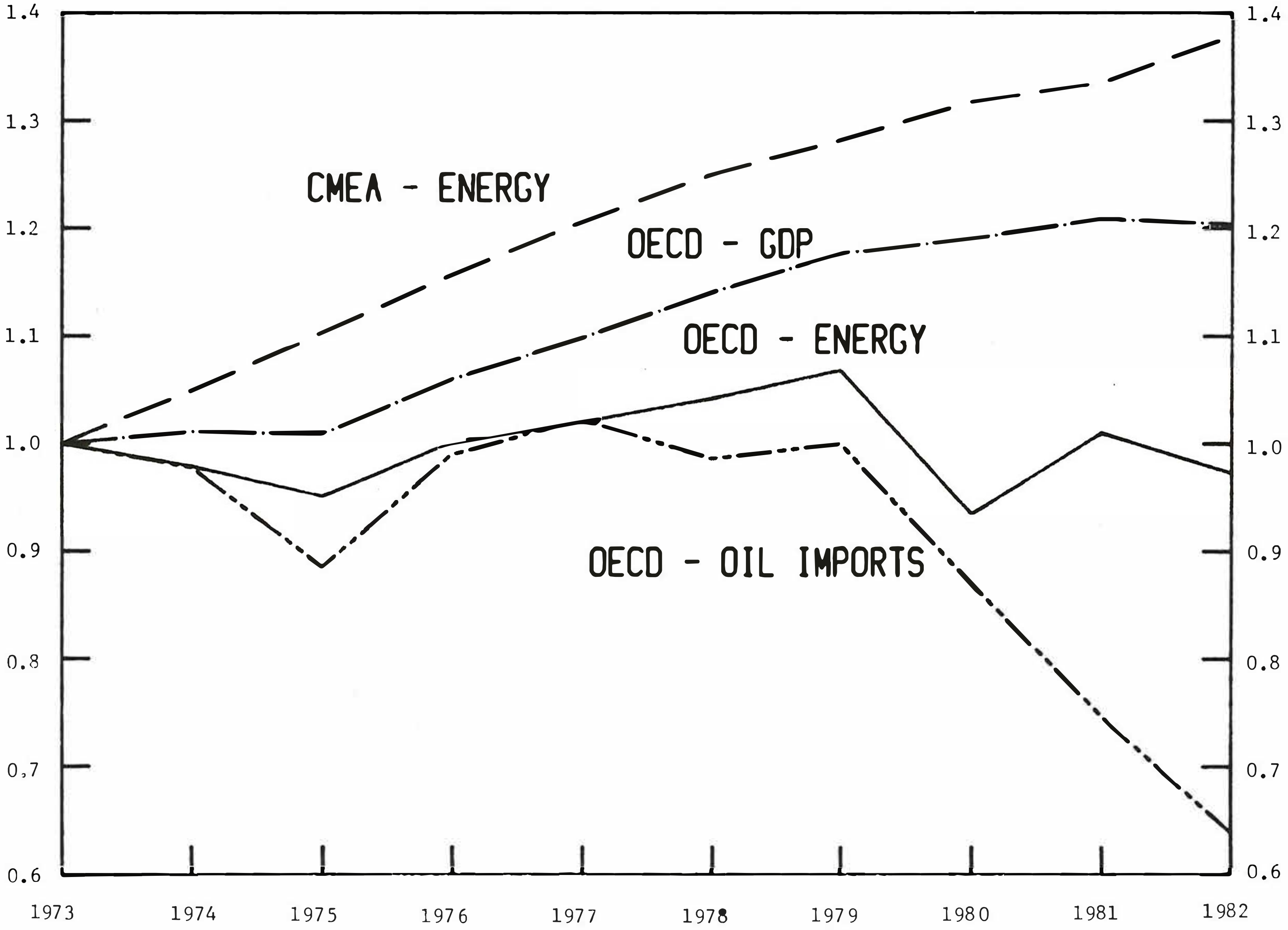


Figure 1

Figure 2

Recent trends in energy use for OECD (Organization for Economic Cooperation and Development (OECD) countries and for Council for Mutual Economic Assistance (CMEA) countries, and the trend in GDP for OECD countries, relative to 1973 levels.



PRIMARY ENERGY CONSUMPTION, NET OIL IMPORTS, AND GDP, 1973-1982 (1973 = 1.00)

Figure 2

Figure 3

Alternative projections of global primary energy use to the year 2020, disaggregated by consuming region. The WEC high and low scenario values are from (J. -R. Frisch, 1982). While the IIASA study focusses instead on the years 2000 and 2030, the IIASA report (Wolf Haefele *et al.,* 1981) also provides graphical presentations of energy use *levels* for intermediate years, on which the IIASA scenario numbers in this figure and in Figures 4, 6, 7, and 8 are based.

PRIMARY ENERGY PROJECTIONS TO 2020

Developing and Industrialized Countries

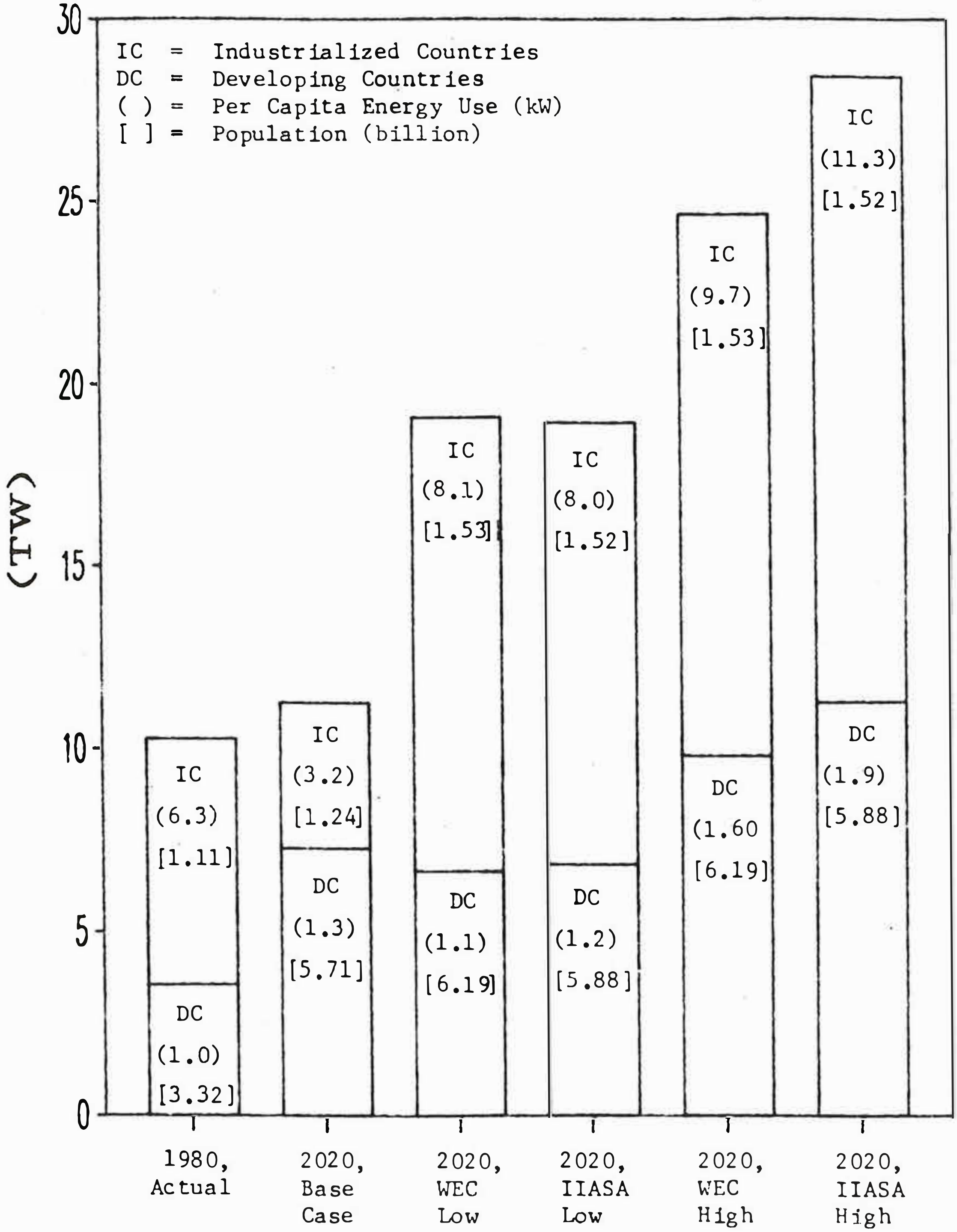


Figure 3

Figure 4

Alternative projections of global primary energy use to the year 2020, disaggregated by primary energy source. The WEC and IIASA scenarios shown are the averages of the high and low scenarios presented in these studies.

PRIMARY ENERGY PROJECTIONS TO 2020

By Energy Carrier

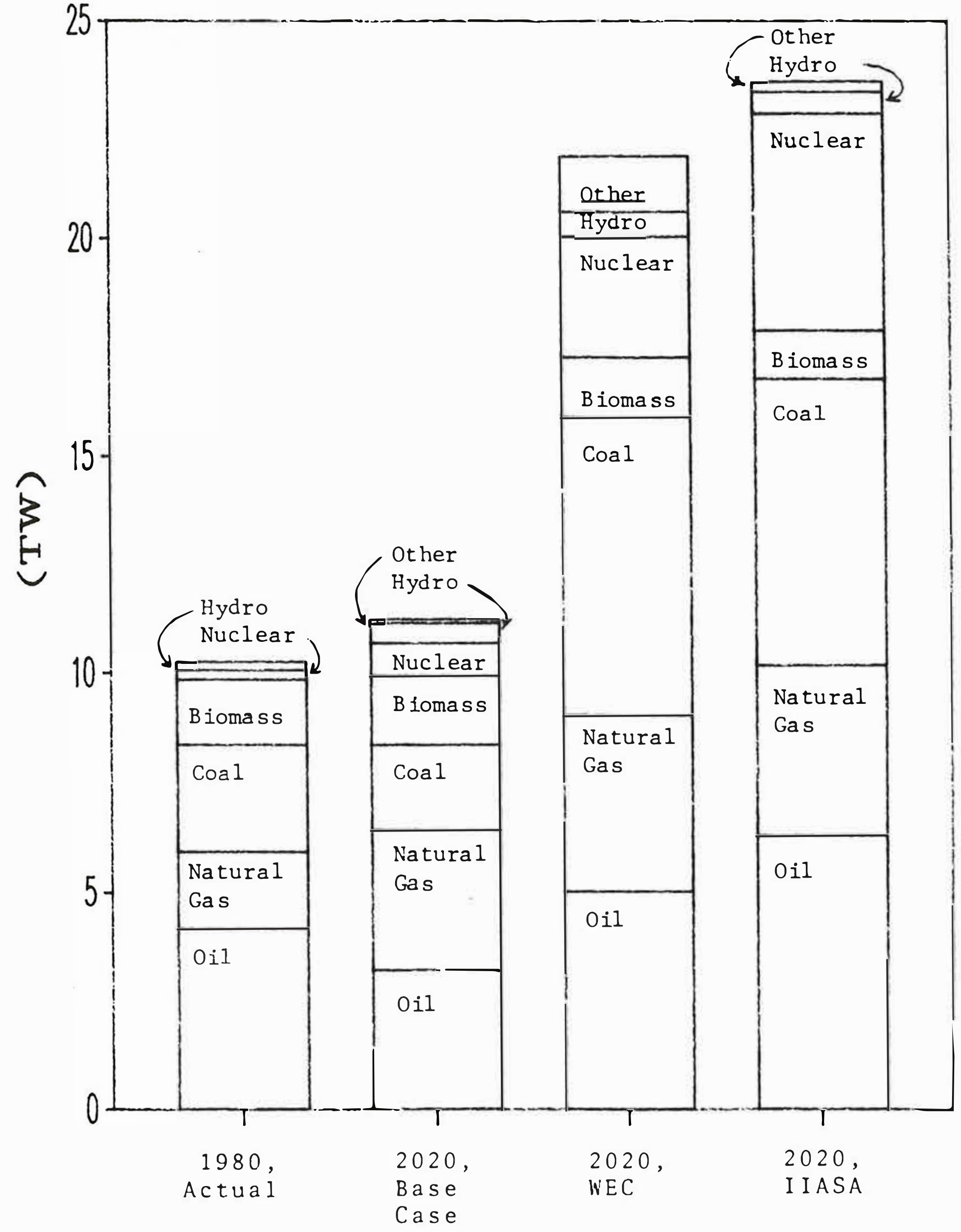


Figure 4

Figure 5

Constrained annual global coal production as a function of the allowable ultimate atmospheric carbon dioxide level, assuming that the CO2 constraint is reflected entirely as a constraint on the the use of coal, along the lines discussed in the text.

CONSTRAINED ANNUAL COAL PRODUCTION

VARIATION WITH ULTIMATE ATMOSPHERIC CO2 LEVEL

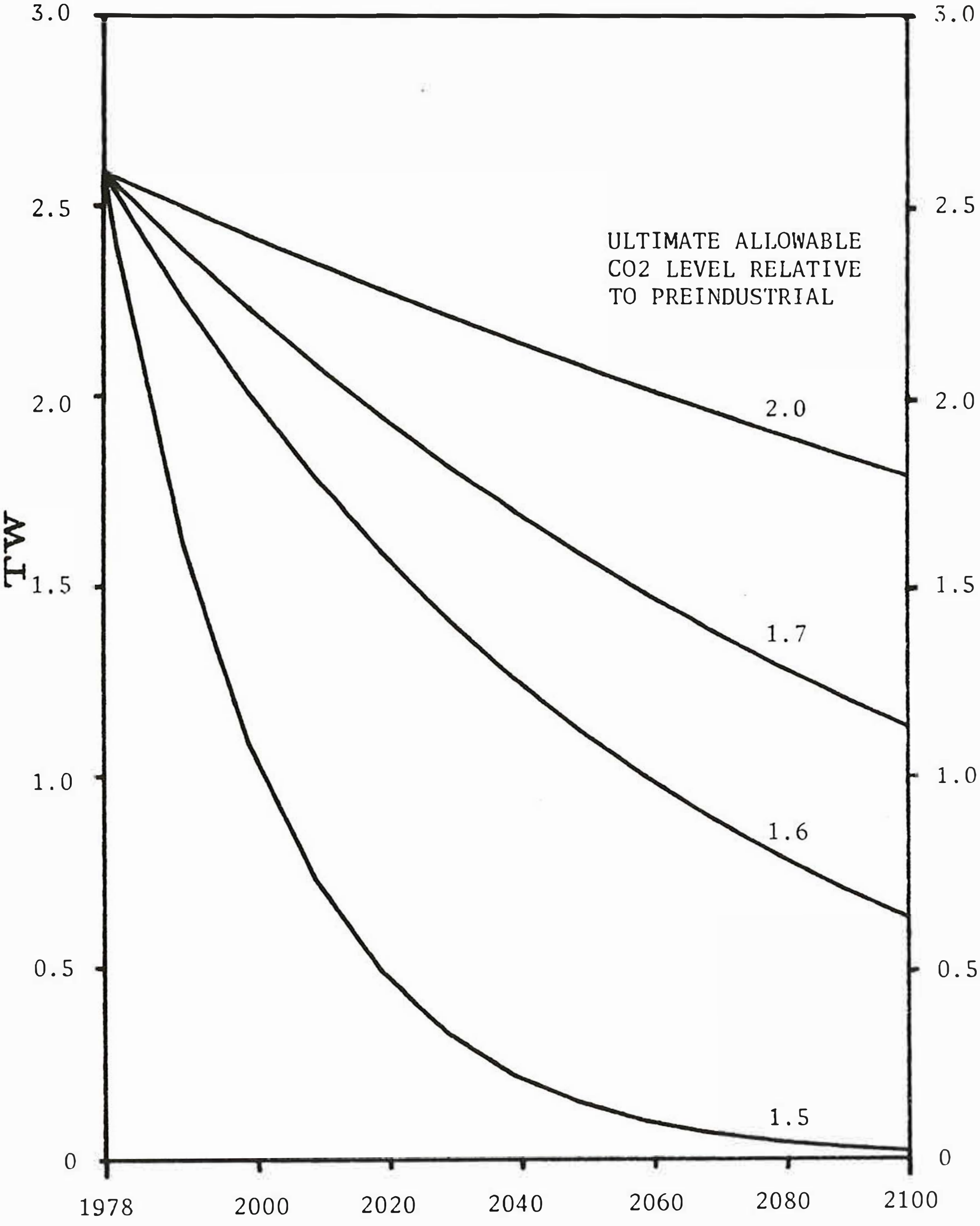


Figure 5

Figure 6

Alternative projections of global coal production.

PROJECTIONS OF COAL PRODUCTION

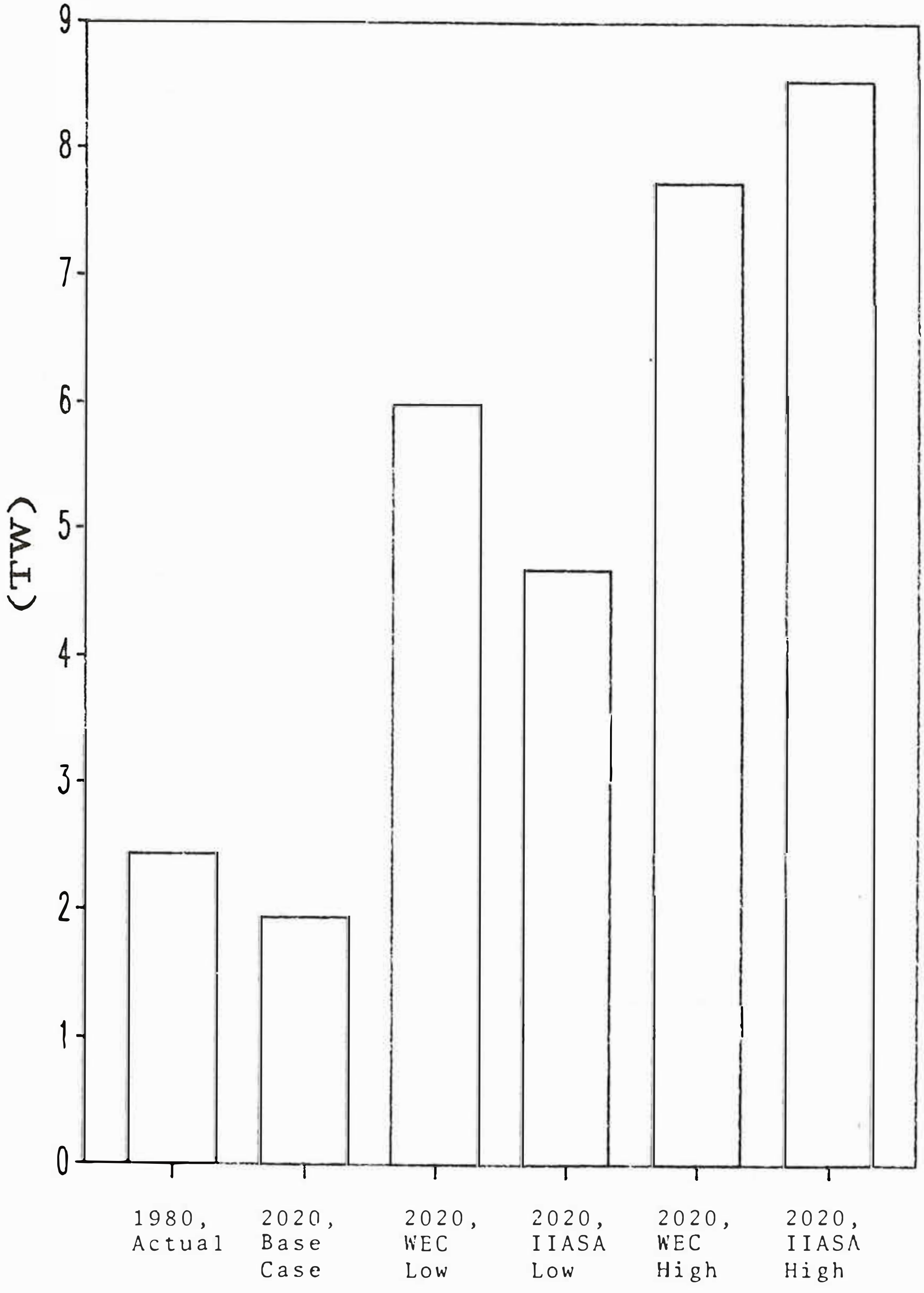


Figure 6

Figure 7

Alternative projections of global oil production, disaggregated into the Middle East/North African (ME/NAf) Region and the rest of the world. Also indicated is the maximum production capacity for the ME/NAf region for the period 2020-2030, as estimated in (Wolf Haefele *et al.*, 1981).

PROJECTIONS OF OIL PRODUCTION

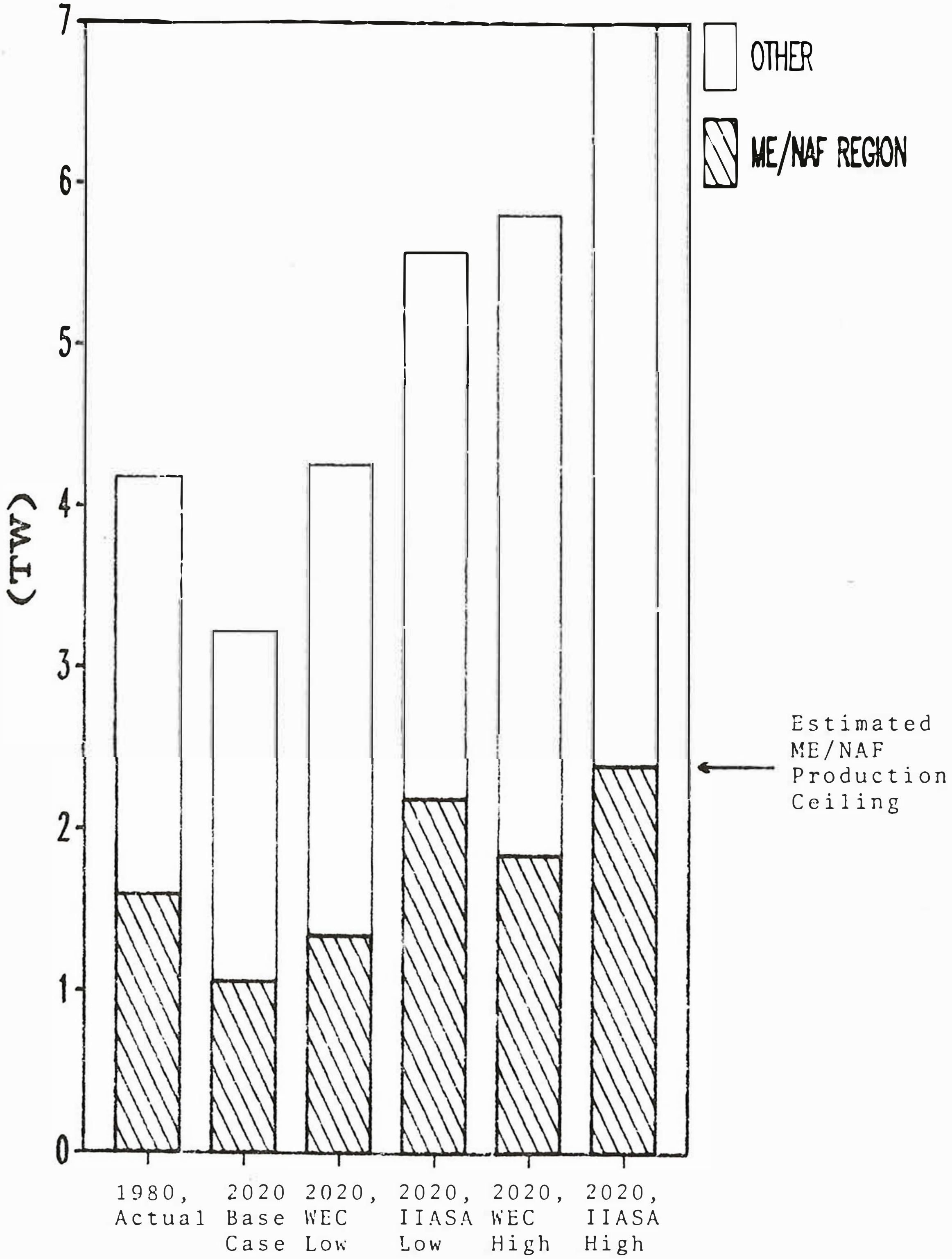


Figure 7

Figure 8

Alterative projections of primary energy use associated with nuclear power generation.

PROJECTIONS OF NUCLEAR PRIMARY ENERGY

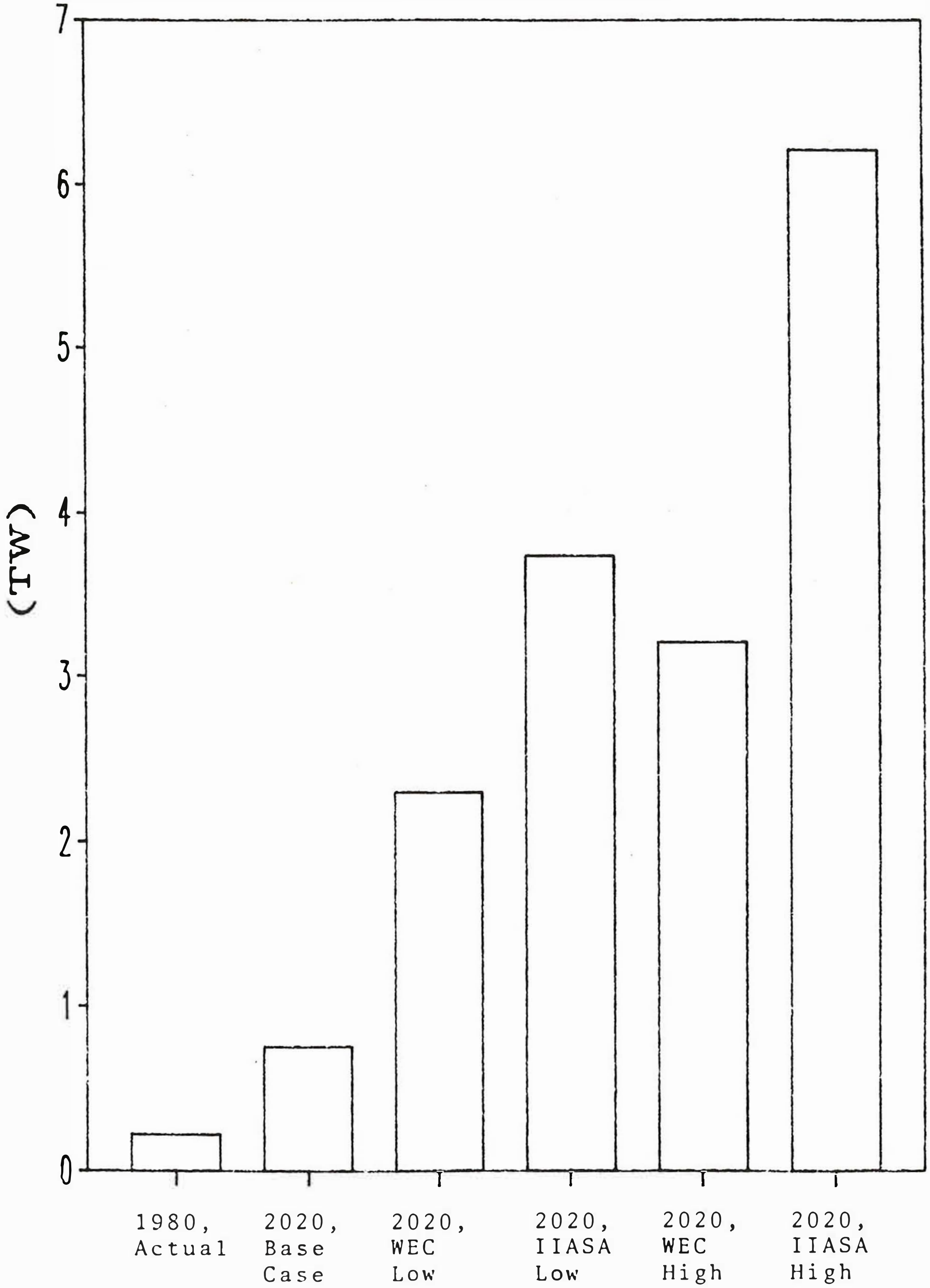
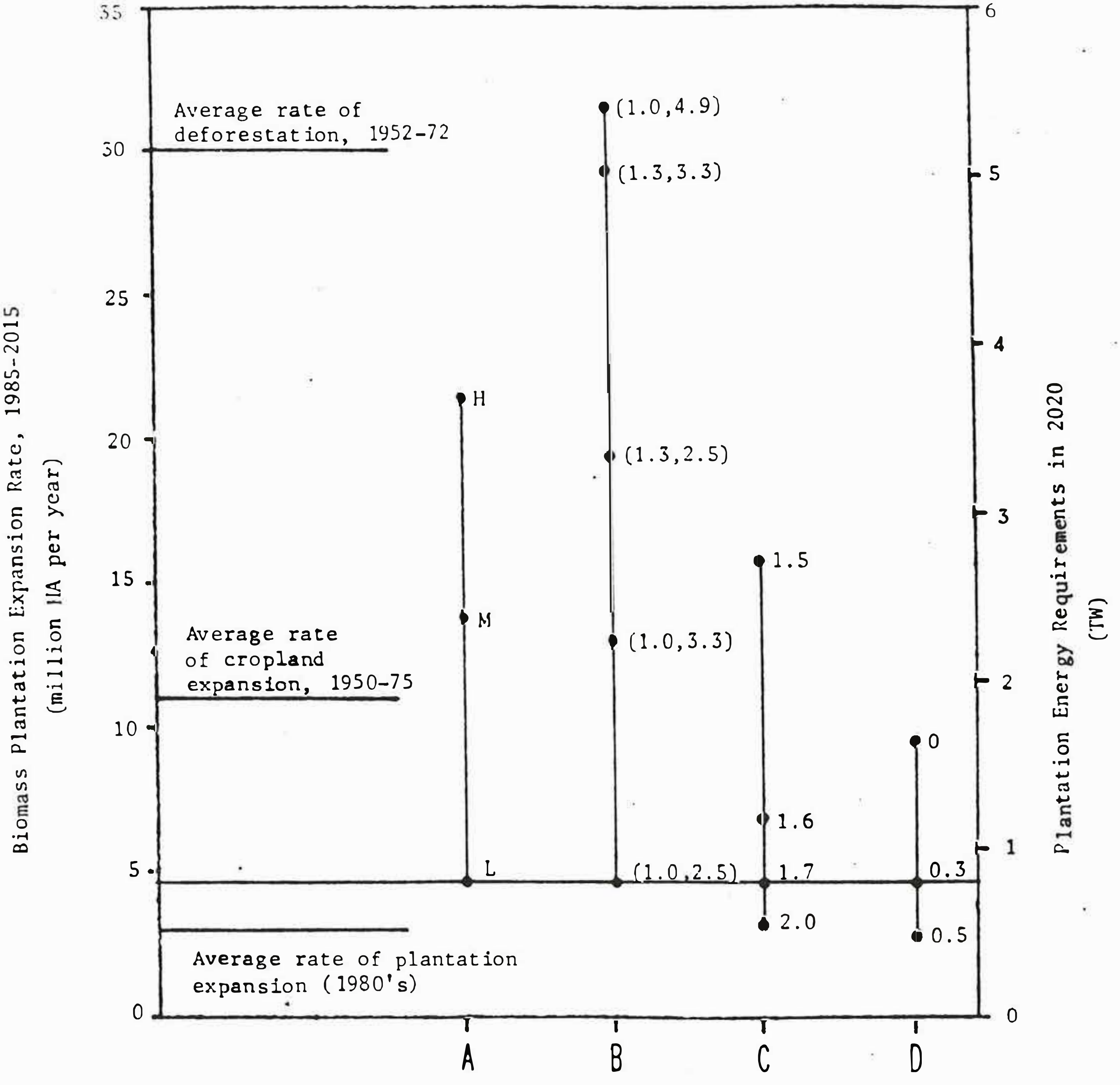


Figure 8

Figure 9

The results of sensitivity analysis, in which biomass is the "swing energy source" to bring energy supply and demand into balance as various scenario assumptions are altered. Shown here are the biomass requirements from energy plantations, farms, and/or woodlots -- both in terms of the required global energy production rate in 2020 (in TW) and in terms of the average plantation expansion rate (PER) in the period 1985-2015 that is required to ensure that enough biomass is available for harvesting in 2020 to meet global bioenergy requirements. See text for detailed assumptions.

IMPACT OF ALTERNATIVE SCENARIO ASSUMPTIONS ON PLANTATION ENERGY REQUIREMENTS



Key:
- A: Population
  - H = U.N. High Variant
  - M = U.N. Medium Variant
  - L = U.N. Low Variant
- B: Per-capita final energy demand (KW)
  - (developing countries, industrialized countries)
- C: Atmospheric CO_2 level relative to pre-industrial
- D: Nuclear electricity supply (TW)

Figure 9

Notes

Section 1

(1.A) The following are estimates of ultimately recoverable oil resources (as of 1977) and oil consumption (in 1978):

Region (a)	Oil Resources (b) (in TW-years)	Oil Consumption (c) (in TW)
I. NA	39.7	1.28
II. SU/EE	66.3	0.56
III. WE/JANZ	22.7	1.22
IV. LA	32.6	0.23
V. Af/SEA	30.0	0.21
VI. ME/NAf	154.8	0.11
VII. C/CPA	18.1	0.12
TOTALS	364.2	3.73

Notes

(a) The seven regions indicated here are defined as follows:

I	NA (North America)
II	SU/EE (The Soviet Union; Eastern Europe)
III	WE/JANZ (Western Europe; Japan, Australia; New Zealand; South Africa; Israel)
IV	LA (Latin America)
V	Af/SEA (Africa, except northern Africa and South Africa; South Asia; Southeast Asia)
VI	ME/NAf (Middle East; Northern Africa)
VII	C/CPA (China, other Centrally Planned Asian Economies)

(b) See Table 2.6, p. 57 in (Wolf Haefele *et al.,* 1981).

(c) See (J.-R. Frisch, 1982).

Section 2

(2.A) Recently there have been several global energy studies that depart from the traditional energy supply orientation. A study by Colombo and Bernardini (U. Colombo and O. Bernardini, July 1979) explores an energy supply-constrained energy future for the year 2030 (16 TW of primary global energy use) as an alternative to the IIASA scenarios. This study shares a number of features with the present one, including an emphasis on energy efficiency; but our analysis indicates a greater potential for energy efficiency improvement. A 1983 MIT study (D.J. Rose, M.M. Miller, and C. Agnew, November, 1983) exploring alternative energy strategies for coping with the CO2 problem found that improved energy efficiency offers the single most important opportunity to ameliorate the CO2 build-up, and described several viable scenarios with demand levels in the neighborhood of 15 TW for the year 2025. A 1981 study by Lovins *et al.* (A.B. Lovins, L.H. Lovins, F. Krause, W. Bach, June 1981) is perhaps the first global study to stress the importance of pursuing alternative energy strategies, including energy efficiency improvement, as a means of coping with the CO2 problem. Its targetted global primary energy use level for the year 2030 is only 5.2 TW. One of the main reasons this is so low is that the authors assume per capita primary energy use in developing countries can be reduced to 1/4 kW -- about 1/4 the 1980 level. We are skeptical that development needs can be satisfied with such a low level of energy use in developing countries.

Section 4

(4.A) In 1975 per capita GNP in the WE/JANZ region was $6250 (1982$), while that of Sweden was $11,050 (Bureau of the Census, 1984). Also the per capita GDP level for all industrialized countries in 1975 was about the same as that of the WE/JANZ region. Thus the per capita GNP level of Sweden was about 75% greater than the average for all industrialized countries in 1975.

(4.B) The following is and hypothetical final energy use scenario for a country in a warm climate, with a level of amenities (except for space heating) comparable to that in the WE/JANZ (a) region in the 1970s, but with currently best available or advanced energy utilization technologies:

	Activity Level	Technology, Performance	Average Rate of Energy Use (Watts per Capita) Electricity	Fuel	Total
Residential (b)	4 persons/HH				
Cooking	Brazilian cooking level (c)	70% efficient gas stove (d)		34	
Hot Water	50 l of hot water/capita/day (e)	heat pump WH, COP = 2.5 (f)	29.0		
Refrigeration	1 315 l refrigerator-freezer/HH	Electrolux, 475 kWh/year (g)	13.5		
Lights	New Jersey (US) level of lighting (h)	Compact Fluorescent Bulbs (h)	3.8		
TV	1 color TV/HH, 4 hours/day	75 Watt unit	3.1		
Clothes Washer	1/HH, 1 cycle/day	0.2 kWh/cycle (i)	2.1		
Subtotal			51	34	85
Commercial	5.4 sq. m floor space/capita (WE/JANZ ave, '75)	Performance of Harnosand Building (all uses, ex. space heating) (j)	22	-	22
Transportation					
Automobiles	0.19 autos/capita, 15,000 km/car/yr (WE/JANZ ave, '75)	Cummins/NASA Lewis Car @ 3.0 l/100 km (k)		107	
Intercity bus	1850 p-km/capita (WE/JANZ ave,'75)	3/4 energy intensity in '75 (l)		26	
Passenger train	3175 p-km/capita (WE/JANZ ave,'75)(m)	3/4 energy intensity in '75 (n)	4.5	32	
Urban Mass Transit	520 p-km/capita (WE/JANZ ave,'75) (o)	3/4 energy intensity in '75 (p)	2.0	8	
Air Travel	345 p-km/capita (WE/JANZ ave,'75)	1/2 US energy intensity in '80 (q)		21	
Truck Freight	1495 t-km/capita (WE/JANZ ave,'75)	0.67 MJ/t-km (r)		32	
Rail Freight	814 t-km/capita (WE/JANZ ave,'75)	Electric rail @ 0.18 MJ/t-km (s)	5		
Water Freight (incl. bunkers)	1/2 OECD Europe ave, '78 (t)	60% of OECD energy intensity (u)		50	
Subtotal			12	276	288
Manufacturing					
Raw Steel	320 kg/capita (OECD Eur ave, '78)	ave, Plasmasmelt & Elred Processes (v)	28	77	
Cement	479 kg/capita (OECD Eur ave, '80)	Swedish ave in 1983 (w)	6	54	
Primary Aluminum	9.7 kg/capita (OECD Eur ave, '80)	Alcoa process (x)	11	26	
Paper and Paperboard	106 kg/capita (OECD Eur ave, '79)	Ave of 1977 Swedish designs (y)	11	24	
Nitrogenous Fertilizer	26 kg N/capita (OECD Eur ave, '79/80)	Ammonia derived from methane (z)	-	36	
Other (aa)			65	212	
Subtotal	Swedish industrial mix w/ '75 W. European level of GDP/capita (bb)	Energy intensity for Swedish industry w/ '75 level of goods and services and advanced technology (cc)	121	429	550
Agriculture	WE/JANZ ave, '75	3/4 of WE/JANZ energy intensity (dd)	4	41	45
Mining, Construction	WE/JANZ ave, '75	3/4 of WE/JANZ energy intensity (dd)	-	59	59
TOTALS			210	839	1049

Notes

(a) Here WE/JANZ stands for Western Europe, Japan, Australia, New Zealand, and South Africa. The WE/JANZ 1975 average values for activity levels and energy intensities given in this table are from (A.M. Khan and A. Holzl, 1982).

(b) Activity levels for the residential sector are estimates, owing to lack of data for the WE/JANZ region.

(c) In Brazil cooking with LPG averages one 13 kg cannister per month for a family of 5, corresponding to per capita fuel consumption rate of 49 Watts, for an ordinary gas stove with a burner efficiency of about 50%.

(d) Assuming gas stoves with an efficiency of 70%. Such stoves, having low NOx emissions, have been developed by Thermoelectron Corporation for the Gas Research Institute in the United States (K.C. Shukla and J.R. Hurley, July 1983).

(e) In the US the average is about 100 liters per capita per day.

(f) For water heated from 20 to 50 degrees C. The assumed heat pump performance is comparable to that of the most efficient heat pump water heaters available in the US in 1982. These heat pump water heaters would provide a modest degree of air conditioning comfort as well, extracting some 5.5 GJ of heat from the living space each year.

(g) This Electrolux model was the most energy-efficient 2-door refrigerator/freezer available in Europe in 1982.

(h) It is assumed that 5 compact fluorescent light bulbs are used on average 4 hours a day. These bulbs, which can be screwed into ordinary incandescent sockets, draw 18 W but put out as much light as 75 W incandescent bulbs.

(i) Typical value for US washing machines.

(j) The Harnosand Building was the most energy-efficient commercial building in Sweden in 1981, at the time it was built. It used 0.13 GJ of electricity per square meter of floor area for all purposes other than space heating. For details, see (T.B. Johansson and R.H. Williams, 1985).

(k) The Cummins/NASA Lewis car is a design for a 51 kW, 4-5 passenger car (1360 kg curb weight) in a 1984 Ford Tempo body, with a 4-cylinder, direct-injection, turbocharged, adiabatic diesel engine with multi-fuel capability, and a continuously variable transmission (R.R. Sekar, R. Kamo, and J.C. Wood, 1984).

(l) In 1975 the average energy intensity of intercity buses was 0.60 MJ/p-km. A 25% reduction is assumed from the introduction of adiabatic diesel engines with turbo-compounding.

(m) In 1975 the the diesel/electric mix was in the ratio 70/30.

(n) In 1975 the average energy intensity of passenger trains was 0.60 MJ/p-km for diesel units and 0.20 MJ/p-km for electric units. A 25% reduction in energy intensity is assumed, arising from a switch to adiabatic diesels with turbo-compounding and the use of electric motor control technology.

(o) In 1975 the diesel/electric mix was in the ratio 60/40.

(p) In 1975 the average energy intensity of urban mass transit was 1.13 MJ/p-km for diesel buses and 0.41 MJ/p-km for electric mass transit. A 25% reduction in energy intensity is assumed, arising from a switch to adiabatic diesels with turbo-compounding and the use of electric motor control technology.

(q) In 1980 the US average energy intensity for air travel was 3.8 MJ/p-km. With the various improvements described in (F. von Hippel, 1981) this could be reduced by half.

(r) The assumed energy intensity is 1/3 less than the simple average today in Sweden for single unit trucks (1.26 MJ per tonne-km) and combination trucks (0.76 MJ per tonne-km), to take into account improvements via use of adiabatic diesels with turbo-compounding.

(s) The average energy intensity for electric rail in Sweden, with an average load of 300 tonnes and an average load factor of about 40%.

(t) The 119 kg of oil use per capita for water freight in 1978 in OECD Europe is assumed to be reduced in half because of reduced oil use (58% of Western European import tonnage and 29% of that of exports were oil in 1977) and emphasis on self reliance.

(u) A 40% reduction in fuel intensity is assumed, reflecting innovations such as the adiabatic diesel and turbocompounding.

(v) Assuming a 50/50 mix of the Elred process [requiring 10.7 GJ of fuel and 1.3 GJ of electricity per tonne] and the Plasmasmelt process [requiring 4.6 GJ of fuel and 4.2 GJ of electricity per tonne] for steelmaking. See (T.B. Johansson and R.H. Willliams, 1985).

(w) Assuming an energy intensity of 3.56 GJ of fuel and 0.40 GJ of electricity per tonne, the average for Sweden in 1983.

(x) Assuming an energy intensity of 84 GJ per tonne of fuel (the US average in 1978) and 36 GJ of electricity [the requirements for the Alcoa process now being developed -- see (Theodore R. Beck, January 1977).

(y) Assuming an energy intensity of 7.3 GJ of fuel and 3.2 GJ of electricity per tonne (the average for 1977 Swedish designs -- see

(z) Assuming an energy intensity of 44 GJ of fuel per tonne of nitrogen in ammonia, the value with steam reforming of natural gas in a new fertilizer plant (D.A. Waitzman *et al.,* 1978).

(aa) This is the residual, the difference between the manufacturing total and the sum of the items calculated explicitly. Energy usage associated with "other" for the non-manufacturing sectors is negligible and thus is not shown explicitly in this table.

(bb) Assuming a per capita GDP level equal to that of Western Europe in 1975, which was 55% of that in Sweden in 1975.

(cc) With advanced energy-efficient technology final energy use per capita for industry would have been 1.0 kW per capita in Sweden at the 1975 level of goods and services consumption [see (T.B. Johansson, P. Steen, E. Bogren, and R. Fredricksson, 1983)]. Since the per capita GDP in Western Europe was 55% of that of Sweden in 1975, we take 550 Watts as the norm for total industrial energy use per capita with advanced technology. We also assume that 22% of final energy demand in industry is electricity, the 1975 value for Sweden.

(dd) Assuming a 25% reduction in energy intensity, owing to innovations such as the use of advanced diesel engines.

(4.C) The following are alternative UN global population projections (United Nations, 1981a), in billions:

	1980	2020		
		Low Variant	Medium Variant	High Variant
Industrialized Countries	1.11	1.24	1.35	1.44
Developing Countries	3.32	5.71	6.47	7.14
WORLD	4.43	6.95	7.82	8.58

(4.D) The following is a summary of the main features of our base case energy demand scenario:

	Industrialized Countries		Developing Countries		World	
	1980	2020	1980	2020	1980	2020
Population (billion) (a)	1.11	1.24	3.32	5.71	4.43	6.95
Final Energy Use (b), in TW						
Fuels	4.77		2.77		7.54	7.23
Electricity	0.70		0.13		0.83	1.58 (c)
TOTALS	5.47	3.10	2.90	5.71	8.37	8.81
Per Capita Final Energy Use (kW)	4.92	2.5 (d)	0.87	1.0 (d)	1.89	1.27

Notes

(a) Assuming the 1980 UN low variant population projection.

(b) In these energy balances final energy use is defined as the total fuel (including bunkers) and electricity consumed by "final consumers". Excluded are losses in the generation, transmission and distribution of electricity, and the consumption of petroleum fuels by refineries.

(c) In 1980 10% of final global energy use was accounted for by electricity, which was about 0.8 times as large as the percentage for the US. In this global scenario it is assumed that in 2020 the global electrical fraction of final demand is again 0.8 times the value projected for the US in the US country study [see (J. Goldemberg, T.B. Johansson, A.K.N. Reddy, and R.H. Williams, 1985)], or 18%.

(d) Following the discussion in the text a base case scenario for 2020 is described wherein per capita energy use in industrialized countries is reduced in half and that in developing countries is assumed to be about the same as in 1980, or 1.0 kW.

(4.E) For our calculations of the allowable fossil fuel usage consistent with alternative ceilings on the atmospheric carbon dioxide level we assume: (i) that 0.63, 0.43, and 0.78 billion tonnes of carbon are released per TW-yr of oil, natural gas, and coal consumption, respectively; (ii) that 50% of the released carbon dioxide remains in the atmosphere; (iii) that the preindustrial atmospheric carbon level (as carbon dioxide) was 615 billion tonnes (290 ppm); and (iv) that the level in 1979 was 708.5 billion tonnes (334 ppm) or 1.15 times the pre-industrial level.

We also assume that ultimately the amount of oil and natural gas produced is equal to the present estimates of ultimately recoverable resources [365 TW-years for oil and 349 TW-years for natural gas -- see (1.A) and (4.I)]. Thus ultimately the amount of carbon as carbon dioxide remaining in the atmosphere from oil and gas use would be

$$0.5 \times [0.63 \times 365 + 0.43 \times 349] = 190 \text{ billion tonnes,}$$

or 0.31 times the preindustrial atmospheric level.

If half of the world's geological coal resources (8535 TW-Years -- see the following table) were eventually used up, the amount of net carbon build-up in the atmosphere as carbon dioxide would be

$$0.5 \times 0.5 \times 0.78 \times 8535 = 1660 \text{ billion tonnes,}$$

or 2.7 times the preindustrial level. Thus if this much coal but no more oil and gas were used up, the atmospheric carbon dioxide level would reach 3.85 times the pre-industrial level.

The following is an estimate of the total world geological resources of coal (a):

Country	Trillion Tonnes of Coal Equivalent	TW-Years (b)	Per Cent
USSR	4.41	4096	48
USA	2.33	2164	25
China	1.31	1217	14
Other	1.14	1059	12
TOTALS	9.19	8535	100

Notes

(a) (World Energy Conference, 1978).

(b) For a heating value of 29.3 GJ per tonne of coal-equivalent.

(4.F) We assume that allowable ultimate carbon dioxide levels are reflected in alternative coal consumption levels, and that coal production in a given year is proportional to the remaining coal left in the ground that can be eventually used without exceeding the specified ceiling on the atmospheric carbon dioxide level. Thus, for the above assumptions about oil and gas use, the allowable coal consumption schedule as a function of the atmospheric carbon dioxide ceiling is the following:

Maximum CO2 level as a fraction of pre-industrial level	Permissible total prod. (TW-yr)	1978	2000	2020	2040	2060	2080	2100
1.50	65.50	2.59	1.09	0.49	0.22	0.10	0.05	0.02
1.60	223.20	2.59	2.01	1.59	1.26	1.00	0.79	0.63
1.70	380.91	2.59	2.23	1.95	1.70	1.48	1.29	1.13
1.80	538.62	2.59	2.33	2.12	1.92	1.75	1.59	1.44
1.90	696.33	2.59	2.39	2.22	2.06	1.91	1.77	1.65
2.00	854.04	2.59	2.42	2.28	2.15	2.02	1.90	1.79

(4.G) In Tables 17-6 and 17-7, pages 531-532, in (Wolf Haefele *et al.,* 1981) it is estimated that the global coal eresources recoverable @ a cost of up to $40 per tonne (in 1982 $) [$25 per tonne in 1975 $] amounts to 560 TW-years (606 billion tonnes), while that available in the cost range $40 to $80 per tonne is 1019 TW-years (1105 billion tonnes). Coal @ $80 per tonne is equivalent to oil @ $17 per barrel, or 1/2 the world oil price in 1982.

(4.H) The distribution of world oil production (in million barrels per day) is as follows for our base case (BC) scenario and the WEC and IIASA scenarios (in million barrels per day), in relation to recent world production trends:

	1979	1980	1981	1982	1983	2020				
						BC	WEC (1982)		IIASA (1981)	
							Low	High	Low	High
ME/NAf	25.9	22.4	19.0	16.3	14.9	15	19	26	31	34
Elsewhere	39.9	40.4	40.2	40.7	41.5	30	41	56	47	64
TOTALS	65.8	62.8	59.2	57.0	56.4	45	60	82	78	98

(4.I) The following are estimates of ultimately recoverable natural gas resources (as of 1977) and natural gas consumption (in 1978):

Region	Gas Resources (a) (in TW-years)	Gas Consumption (b) (in TW)
I. NA	60.5	0.74
II. SU/EE	96.4	0.47
III. WE/JANZ	23.1	0.27
IV. LA	20.9	0.07
V. Af/SEA	18.4	0.02
VI. ME/NAf	117.1	0.04
VII. C/CPA	12.5	0.01
TOTALS	348.9	1.62

Notes

(a) See Table 2.7, p. 65 in (Wolf Haefele, 1981).

(b) See (J.-R. Frisch, 1982).

(4.J) One possibility is to use compressed natural gas directly as motor vehicle fuel (J.P. West and L.G. Brown, April 1979). In Italy some 270,000 vehicles were operated on compressed natural gas (CNG) in 1980; New Zealand has plans for converting 150,000 vehicles to CNG by 1985; and both Canada and Australia are gearing up for major conversions. Alternatively, natural gas might be converted to methanol.

(4.K) If world oil demand fell from 4.18 TW in 1980 to the base case scenario level of 3.21 TW in 2020, the required cumulative world oil production, 1981-2020, would be some 148 TW-years in this period. If in the period 1983-2020 production in the ME/NAf region were maintained at the 1983 "world oil glut level" of 1.06 TW (15 million barrels per day), cumulative oil requirements from regions other than the ME/NAf region in this period would amount to some

$$148 - (1.36 \times 3) - (1.06 \times 37) = 104.7 \text{ TW-years},$$

For comparison, world oil resources remaining outside the ME/NAf region and estimated to be ultimately recoverable at a price less than $26 per barrel (1982 $) is some 132 TW-years [see Table 17-6, p. 531 of (Wolf Haefele *et al.*, 1981)].

(4.L) The following are recent official projections of global nuclear electricity projections to the year 2000 (in TW of continuous electricity produced):

	1980 (a)	2000
US	0.0315	0.080 to 0.082 (b)
Other OECD	0.0346	0.097 to 0.104 (b)
Subtotal, OECD	0.0661	0.177 to 0.186 (b)
Other Market Economies	0.0016	0.018 to 0.027 (b)
TOTAL, Market Economies	0.0677	0.195 to 0.213
Soviet Union	0.0071	0.065 to 0.124 (c)
Eastern Europe & Cuba	0.0027	0.026 (c)
TOTAL, CPE	0.0097	0.091 to 0.124
TOTAL, WORLD	0.0774	0.286 to 0.337

Notes

(a) (The British Petroleum Company, 1982).

(b) (Office of Policy, Planning, and Analysis, US Department of Energy, October 1983).

(c) (International Energy Agency, 1982a).

(4.M) On the basis of economic calculations presented in (R.O. Sandberg, and C. Braun, April 8-11, 1984) the uranium price would have to rise to $100 per lb. of U308 (triple the present price) before plutonium recycle would be able to compete with current once-through fuel cycles. And even if the price of uranium should increase to $150 per lb. the cost advantage of recycle would amount to less than 2% of the busbar cost of power generation.

(4.N) The following is the assumed global electricity supply mix for our base case scenario (in average TW produced at the power plants):

	1980	2020
Hydro	0.19	0.46 (a)
Wind and Photovoltaics	-	0.09 (b)
Cogeneration		
Biomass	-	0.14 (c)
Fossil Fuel	-	0.13 (c)
Central Station		
Nuclear	0.08 (d)	0.30 (e)
Fossil Fuel	0.66 (f)	0.66 (g)
TOTALS	0.93 (h)	1.78 (h)

Notes

(a) It is assumed that 25% of the total electricity supply (4030 TWh/year) is hydro. This is 2/5 of the global economic hydro potential (9700 TWh/year) and 1/5 of the global technically usable potential (19,400 TWh per year) estimated in 1976 for the WEC (Ellis L. Armstrong, 1978). The 1976 WEC estimates of the economic potential are probably low, in light of subsequent electricity price increases and better resource estimates -- e.g, more recent estimates for Brazil and India indicate economic potentials there some 75% higher than the 1976 WEC estimates.

(b) It is assumed that 5% of the total electricity supply is wind and photovoltaics. Owing to the large uncertainties in the future of photovoltaics technology we do not specify how the wind/photovoltaics mix might be disaggregated.

In the event that photovoltaics technology is not commercialized, all of this electricity would be provided by wind. To put the resulting wind value (0.1 TW) into perspective, it can be compared to alternative assessments of the wind potential. The IIASA study (Wolf Haefele et al., 1981) estimated that globally the technical potential for wind power is 3 TW and the "realizable" potential is 1 TW. In another analysis for North America it is estimated that on 16% of the North American land area (mainly in the great plains) the wind energy density is in excess of 400 Watts per square meters, and that the mean electric power recoverable from this wind via Boeing Mod-2 windmills (2.5 MW each) spaced 1.5 km apart is 0.9 TW (Gordon Thompson, July 1981).

However, if the promise of photovoltaic technology is realized (E.A. Demeo and R.W. Taylor, 1984) the photovoltaic contribution could be considerable .

(c) Here it is assumed that the cogeneration fraction of total electricity production is 15%, the same as the percentage which we have estimated could be provided in the US in 2020 by the major steam-using industries. Here a 50/50 mix of biomass and fossil fuels is assumed for fuel inputs.

(d) Includes geothermal (which is small).

(e) It is assumed that in 2020 nuclear electricity is the same level officially forecast for 2000 in the early 1980s.

(f) Includes fossil fuel production via cogeneration (which is small).

(g) Central station power generation based on fossil fossil fuels is assumed to be the residual.

(h) Electricity demand (4.D) divided by 0.89 to account for T&D losses.

(4.0) The following is the assumed global primary energy supply mix for the base case scenario (in TW):

	1980	2020
Nuclear Power	0.22 (a)	0.75 (b,c)
Hydro (d)	0.19	0.46 (c)
Wind and Photovoltaic Electricity (d)	-	0.09 (c)
Fossil Fuels		
Coal	2.44	1.94
Oil	4.18	3.21
Natural Gas	1.74	3.21
SUBTOTAL	8.36	8.36 (f)
Biomass		
Organic Wastes		0.79 (g)
Plantations		0.79 (h)
SUBTOTAL	1.49 (i)	1.58 (j)
TOTALS	10.3	11.2

Notes

(a) It is assumed that 2.8 units of fuel are required to produce 1 unit of electricity in thermal power plants in 1980.

(b) It is assumed that 2.5 units of fuel are required to produce 1 unit of electricity in nuclear and coal-fired thermal power plants in 2020.

(c) See (4.N).

(d) The primary energy consumption associated with hydro, wind and photovoltaic electricity production is assumed to be the energy value of the output of these systems.

(e) It is assumed that on average 1.5 units of fuel is required to produce 1 unit of cogenerated electricity.

(f) Total fossil fuel consumption is assumed to be 8.36 TW, as in 1980.

(g) In the base case scenario it is assumed that half of the biomass is provided by organic wastes and half by managed biomass production. The level of organic waste use for energy purposes corresponds to about 1/5 of the estimated organic waste production level in 2020 [see (4.P)].

(h) Assuming 18 GJ per tonne of dry wood, this implies that 1.4 billion tonnes of wood are required annually. At an average yield of 10 tonnes per hectare per year, some 140 million hectares of plantation area would be required, which is less than 4% of the land area under forest today.

(i) Bioenergy data for less developed countries are from (D.O. Hall *et al.*, 1982b). For the United States bioenergy consumption by the paper and pulp industry in 1980 was 1.1 EJ (American Paper Institute, 1981), while wood consumption for household fuel was 0.87 EJ (Energy Information Administration, June 1982). Noncommercial energy use in other industrialized market economies was obtained from (International Energy Agency, 1982b). Fuelwood consumption data for Eastern Europe and the Soviet Union are from (United Nations, 1981b).

(j) From (4.D) the total final demand for all fuels is 7.23 TW. The demand for biomass fuels is the difference between the this total and the final use of fossil fuels. The latter is calculated as follows. Assuming that 3/4 of central station power generation is via coal converted @ 40% conversion efficiency coal used for direct purposes is:

$$1.94 - 0.75 \times 2.5 \times 0.66 = 0.70 \text{ TW}.$$

Assuming that 1/4 of central station power generation is via natural gas in steam-injected gas turbines @ 50% conversion efficiency and that 1/2 of the fossil fuel based cogeneration is via natural gas, for which 1.5 units of extra fuel is needed to produce each unit of electricity, natural gas use for direct purposes is:

$$3.21 - 0.25 \times 2.0 \times 0.66 - 0.5 \times 1.5 \times 0.13 = 2.78 \text{ TW}.$$

Assuming that 1/2 of fossil fuel based cogeneration is via oil, for which 1.5 units of extra fuel is needed to produce each unit of electricity, and that 10% of gross oil use is consumed in refining operations, oil use for direct purposes is:

$$3.21 - 0.5 \times 1.5 \times 0.13 - 0.1 \times 3.21 = 2.79 \text{ TW}.$$

Thus, the direct fuel requirements from biomass sources would be:

$$7.23 - 0.70 - 2.78 - 2.79 = 0.96 \text{ TW}.$$

Assuming average conversion losses of 30% in producing final energy carriers from biomass, the total amount of biomass required for direct fuels use would be 1.37 TW. In addition, some 0.21 TW would be required to produce 0.14 TW of cogenerated electricity [see (4.N)], assuming the same conversion efficiency as for electricity production via fossil fuels.

(4.P) The following is an estimate (in TW) of the global organic waste production rate in 1980 and projected to the year 2020:

	1980	2020
Forest Product Industry Wastes		
United States (a)	0.11	0.14
Rest of World (b)	0.27	0.44
SUBTOTALS	0.38	0.58
Crop Residues		
Industrialized Countries (c)	0.51	0.57
Developing Countries (c)	0.60	1.04
SUBTOTALS	1.11	1.61
Manure		
Industrialized Countries (c)	0.38	0.42
Developing Countries (c)	0.73	1.26
SUBTOTALS	1.11	1.68
Urban Refuse		
United States (d)	0.046	0.060
Other Industrialized Countries (e)	0.090	0.096
Developing Countries (f)	0.034	0.058
SUBTOTALS	0.17	0.21
TOTALS	2.77	4.08

Notes

(a) In 1979 roundwood production in the U.S. was 1.53 CM per capita (United Nations, 1981c) and residue production per unit of roundwood production was (Office of Technology Assessment, 1980):

Primary and Secondary Manufacturing Residues	0.406
Logging Residues	0.377
Stand Improvement Cuttings	0.203
TOTAL	0.986

These same values are assumed to hold for 1980 (2020), when the U.S. population was (is expected to be) 228 (296) million. At 10 GJ/CM total residue production in 1980 (2020) was (would be) 3.42EJ (4.53 EJ).

(b) In 1979 roundwood production outside the U.S. was 0.65 CM/capita (United Nations, 1981c). Here it will be assumed that residue production in the rest of the world is like that in the European Economic Community, where the ratio of residues to roundwood production is 0.32 (W. Paly and P. Chartier, 1980). For a population in 1980 (2020) of 4.14 billion (6.65 billion) residue production would be 8.61 EJ (13.83 EJ).

(c) Per capita production rates for 1975 are estimated in (Theodore B. Taylor, Robert P. Taylor, and Steven Weiss, March 1, 1982) to be (in watts):

	Industrialized Countries	Developing Countries
Crop Residues	460	182
Manure	342	221

These same rates are assumed for 1980 and 2020.

(d) In the U.S. urban refuse with an average heating value of 10.7 MJ/kg is generated at a rate of 1.63 kg per capita per day. It is assumed that this rate persists.

(e) In Europe refuse with an average heating value of 8.8 MJ/kg is generated today at a rate of 1.0 kg per capita per day (U.S. Environmental Protection Agency, November 1979). It is assumed that this rate applies on average to all industrialized countries outside the U.S, in both 1980 and 2020.

(f) It is assumed that one tenth of the population (the urban elite) generate urban refuse at the European rate.

(4.Q) While in principle a high level of crop residue recovery might be achieved by introducing harvesting techniques which recover residues simultaneously with the primary products, only part of these wastes would be available for energy purposes. In developing countries crop residues are often used as fodder for livestock. And some residues will have to be left behind to provide nutrients and to maintain soil quality.

To the extent that crop residues and manure are utilized for biogas production, however, it may often be feasible to return the nutrient-rich residuum from the biodigesters to the soil for such purposes.

In the case of forest residues, it may be necessary to restrict removals to the larger pieces, leaving behind the leaves or needles and twigs, in which the nutrients tend to be concentrated.

(4.R) As pointed out in Appendix A, various studies indicate bioenergy productivities on managed plantations ranging from about 7 dry tonnes per hectare per year (Mesquite, Saltbush, Kochia) in arid regions, to 10 to 15 tonnes (Willow, Poplar) in Sweden, to 40 to 60 tonnes (Eucalyptus, Leucaena) in Brazil or India.

One problem with many of these estimates is that the empirical evidence is often based on unusually good experience for limited plots where growing conditions are especially favorable. What is needed for energy planning purposes when targetting the production of billions of tonnes of biomass per year is long term experience on large plantations.

Foresters and ecologists with whom we discussed the task of making global projections did not feel that an average productivity of 10 tonnes per hectare per year was excessive for large scale production on managed plantations or energy farms.

Section 5

(5.A) In 1980 the amount of reforestation in 76 developing countries (excluding China) amounted to 1.15 million hectares (FAO, 1982).

Between 1950 and 1979 100 million hectares in China were replanted in forests, but only 28 million hectares of replanted area yielded surviving forests. Over the 10 year period 1972-1981 the rate of planting averaged 4.7 million hectares per year. In many areas the survival rate has increased recently to 50% or more. The official Chinese policy is to increase forest area from 122 million hectares in 1981 to 192 million hectares in 2000 -- i.e., at an annual rate of 3.5 million hectares per year (Bin Zhu, April 1984).

(5.B) Here we estimate the cumulative level of carbon dioxide in the atmosphere, assuming fossil fuels are phased out linearly from the 2020 levels indicated in (4.0), with the carbon release assumptions presented in (4.E). Under these assumptions the carbon remaining in the atmosphere as a result of emissions in the period 1980 to 2020 is:

For oil:

$$0.5 \times 0.5 \times (4.18 + 3.21) \times 40 \text{ years} \times 0.63 = 46.6 \text{ billion tonnes,}$$

For natural gas:

$$0.5 \times 0.5 \times (1.74 + 3.21) \times 40 \text{ years} \times 0.43 = 21.3 \text{ billion tonnes,}$$

For coal:

$$0.5 \times 2.44 \times [1 - \exp(-40 \times 0.0068)]/0.0068 \times 0.78 = 33.3 \text{ billion tonnes.}$$

Thus the total atmospheric carbon increment in this period would be 101.2 billion tonnes.

If fossil fuel use were to decline linearly to zero, 2020 to 2050, the cumulative carbon dioxide build-up in this period would be:

$$0.5 \times 0.5 \times 30 \times [3.21 \times (0.63 + 0.43) + 1.94 \times 0.78] = 36.9 \text{ billion tonnes.}$$

Thus with this fossil fuel phaseout scenario the ultimate level of carbon in the atmosphere (as carbon dioxide) would be

$$708.5 + 101.2 + 36.9 = 847 \text{ billion tonnes (399 ppm)},$$

which is 1.38 times the preindustrial level.

(5.C) To estimate the solar collector area required to provide hydrogen via electrolyss from amorphous silicon solar cells at the level of fossil fuel consumption in 2020 for the base case scenario (8.4 TW), we assume:

- o An average insolation rate of 200 Watts/square meter for sunny (desert) areas;
- o An average efficiency of amorphous silicon solar cells of 15% [a practical target value for tandem, multi-layered cells, according to a 1984 EPRI review (E.A. DeMeo and R.W. Taylor, 1984)].
- o An average efficiency for electrolysis of 80%.

Under these conditions the collector area required would be some 0.350 million square kilometers -- which is half the size of the state of Texas (0.691 million square kilometers) or 2% of the area of warm deserts of the world (17.8 million square kilometers).

(5.D) Let us suppose that P(t), the number of power plants in the year "t", is given by:

$$dP(t)/dt = - (1/T) \times P(t) + N,$$

where N is a constant rate of addition of new capacity in the period 2000 to 2020 and T is the average lifetime of a nuclear power plant. Then:

$$N = (1/T) \times [P(2020) - P(2000)\exp(-20/T)]/[1 - \exp(-20/T)].$$

With a 65% capacity factor:

$$P(2000) = 300/.65 = 460 \text{ GW(e)},$$

and for the high nuclear power scenario:

$$P(2020) = 500/.65 = 770 \text{ GW(e)}.$$

Thus, if T = 30 years, N = 36 GW(e) per year.

(5.E) The following is a summary of the main demand characteristics of the high demand scenario:

	Industrialized Countries		Developing Countries		World	
	1980	2020	1980	2020	1980	2020
Population (billion) (a)	1.11	1.24	3.32	5.71	4.43	6.95
Final Energy Use, in TW						
Fuels	4.77		2.77		7.54	9.67
Electricity	0.70		0.13		0.83	2.12 (b)
TOTALS	5.47	6.08	2.90	5.71	8.37	11.79
Per Capita Final Energy Use (kW)	4.92	4.9 (c)	0.87	1.0 (c)	1.89	1.70

Notes

(a) Assuming the 1980 UN low variant population projection.

(b) Assuming, as in the base case scenario, that 18% of final energy use is accounted for by electricity in 2020.

(c) In the high demand scenario it is assumed that per capita energy use in industrialized (developing) countries in 2020 is about the same as in 1980 or 4.9 kW (1.0 kW).

(5.F) The distribution of world oil production (in million barrels per day) is as follows for our base case (BC) and high demand (HD) scenarios, in relation to that for the WEC and IIASA scenarios (the averages for the high and low scenarios) and for recent years:

	1979	1980	1981	1982	1983	2020			
						BC	HD	WEC	IIASA
ME/NAf	25.9	22.4	19.0	16.3	14.9	15	15	22.5	32.5
Elsewhere	39.9	40.4	40.2	40.7	41.5	30	48	48.5	55.5
TOTALS	65.8	62.8	59.2	57.0	56.4	45	63	71	88

(5.G) The following is the assumed global primary energy supply mix for the high demand scenario (in TW):

	1980	2020	
Nuclear Power	0.22	0.75	(a,b)
Hydro (c)	0.19	0.60	(b)
Wind and Photovoltaic Electricity (c)	-	0.12	(b)
Fossil Fuels			
Coal	2.44	1.95	
Oil	4.18	4.46	(d)
Natural Gas	1.74	4.46	(d)
SUBTOTAL	8.36	10.87	
Biomass			
Organic Wastes		1.01	(e)
Plantations		2.00	(f)
SUBTOTAL	1.49	3.01	
TOTALS	10.3	15.34	

Notes

(a) It is assumed that 2.5 units of fuel are required to produce 1 unit of electricity in nuclear power plants in 2020.

(b) See (5.H).

(c) The primary energy consumption associated with hydro, wind and photovoltaic electricity production is assumed to be the energy value of the output of these systems.

(d) Oil and gas production levels (assumed to be equal) are the residual.

(e) It is assumed that 25% of the produced organic wastes can be recovered for energy purposes.

(f) Assuming that the PER, 1985-2015, is limited to 12 million hectares per year, that the average plantation yield is 10 tonnes per year, and that wood has a heating value of 18 GJ per dry tonne. Under these conditions some 3.5 billion tonnes of wood would be harvested on 350 million hectares in 2020.

(5.H) The following is the assumed global electricity supply mix for the high demand scenario (in average TW produced at the power plants):

	1980	2020
Hydro	0.19	0.60 (a)
Wind and Photovoltaics	-	0.12 (b)
Cogeneration		
Biomass	-	0.18 (c)
Fossil Fuel	-	0.18 (c)
Central Station		
Nuclear	0.08	0.30 (d)
Fossil Fuel	0.66	1.00 (e)
TOTALS	0.93 (f)	2.38 (f)

Notes

(a) As in the base case it is assumed that 25% of the total electricity supply (5300 TWh/year) is hydro. For comparison the 1976 WEC estimate of the global economic potential is 9700 TWh/year.

(b) As in the base case it is assumed that 5% of the total electricity supply is wind and photovoltaics.

(c) As in the base case it is assumed that the cogeneration fraction of total electricity production is 15%, with a 50/50 mix of biomass and fossil fuel inputs.

(d) As in the base case it is assumed that in 2020 nuclear electricity is the same level officially forecast for 2000 in the early 1980s.

(e) Central station power generation based on fossil fuels is assumed to be the residual.

(f) Electricity production is equal to the electricity demand level [see (5.E)] divided by 0.89 to account for T&D losses.

(5.I) If world oil demand increased from 4.18 TW in 1980 to the high demand scenario level of 4.46 TW in 2020, the required cumulative world oil production, 1981-2020, would be some 173 TW-years in this period. If in the period 1983-2020 production in the ME/NAf region were maintained at the 1983 "world oil glut level" of 1.06 TW (15 million barrels per day), cumulative oil requirements from regions other than the ME/NAf region in this period would amount to some

$$173 - (1.36 \times 3) - (1.06 \times 37) = 130 \text{ TW-years.}$$

For comparison the remaining world oil resources outside the ME/NAf region and estimated in (Wolf Haefele et al., 1981) to be ultimately recoverable at a price less than $26 per barrel (1982 $) is some 132 TW-years [see Table 17-6, p. 531 of (Wolf Haefele et al., 1981)].

(5.J) Using the carbon dioxide production coefficients given in (4.E) for alternative fossil fuels, and assuming that half of the released carbon dioxide stays in the atmosphere, we obtain the following net additions of carbon (in billion tonnes) to the atmosphere in 2020:

Base Case Scenario	4.9
High Demand Scenario	6.2
WEC Scenarios (ave. of High and Low)	10.2
IIASA Scenarios (ave. of High and Low)	10.8

(5.K) In (Wolf Haefele et al., 1981) the peak oil production capacity for the ME/NAf region in the period 2020-2030 is estimated to be some 34 million barrels per day (2.4 TW).

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