Working Paper

Global Energy / CO_2 Projections

Yuri Sinyak

WP-90-51
September 1990

IIASA

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Foreword

Once again, energy has become the focus of many national and international studies. But instead of concentrating on the energy resources and their depletion, which was the main point of the energy-related studies following the energy crises in the 1970s, the scope and direction of the long-term energy research activities is presently determined by climatic changes and risks to mankind and environment associated with the operation of energy systems. There are many uncertainties related to this problem, from energy demand assessments, especially in the developing world, to the rate of restructuring energy supply in view of the pressing necessity to reduce greenhouse gas emissions to mitigate or postpone future climatic changes. Available results in this area obtained elsewhere are still inconsistent, incomparable and hardly justified; and there is no clear understanding on how to combine the needs for improving life standards in the developing world with an increasing population and the inevitable growth of energy demand. This is the reason why IIASA recently resumed the energy research activity with a major emphasis on climatic changes and possible measures towards low-emission energy systems.

This working paper contains first results of IIASA's approach to solving the problem. The paper demonstrates the impact of different strategies with regard to the energy-economy development and the reshaping of the global energy system to reduce CO_2 emissions until the middle of the next century. The author shows that, in order to alleviate the negative impacts of energy systems on the climate, it will be necessary to undertake tremendous efforts to improve the energy use efficiency, to drastically change the primary energy mix, and, at the same time, to take action to reduce greenhouse emissions from other sources and increase the CO_2 sink through enhanced reforestation. The paper stresses once more the utmost importance of treating climate changes as a genuinely global problem, whose resolution requires international cooperation.

Bo R. Döös
Acting Program Leader
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1 Social and Economic Problems of the 21st Century and the Role of Energy Supply Systems

On the eve of the 21st century, world society is trying to formulate with hope and care the long-term features of its future. The main reasons for this are the growing crisis in interrelations between man and his environment, the increasing polarization of rich and poor countries, and the rethinking and reevaluations of uses and abuses of technological progress. We are entering the next century with many problems. Several of these problems can be only vaguely outlined now, and their impacts are still uncertain; but others have surfaced and demand immediate actions. Ways of coping with some of these difficulties are known, but for others it is necessary to undertake intensive studies with the collaborative efforts of many countries at different social and economic development levels and with different political systems. One thing is evident now: collaboration of all nations is the actual measure for mankind's safety. The complexity of most of the new problems increases at fast speed, which could only be compared with the speed of technological progress itself (if not faster!). Many of the problems arise simultaneously and amplify each other, thereby producing new difficulties and new problems.

Under these circumstances, the role of forecasting must be emphasized as the scientific approach to select the most important links between society and environment that demand special attention and collective study. Forecasts have not always been successful. However, in many cases preventive measures based on successful projections have been undertaken to avoid catastrophes or severe shocks on the national or international scene. These actions justify the usefulness and even the necessity of forecasting approaches in many spheres of human activities. Forecasting methods are being constantly improved; mankind learns by its mistakes. Successful forecasting remains to be a kind of art and completely depends on the background and outlook of the experts engaged in the activity. Therefore, the application of more than one approach in the elaboration of forecasts must be a main principle in forecasting.

We are not going to investigate here all the problems of mankind in the next century. We will only try to list several of them and show where energy problems are placed on this list against the background of contradictions and difficulties that will be characteristic of the next century. Global goals (or ideals!) for the next century could be briefly summarized as follows:

- A safe natural environment by reducing anthropogenic impacts.
- Development of poor countries with the aim at reducing the gap between developed and developing countries in their approach to and use of material and humanitarian values achieved by mankind. This process should be intensified with industrialized countries playing an active role and, based on new technological concepts, guaranteeing a safe environment and the continued existence of mankind.
- Peaceful coexistence and collaboration of states with different political systems, religions, cultures, and histories.
- Global disarmament and an alternative to war as a method of solving disputes between nations.

These goals will be difficult to achieve. Nevertheless, they outline the initial assumptions (optimistic in their matter) that will likely specify the background of global development over the next decades.

The successful solution of global problems is unlikely without a favorable political climate; removal of all local and global military conflicts; creation of new economic relations providing efficient collaboration of developed and developing countries in solving regional and global problems; and further improvements in democratic forms of government.

The role of moral and ethic principles will slowly increase [1] and be reflected in the following:

- Improving the intellectual potential of society.
- Eliminating all forms of national and religious contradictions; removal of genocide, racism, and nationalism.
- Enhancing national cultures.
- Raising the intellectual level of mankind, and providing all members of the society with equal rights to education.
- Developing a broad-scale humanitarian approach to solving social, economic, and environmental problems including the ethics of refusals and satisfying reasonable needs for material consumption.
- Reducing various forms of egotistical viewpoints, especially in solving social and ecological problems.

Technological progress will keep its leading role in social and economic development but will be governed by the following general principles:

- Humanization of technologies, technological concepts, and technical education.
- Safety criteria as major parameters in the research and design of new technologies and industries.
- Increases in life expectancy of humans and improvements in mankind's genotype.
- Abolishment of hunger and supplying the world population with high-quality food stuffs.
- Conservation of material resources use.
- Creation of new materials capable of supporting technological progress in the next century.
- Penetration of new spaces (e.g., oceans and cosmos);

From this viewpoint some new areas of technological progress will change our understanding of the industrial potential and structures in the next century (and will probably produce new environmental, moral, and ethical problems). These areas include:

- New materials: composite and ceramic.
- Genetic engineering and biotechnology.
- Micro- and optic- electronics.
- Nuclear fusion.
- Fine films and membranes.

As can be seen from this list (far from being complete and reflecting the author's subjective viewpoint), energy related problems, though not dominant, will continue to be among the high-priority global problems.

Energy is the essential element of mankind's existence and the moving force of all material culture. However, it is quite reasonable to assume that after reaching some level of material culture its role in social and educational progress will begin to decline giving superiority to humanitarian values. If this assumption is true, then a future gap between the growth rates of economy and energy demand will be justified. This trend has occurred in many highly developed countries during the 1980s and undoubtedly will continue over the next century (especially if it is stimulated by active government policies aimed at abating local and global environmental disruptions). Economic development at a stable (or even declining) energy consumption level is likely to be reality in the near future. This phenomenon will remove some stress from the global energy scene. On the other hand, there are several new energy technologies that already exist or are known in principle and could supply mankind with practically inexhaustible energy resources. Much depends on the costs of these technologies (as compared with existing ones), their development lead time, and their penetration. It is clear now that the exhaustion of cheap conventional energy resources will lead to the wide application of new energy technologies relying on abundant and inexhaustible energy sources. All this gives hope that mankind will not perish because of a lack of energy sources.

The real problem is how to provide further global energy systems development without additional burdens to the economy and the environment as well as with less risks to humanity and the biosphere. The leading principle in solving this problem is based on the introduction of the *social cost approach* for substantiating energy systems development and the choice of proper energy technologies. Social costs incorporate all costs and investments made during the lifetime of a technology and all direct and indirect costs associated with its impacts on human health, the biosphere, and climate. Only such a broad methodological concept, based on social cost assessments, is applicable in solving long-term energy problems.

The global situation of energy systems worldwide on the eve of the 21st century can be summarized as follows:

- Mankind makes its first steps toward the transition period from energy systems based on exhaustible fossil fuel resources to practically inexhaustible energy sources (e.g., fission and fusion, renewable energy resources).

- Ecological and safety aspects will be the main points of all future energy systems development concepts.

- Global energy demand is likely to continue to grow during the next century (at least during the first half) because of increasing population and further development of material production in developing countries, though energy demand growth will be much slower than in the past because of energy-savings and conservation measures at all stages of the energy flow from production to end-use. Energy demand growth will soon stabilize (at the end of the next century) at a level three to six times higher than that of today's.

- In case of expected relatively low energy demand growth rates, fossil fuel resources at any rate (even hydrocarbons) will play a leading role in energy supply until the middle of the next century.

- Renewable energy sources will hardly play a remarkable role in the world energy balance because of their low density and high costs except in countries with more favorable conditions, where this type of energy will be able to cover local energy needs. (The situation might change, of course, if fossil fuel use is limited because of climatic changes and if new technological breakthroughs and improvements in the safety of nuclear reactors are achieved.)

- Capital intensities of energy supply will increase but will keep the share of energy systems in total investments at a constant level (or even decline in the future), which will justify the needs for further intense efforts in energy savings and the transition to cheaper energy carriers. (This tendency will become more important as ecological requirements for energy technologies grow.)

In total, the global energy situation during the next century will not be critical if we follow a *reasonable long-term strategy* for energy systems development. However, to escape critical situations in the future, it will be necessary to find new concepts of energy development that, on a broader scale, take into account social, economic, and environmental impacts of energy development.

2 Energy-Environment Interactions as a Central Point of Energy Research Activities

The negative impacts depend on the energy production scale, which is followed by large amounts of waste (often toxic), e.g., flue gases and waste water. Toxic substances through migration of natural circulation of matter and energy enter trophic chains; accumulate in soil and species; reduce agricultural, forestry, and fishery production; speed up corrosion processes; and destroy buildings and landscapes. Air pollution and the declining quality of foodstuffs have negative impacts on human health and productivity. Microflora of natural biocenoses, which are responsible for self-cleaning of the environment, can transform into hostile (sometimes even pathogenic) agents in the natural system.

The reduction of toxic substances in waste water to the permissible level demands large quantities of fresh water (often ten or even one hundred times more than the volume of waste water). This action could results in the exhaustion of fresh-water resources, therefore it is not an adequate solution. The problem has to be solved at the sources where the pollutants are formed.

The following example illustrates the negative impacts energy systems have on the environment in the USSR. Air pollutants released into the atmosphere by these systems amount to 100–120 million tons of chemical substances per year, including 20 million tons of fly ash and soot, 40 million tons of carbon dioxide, 30 million tons of sulfur dioxide, 20 million tons of hydrocarbons, and 10 million tons of nitrogen oxides.

About 40 million tons of toxic pollutants (mainly hydrocarbons and NO_x) are generated by automobiles; with the high share of automobiles in large cities, this creates especially dangerous ground-layer concentrations of toxic pollutants. Hundreds of cities have pollutant concentrations higher than permissible national standards.

Thermal power plants release 2 million tons of salt and chemical components per year and produce 2 to 3 cubic kilometers of waste water (part of which contains oil products), requiring 10 to 20 times more fresh water to dilute to standard levels. The construction of hydroelectric stations was accompanied by the reduction of several million hectares of productive agricultural lands, unrecoverable damage to fishery, degradation of living conditions of many rivers, and change in the landscape of vast territories.

Fossil fuels production causes extensive damage to the environment (e.g., in the northern part of the Tjumen region, the total cumulative damage from crude oil and natural gas production and transportation over the past 25 years is estimated to be more than 40 billion rubles; in regions with coal surface mining, such as Kuzbass or Ekubastuz, millions of hectares of agricultural land became unusable).

Nuclear energy's safety has reached a critical level, which makes further development doubtful in many regions of the USSR as well as in other countries. According to some findings, economic damages from environmental pollution caused by energy systems are severalfold that of fuel market prices (in large cities it is even five- to tenfold), which is practically not taken into account when developing energy policies or deciding on technologial concepts for energy developments.

In total, the acute ecological situation common in the USSR is typical for several other nations. In spite of successes in environmental protection achieved by some developed countries, the global ecological situation is growing worse.

Atmospheric carbon dioxide is the major contributor to radiative forcing [55% in the mid-1980s and approximately two-thirds in the long-term perspective after the banning of chlorofluorocarbons (CFCs)]. According to rough estimates, during the last 100–120 years more than 200 billion tons of anthropogenic carbon (or 700 billion tons of carbon dioxide) were released into the atmosphere, of which two-thirds are the result of industrial activity – i.e., by burning of fossil fuels.

The energy sector, which generates 46% of the present greenhouse-effect gases, will keep its leading role in the future, increasing its share to 65% according to the IPCC (1990). Studies investigating the consequences of greenhouse-gas concentrations in the atmosphere predict an increase in surface air temperatures by 3 ± 1.5°C for a doubling of the "equivalent" atmospheric concentrations of CO_2. Climate changes in the polar region could be three to four times higher compared with the average of the planet. In moderate latitudes the increase could be two- to threefold. Global warming will increase evaporation, which results in increased water-vapor content and enhances the greenhouse effect because water vapor actively absorbs long-wave radiation. On the other hand, increasing water vapor in the atmosphere will cause the opposite effect because of increased cloudiness that is followed by the albedo's change and thus reduces the global warming. But the increase in global warming is definitly expected to be the predominant process. Anthropogenic trace gases such as N_2O, CH_4, and CFCs could also affect global warming because many absorb reflected radiation at a wave length of 8–12 μm. Because of the higher annual growth rates of emission for other greenhouse gases, global warming could occur earlier than calculated on the basis of energy projections.

The changed radiation balance will not only result in a global warming. Large-scale precipitation pattern will also be modified implying consequences for human activities (agriculture, forestry, and water-resource management). The agricultural zones in the Northern Hemisphere will shift north, which could be followed by the reduction of agricultural product yields because of the precipitation reduction in steppe and forest-steppe zones, i.e., in zones with highly productive soils.

Global warming will inevitably increase sea level, because of both melting of glaciers and the expanding of ocean water. The Arctic ice cover will reduce, although it might initially increase in thickness. The sea level will ultimately go up by 35–65 cm (IPCC, 1990). To overcome these negative impacts will require worldwide efforts.

It is evident now that the ultimate solution of global environmental problems at all levels is impossible without introducing energy technologies that are more environmentally benign – presently this is not accounted for in long-term energy programs. This could be accomplished with understanding of the importance of this policy from the public, the scientific community, and decision makers. Such a policy would call for new construction work with short pay-back periods, which is due to a large reduction in the environmental and human health losses (calculating the pay-back time on the basis of the social cost concept). Efforts must be made to assess environmental losses (locally and globally, short and long term) and, even more important, to supplement these calculations with reliable ecological and climatic information. When choosing new energy technologies or defining strategies for energy systems development, it is necessary to compare the additional pollution abatement costs with the reduction in damages due to the abatement. Such an approach of assigning a priority index to all abatement measures, based on a cost-benefit analysis, could provide effective environmental programs and minimize the negative consequences of global warming. This new element in global energy studies requires detailed investigation on a broad, international basis and the approval of different scientific institutions.

3 New Ways of Technological Progress and its Impacts on Energy Demand and Supply

The achieved levels of social and economic progress are characterized by the increasing role science plays as a driving force of changes taking place in society and its relations to the environment. This tendency appeared recently, and will demonstrate its forms and efficiencies in the years to come. At the same time scientific activities, with positive as well as negative impacts on civilization, will be analyzed from a viewpoint of more rigid requirements and constraints based on social, ecological, safety, and economic criteria. The ethics of responsibility for mankind's fate will play a growing role when solving the increasing number of technological problems.

As stressed above, the role of material production will remain predominant in global social and economic developments, though its importance will systematically decline. This means that technological progress takes place first of all in the field of material production, where its impact has the largest efficiency. But in time, the importance of nonmaterial spheres of societal life will steadily rise, providing changes in lifestyles.

Mankind should try to aquire a new concept of material production development, which features the following:

- Ecology and safety of new technologies and products.
- Social cost effectiveness.
- Miniaturization of product goods.
- Material and energy savings at production and consumption levels.
- Respect for national and local features, traditions, culture and religion when choosing new technologies and material concepts.
- Concerns about the impacts of long-term concepts and projections on today's solutions.

These requirements will have to be included in new energy concepts and technologies when elaborating long-term energy projections at global and regional levels. One thing is certainly clear: the application of these approaches to material production systems (including energy systems) requires less energy per unit of goods or services produced by society and will further increase the gap between economic and energy demand trends.

4 Long-Term Global Energy Projections

4.1 Background

The main goal of long-term forecasting of social and economic events, such as energy projections, is not to define the accurate quantitative values of different factors characterizing the state of the art of the system under consideration. Rather it is to clarify principal trends and tendencies that will dominate over the projected period and that may bring about new and unforeseen difficulties and problems capable of changing the flow of progress. Long-term energy projections can have different intentions. Of most interest to us are the problems of exhausting cheap fossil fuel resources and the impacts of air pollution on the climate, caused by different energy consumers and energy systems as a whole.

The most promising approach to long-term projections is based on the simulation of the world energy system in its development and restructure. Such an approach provides the possibility for evaluating the prospected outcomes of systems development under different sets of input hypothesis and data. Scenario projections also have a few drawbacks, one of which is the subjective judgment resulting from the philosophies of the author. From this viewpoint, the projections in this paper might also suffer from a similar "disease."

Correct, long-term projections – especially for complex systems in social, economic, and technical areas – are rare. The selection of experts for the projection process has to be done with great care. Of course, this is often very difficult to fulfill and does not, however, imply the usefulness of long-term projections at all. On the contrary, even odd projections could play a positive role (for example, as a learning step to the next ones). Post-analyses of long-term projections lead to improvements in the way of thinking, the methodologies used, etc., and to more efficient future projections.

The main trends and tendencies of energy systems worldwide, briefly analyzed above, are used implicitly for the long-term energy demand projections given below. Energy demand is assessed with the help of a simplified model, calculating demand as a function of GNP growth rates and energy/GNP elasticities. The share of electricity generation in primary energy is evaluated on the basis of past experience and future assumptions of the role of electricity and electrification in the social and economic development of regions. To convert primary energy into electrical units, we used specific fuel consumption assessments for the generation of 1 kWh at thermal power plants, taking into account different technical levels of electricity generation systems in developed and developing countries and expected technological progress in the area of consideration. As energy projection output indicators we specified some relative values (e.g., energy consumption per capita and per unit of GNP), which are analyzed over the time period or between regions to establish an accurate projection procedure.

If there is a strong fluctuation in output indicators or if they are incompatible with initial assumptions or judgments, then new iterations will be made until the output indicators reach "reasonable" levels. However, it is again quite evident that these "reasonable" levels are highly dependent on the persons engaged in the projection activity. This is one reason for the subjective character of conclusions and findings of this study as well as all studies based on a scenario approach. The projections described below are based on "moderately conservative views" concerning changes in economies and energy systems. This means that in real life the changes might be much larger and faster and will result in more changes in energy supply and demand as compared with those assumed in this study.

The energy projections are carried out for the major regions of the world as determined by the World Energy Conference. All socialist countries, including China, are considered as one region. For all regions we assessed expected levels of total primary energy demand and electricity generation. Fossil fuel production by fuel types and generation of other forms of primary energy (nuclear, hydro, and other renewables) are evaluated for the world as a whole.

The total time period under consideration is split into two sub-periods: 1990–2020, with 10-year intervals, and 2020–2060, with two 20-year intervals.

The demographic projections are considered to be the most important factor for energy forecasts. The trend of world population is difficult to forecast. According to many assessments, world population will reach over 6 billion by the beginning of the next century. It is evident that nowadays the world population growth rate is declining. The highest population growth rate was during the period 1970–1980, when the annual average growth rate was equal to 1.95% for the world as a whole and 2.37% for developing countries. During the next five-year period it declined to 1.7% for the world, and was equal to 2.9% for Africa, 1.7% for Asia, 0.9% for North America, and only 0.3% for Europe.

At the start of the 21st century, the world average population growth rate is likely to be 1.44% (0.53% for developed and 1.72% for developing countries). The population of Africa and Latin America will have the highest growth rates. On the other hand, the majority of West European and North American nations will notice a stabilization in population growth. World population by the year 2025 is expected to reach 8 billion. According to many world/regional demographic assessments, world population will continue to increase until the end of the next century and then will stabilize at the level of 10 to 12 billion; the stabilization of population growth in developed countries will be much earlier (e.g., "zero growth" in the USA could be a reality by 2030–2040 and in Western Europe in the first quarter of the next century).

The share of the population not living in rural areas or settlements will continue to increase and by 2000 half the world population is likely to live in cities (this share will be even higher in developed countries, 78% for Europe and 83% for Australia and Oceania). By the year 2025, two-thirds of the world's population will live in cities that will be characterized by life-styles and patterns of energy consumption. First of all, this trend will result in a further strong reduction in noncommercial fuel consumption (fuelwood, charcoal, dung, etc.) and in the expansion of centralized energy supply systems (electricity and heat supply grids, oil and gas pipeline networks) with higher energy efficiency, more flexibility and reliability, and higher costs.

The regional economic development growth rates are exogenous, using assumptions about the social progress and economic basis of regions with different economic development levels. The concept of GNP per capita stabilization is applied to developed countries; this means that after reaching a certain level (of course, much higher than today's), the GNP per capita remains almost unchanged over a long period.

Other input parameters are evaluated on the basis of expected economic and energy systems parameters of different regions. The quantitative parameters used in the model are summarized in *Table 1.*

Two major factors for scenario elaboration are selected which are extremely important for future energy demand projections:

- Energy conservation policy (*moderate*, under prevailing implementation of market forces for reconstruction of energy systems; *enhanced*, with the support of the government and special incentive regulations).
- Rates and ways of changing the primary energy mix (refers to nuclear energy and fossil fuel production, in particular to natural gas, in view of environmental and climatic changes).

As a result the following scenarios and options within the scenarios are chosen for consideration:

Base Case, Scenario A

A1 Business-as-usual (with normal technological progress in energy systems without special constraints on levels and structures of primary energy production); energy conservation is controlled only by market forces.

A2 The same as in A1 but with a nuclear moratorium after 2010 (after this time the share of nuclear energy is assumed to stabilize at the achieved level until 2060).

A3 The same as in A1 but with a nuclear reduction after 2010 (practically stop nuclear energy production until 2060).

A4 The same as in A1 but with limited fossil fuels use starting at 2010 ("greenhosue abatement option").

Enhanced Energy-Saving, Scenario B

B1 Economic and social development is carried out under special state regulations to support enhanced energy savings, no special limitations for the primary energy mix.

B2 The same as in B1 but with a nuclear moratorium after 2010.

B3 The same as in B1 but with a nuclear energy reduction after 2010.

B4 The same as in B1 but with limited fossil fuels use after 2010.

Table 1: Input data for the global energy scenarios

A) Base Scenario

Regions	Units	1980	1990	2000	2010	2020	2040	2060
North America								
Population	mln.	248	274	296	315	330	336	340
GNP annual growth	%/yr	3.03	2.5	2	1.5	1	0.8	0.5
Energy/GNP elasticity	%	0.26	0.25	0.2	0.1	0	-0.1	-0.5
Electricity share	%	32	35	38	45	50	52	55
Western Europe								
Population	mln.	422	440	461	480	490	490	490
GNP annual growth	%/yr	2.97	2.5	2.5	2	1	1	0.5
Energy/GNP elasticity	%	0.61	0.35	0.25	0.2	0.1	0	-0.5
Electricity share	%	39.8	45	50	55	60	65	65
Pacific Region								
Population	mln.	135	143	151	154	156	157	157
GNP annual growth	%/yr	4.6	4	3.5	2.5	1	0	0
Energy/GNP elasticity	%	0.61	0.35	0.2	0.1	0	-0.2	-0.6
Electricity share	%	43	47	52	57	65	67	68
North Africa and Middle East								
Population	mln.	158	212	245	275	300	320	335
GNP annual growth	%/yr	4	4	3.5	2.5	2.5	2.2	2.2
Energy/GNP elasticity	%	1.17	1.1	1.1	1	0.9	0.7	0.5
Electricity share	%	29	32	36	45	50	55	60
Africa south to Sahara								
Population	mln.	361	490	667	880	1245	1300	1350
GNP annual growth	%/yr	4.05	4	4	4	4	4	4
Energy/GNP elasticity	%	1.39	1.3	1.25	1.2	1.1	1	0.9
Electricity share	%	52	50	48	45	40	45	50
South Asia								
Population	mln.	986	1160	1386	1550	1865	2000	2200
GNP annual growth	%/yr	3.44	4	4	4	4	4	4
Energy/GNP elasticity	%	1.83	1.5	.4	1.2	1.1	0.9	0.7
Electricity share	%	42	42	45	47	49	50	50
South-East Asia								
Population	mln.	343	417	498	550	637	700	740
GNP annual growth	%/yr	7.1	4	4	4	4	4	4
Energy/GNP elasticity	%	1.28	1.25	1.2	1.1	1	0.9	0.7
Electricity share	%	33	35	37	40	42	44	46

Latin America								
Population	mln.	364	480	625	820	960	1080	1220
GNP annual growth	%/yr	6.16	4	4	4	4	3.5	3.5
Energy/GNP elasticity	%	1.06	1.05	1	0.9	0.8	0.6	0.4
Electricity share	%	37	40	42	45	50	55	60
Socialist Countries								
Population	mln.	1451	1650	1810	1930	2050	2100	2120
GNP annual growth	%/yr	6.2	5	4	4	4	4	3.5
Energy/GNP elasticity	%	1.06	0.75	0.65	0.5	0.35	0.2	0.05
Electricity share	%	28	31	35	38	42	47	53

Note: Electricity share is given as the ratio of primary energy consumed for electricity generation in total primary energy demand; nuclear, hydro and other renewable electricity as well as electiricty import are expressed as replacement of fossil fuels at thermal power plants.

B) Enhanced Energy Saving Scenario

Regions	Units	1980	1990	2000	2010	2020	2040	2060
North America								
Population	mln.	248	274	296	315	330	336	340
GNP annual growth	%/yr	3.03	2.5	2	1.5	1	0.8	0.5
Energy/GNP elasticity	%	0.26	0.2	0.1	0	-0.1	-0.25	-0.65
Electricity share	%	32	35	38	45	50	52	55
Western Europe								
Population	mln.	422	440	461	480	490	490	490
GNP annual growth	%/yr	2.97	2.5	2.5	2	1	1	0.5
Energy/GNP elasticity	%	0.61	0.35	0.2	0.1	0	-0.15	-0.75
Electricity share	%	40	45	48	52	55	65	65
Pacific Region								
Population	mln.	135	143	151	154	156	157	157
GNP annual growth	%/yr	4.62	4	3.5	2.5	1	0	0
Energy/GNP elasticity	%	0.61	0.3	0.1	0	-0.1	-0.5	-0.75
Electricity share	%	43	47	52	57	65	67	68
North Africa and Middle East								
Population	mln.	158	212	245	275	300	320	335
GNP annual growth	%/yr	4	4	3.5	2.5	2.5	2.2	2.2
Energy/GNP elasticity	%	1.17	1.1	1.1	0.85	0.7	0.5	0.3
Electricity share	%	29	32	36	45	50	55	60

Africa south to Sahara								
Population	mln.	361	490	667	880	1245	1300	1350
GNP annual growth	%/yr	4.05	4	4	4	4	4	4
Energy/GNP elasticity	%	1.39	1.3	1.2	1.1	0.9	0.7	0.5
Electricity share	%	52	50	48	45	40	45	50
South Asia								
Population	mln.	986	1160	1386	1550	1865	2000	2200
GNP annual growth	%/yr	3.44	4	4	4	4	4	4
Energy/GNP elasticity	%	1.83	1.5	1.3	1.1	0.9	0.7	0.45
Electricity share	%	42	42	45	47	49	50	50
South-East Asia								
Population	mln.	343	417	498	550	637	700	740
GNP annual growth	%/yr	7.1	4	4	4	4	4	4
Energy/GNP elasticity	%	1.28	1.25	1.1	0.9	0.7	0.5	0.25
Electricity share	%	33	35	37	40	42	44	46
Latin America								
Population	mln.	364	480	625	820	960	1080	1220
GNP annual growth	%/yr	6.16	4	4	3.5	3.5	3.5	3.5
Energy/GNP elasticity	%	1.06	1.05	1	0.8	0.65	0.4	0.2
Electricity share	%	37	40	42	45	50	55	60
Socialist Countries								
Population	mln.	1451	1650	1810	1930	2050	2100	2120
GNP annual growth	%/yr	6.2	5	4	4	4	4	3.5
Energy/GNP elasticity	%	1.06	0.75	0.6	0.35	0.2	0.05	0
Electricity share	%	28	31	35	38	42	47	53

Note: Electricity share is given as the ratio of primary energy consumed for electricity generation in total primary energy demand; nuclear, hydro and other renewable electricity as well as electiricty import are expressed as replacement of fossil fuels at thermal power plants.

4.2 Social and Economic Progress Worldwide

Global long-term projections of social and economic developments are shown in *Table 2*. Under given assumptions chances are slim that, with present and expected rates of social/economic progress, the main global problems could be successfully solved during the period from 1990 to 2060 (in particular, for example, narrowing the gap in GNP per capita between developed and developing countries). This gap reaches $8,000–$10,000 now and will increase from 1990 to 2060. The situation in Africa (south of the Sahara) and in South Asia, with a high rate of population growth, will be especially tragic; the standard of living in these regions is expected to increase by 2060, but it will remain several times lower than it is in today's developed countries. The economic development of new industrialized regions such as North Africa, the Middle East, or Latin America will be much more favorable, and a per capita level of $3,000 is feasible by the year 2000, which is considered the initial level of industrially developed countries. In the next century, these regions could remarkably reduce the gap in social and economic development. In summary, the GNP per capita gap between developed and developing countries will decrease from the present factor of about ten to four, though in absolute terms the lagging behind of developing countries will probably even increase. The social and economic development of socialist countries as a whole will continue with moderate growth rates, and the GNP per capita gap between developed and socialist countries could be reduced to a factor of two until 2060. At the same time, East European countries and the USSR might reach or come close to the level of developed countries, although Asian countries (in particular, China) will remain far behind developed countries if no special measures are undertaken to enhance the economic and social development of these developing countries.

4.3 World Energy Demand Projections

The results of long-term global/regional energy-demand modeling are summarized in *Table 3*. The main conclusions of the long-term projections for the next 50 to 70 years are as follows:

- Global primary energy demand will increase but with lower growth rates than for GNP. At GNP growth rates of 1.85 in 2000, compared with 1980 rates of 1.6 in 2000-2020 and of 2.5 in 2020–2060, the total energy demand will grow only 1.5 times until 2000; 1.25–1.40 times in 2000–2020; and 1.25–1.75 times in 2020–2060, i.e., the GNP/energy elasticity will be much lower than during the past 30–40 years. Global energy demand will likely reach 20 to 30 billion tce/yr until the end of the projection period (depending on the efforts and efficiencies of global and national energy conservation policies). This level turns out to be remarkably lower than predicted in the early 1980s (including the projections published by the Working Consulting Group of the President of the USSR Academy of Sciences). The tendency of energy projections to go down follows from the energy conservation path of economic development, which recently has become the focus of the majority of national energy programs, despite stable energy prices at lower levels. This global policy will be achieved in various ways and with different efficiencies, depending on the scope of national energy efforts.

- Global energy demand growth will take place, first, because of the inability of developing and socialist countries to solve internal social and economic problems without increased energy consumption.[2] As a result, the developed countries' share in global energy demand will decrease from today's 52% to 38% in 2000 and to only 15%–20% in 2060. The developing countries' share will grow fast: from 11% in 1980 to 18% in 2000 and over 40% in 2060. The share of socialist countries is likely to remain almost at the same level (it will increase from 37% in 1989 to 44% in 2000 and will go down to 33%–37% in 2060). Such fast changes in global energy demand over several decades will shift the weight of global energy problems from developed to developing countries and could produce new

Table 2: Results of economic and energy projections.

A) Base Scenario

Regions	Actual data					Projections			
	1960	1970	1980	1990	2000	2010	2020	2040	2060
<u>North America</u>									
10^3 $(GNP)/cap.	7.2	9.4	11.6	13.5	15.2	16.6	17.5	20	22
t c.e./cap.	7.8	10.8	10.6	10.2	9.8	9.4	8.9	8.6	8.1
10^3 kWh/cap.	4.7	7.2	9.5	10.8	12.0	14.0	16.0	17.5	17
t c.e./10^3 $(GNP)	1.1	1.1	0.9	0.8	0.6	0.6	0.5	0.4	0.4
kWh/$ (GNP)	0.7	0.8	0.8	0.8	0.8	0.9	0.9	0.9	0.8
<u>Western Europe</u>									
10^3 $(GNP)/cap.	4.7	6.9	8.6	10.5	12.8	15.0	16.2	20	22
t c.e./cap.	2.2	3.4	3.8	3.9	4.0	4.0	3.9	3.9	3.8
10^3 kWh/cap.	1.7	3.0	4.3	5.0	6.0	7.0	8.0	9.5	9.0
t c.e./10^3 $(GNP)	0.5	0.5	0.4	0.4	0.3	0.3	0.2	0.2	0.2
kWh/$ (GNP)	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.6
<u>Pacific Region</u>									
10^3 $(GNP)/cap.	2.8	6.4	9.0	12.5	16.7	21.0	23.0	23	23
t c.e./cap.	1.3	3.3	3.9	4.3	4.3	4.3	4.3	4.1	3.6
10^3 kWh/cap.	1.4	3.6	5.2	5.7	6.8	7.9	9.3	10.2	9.1
t c.e./10^3 $(GNP)	0.5	0.5	0.4	0.3	0.3	0.2	0.2	0.2	0.2
kWh/$ (GNP)	0.5	0.6	0.6	0.5	0.4	0.4	0.4	0.3	0.3
<u>North Africa and Middle East</u>									
10^3 $(GNP)/cap.	1.1	2.1	3.1	3.4	4.1	4.7	5.5	8	12
t c.e./cap/	0.3	0.6	1.0	1.1	1.4	1.6	1.8	2.4	2.8
10^3 kWh/cap.	0.1	0.3	0.7	0.7	1.1	2.0	2.6	4.8	6.2
t c.e./10^3 $(GNP)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2
kWh/$ (GNP)	0.1	0.1	0.2	0.2	0.3	0.4	0.5	0.6	0.5
<u>Africa south to Sahara</u>									
10^3 $(GNP)/cap.	0.6	0.7	0.8	0.8	0.9	1.0	1.1	2.3	5
t c.e./cap.	0.2	0.3	0.4	0.5	0.6	0.7	0.8	1.6	3.1
10^3 kWh/cap.	0.1	0.3	0.4	0.5	0.6	0.9	0.9	2.6	5.8
t c.e./10^3 $(GNP)	0.4	0.4	0.5	0.6	0.6	0.7	0.7	0.7	0.6
kWh/$ (GNP)	0.3	0.4	0.6	0.6	0.7	0.8	0.8	1.1	1.2
<u>South Asia</u>									
10^3 $(GNP)/cap.	0.2	0.2	0.2	0.3	0.3	0.4	0.5	1.1	2.2
t c.e./cap.	0.1	0.1	0.2	0.3	0.4	0.5	0.7	1.3	2.0
10^3 kWh/cap.	0.04	0.1	0.2	0.2	0.4	0.7	0.9	2.1	3.7
t c.e./10^3 $(GNP)	0.5	0.6	0.8	1.0	1.1	1.2	1.2	1.2	0.9
kWh/$ (GNP)	0.2	0.5	0.8	0.8	1.1	1.5	1.7	1.9	1.7
<u>South-East Asia</u>									
10^3 $(GNP)/cap.	0.4	0.5	0.8	1.0	1.2	1.6	2.1	4.2	8.7
t c.e./cap.	0.1	0.2	0.5	0.6	0.8	1.1	1.5	2.7	4.5
10^3 kWh/cap.	0.04	0.1	0.4	0.5	0.8	1.3	1.9	4.5	8.3
t c.e./10^3 $(GNP)	0.3	0.5	0.6	0.6	0.7	0.7	0.7	0.6	0.5

kWh/$ (GNP)	0.1	0.3	0.4	0.5	0.6	0.8	0.9	1.1	0.9
Latin America									
10^3 $(GNP)/cap.	1.2	1.6	2.3	2.6	3.0	3.4	4.3	7.5	13
t c.e./cap.	0.5	0.8	1.1	1.3	1.5	1.6	1.9	2.5	3.0
10^3 kWh/cap.	0.3	0.5	1.0	1.2	1.6	2.1	2.9	5.2	6.6
t c.e./10^3 $(GNP)	0.4	0.5	0.5	0.5	0.5	0.5	0.4	0.3	0.2
kWh/$ (GNP)	0.3	0.3	0.4	0.4	0.5	0.6	0.7	0.7	0.5
Socialist Countries									
10^3 $(GNP)/cap.	0.2	0.4	0.7	0.9	1.3	1.8	2.4	5.3	10
t c.e./cap.	0.8	1.7	2.3	2.9	3.4	3.9	4.2	4.8	5.0
10^3 kWh/cap.	0.5	0.9	1.4	2.2	3.4	4.8	5.9	8.4	9.7
t c.e./10^3 $(GNP)	3.7	4.0	3.5	3.1	2.7	2.2	1.7	0.9	0.5
kWh/$ (GNP)	2.2	2.2	2.2	2.4	2.7	2.7	2.4	1.6	0.9

B) Enhanced Energy Saving Scenario

Regions	Actual data					Projections			
	1960	1970	1980	1990	2000	2010	2020	2040	2060
North America									
10^3 $(GNP)/cap.	7.2	9.4	11.6	13.5	15.2	16.6	17.5	20	22
t c.e./cap.	7.8	10.8	10.6	10.0	9.5	8.9	8.4	8.0	7.4
10^3 kWh/cap.	4.7	7.2	9.5	10.7	11.6	13.4	14.5	15.3	15
t c.e./10^3 $(GNP)	1.1	1.1	0.9	0.8	0.6	0.5	0.5	0.4	0.3
kWh/$ (GNP)	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7
Western Europe									
10^3 $(GNP)/cap.	4.7	6.9	8.6	10.5	12.8	15	16	20	22
t c.e./cap.	2.2	3.4	3.8	3.9	3.9	3.9	3.8	3.7	3.4
10^3 kWh/cap.	1.7	3.0	4.3	5.0	5.7	6.4	6.9	8.8	8.2
t c.e./10^3 $(GNP)	0.5	0.5	0.4	0.4	0.3	0.3	0.2	0.2	0.2
kWh/$ (GNP)	0.4	0.4	0.5	0.5	0.5	0.4	0.4	0.4	0.4
Pacific Region									
10^3 $(GNP)/cap.	2.8	6.4	9.0	12.5	16.7	21	23	23	23
t c.e./cap.	1.3	3.4	3.9	4.2	4.1	4.0	3.9	3.5	3.0
10^3 kWh/cap.	1.4	3.6	5.2	5.6	6.4	7.3	8.4	8.7	7.6
t c.e./10^3 $(GNP)	0.5	0.5	0.4	0.3	0.3	0.2	0.2	0.1	0.1
kWh/$ (GNP)	0.5	0.6	0.6	0.5	0.4	0.4	0.4	0.3	0.3
North Africa and Middle East									
10^3 $(GNP)/cap.	1.1	2.1	3.1	3.4	4.1	4.	5.5	8	12
t c.e./cap.	0.3	0.6	1.0	1.1	1.4	1.6	1.7	2.0	2.2
10^3 kWh/cap.	0.1	0.3	0.7	0.9	1.1	1.9	2.4	4.1	4.8
t c.e./10^3 $(GNP)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2
kWh/$ (GNP)	0.1	0.1	0.2	0.2	0.3	0.4	0.4	0.5	0.4
Africa south to Sahara									
10^3 $(GNP)/cap.	0.6	0.7	0.8	0.8	0.9	1.0	1.1	2.3	4.8
t c.e./cap.	0.2	0.3	0.4	0.5	0.6	0.7	0.7	1.1	1.6
10^3 kWh/cap.	0.1	0.3	0.4	0.5	0.6	0.8	0.8	1.8	2.9

t c.e./10^3 $(GNP)	0.4	0.4	0.5	0.6	0.6	0.6	0.6	0.5	0.3
kWh/$ (GNP)	0.3	0.4	0.6	0.6	0.7	0.8	0.7	0.8	0.6
South Asia									
10^3 $(GNP)/cap.	0.2	0.2	0.2	0.3	0.3	0.4	0.5	1.1	2.2
t c.e./cap.	0.1	0.1	0.2	0.3	0.4	0.5	0.6	0.9	1.2
10^3 kWh/cap.	0.0	0.1	0.2	0.2	0.4	0.6	0.8	1.6	2.2
t c.e./10^3 $(GNP)	0.5	0.6	0.8	1.0	1.1	1.1	1.1	0.8	0.6
kWh/$ (GNP)	0.2	0.5	0.8	0.8	1.1	1.4	1.5	1.4	1.0
South-East Asia									
10^3 $(GNP)/cap.	0.4	0.5	0.8	1.0	1.2	1.6	2.1	4.2	8.7
t c.e./cap.	0.1	0.2	0.5	0.6	0.8	1.0	1.2	1.6	1.8
10^3 kWh/cap.	0.0	0.1	0.4	0.5	0.7	1.2	1.5	2.6	3.4
t c.e./10^3 $(GNP)	0.3	0.5	0.6	0.6	0.7	0.6	0.6	0.4	0.2
kWh/$ (GNP)	0.1	0.3	0.4	0.5	0.6	0.7	0.7	0.6	0.4
Latin America									
10^3 $(GNP)/cap.	1.2	1.6	2.3	2.6	3.0	3.2	3.9	6.8	12
t c.e./cap.	0.5	0.8	1.1	1.3	1.5	1.5	1.6	1.9	1.9
10^3 kWh/cap.	0.3	0.5	1.0	1.2	1.6	1.9	2.5	3.8	4.2
t c.e./10^3 $(GNP)	0.4	0.5	0.5	0.5	0.5	0.5	0.4	0.3	0.2
kWh/$ (GNP)	0.3	0.3	0.4	0.4	0.5	0.6	0.7	0.6	0.4
Socialist Countries									
10^3 $(GNP)/cap.	0.2	0.4	0.7	0.9	1.3	1.8	2.5	5.3	10
t c.e./cap.	0.8	1.7	2.3	2.9	3.3	3.6	3.7	3.7	3.7
10^3 kWh/cap.	0.5	0.9	1.4	2.2	3.3	4.4	5.1	6.5	7.3
t c.e./10^3 $(GNP)	3.7	4.0	3.5	3.0	2.6	2.0	1.5	0.7	0.4
kWh/$ (GNP)	2.2	2.2	2.2	2.4	2.6	2.5	2.1	1.2	0.7

Table 3: Energy and electricity demand projections.

A) Base Scenario

Regions		Actual Data 1960	1970	1980	1990	Projections 2000	2010	2020	2040	2060
North America	P	1552	2434	2619	2787	2900	2945	2945	2900	2750
	E	940	1640	2355	2955	3555	4450	5370	6100	5700
Western Europe	P	784	1322	1581	1725	1835	1910	1930	1930	1840
	E	602	1176	1800	2220	2780	3335	3860	4650	4420
Pacific Region	P	135	401	529	607	650	670	670	640	570
	E	145	427	696	815	1030	1210	1450	1590	1430
North Africa	P	30	69	155	240	345	445	555	755	940
and Mid.East	E	8	30	114	150	280	540	795	1540	2090
Africa south	P	46	82	142	235	385	615	945	2070	4200
to Sahara	E	30	78	155	235	410	745	1080	3445	7770
South Asia	P	54	89	164	295	505	810	1245	2525	4390
	E	23	73	164	245	505	1030	1740	4210	8120
South-East Asia	P	26	66	158	255	410	630	940	1900	3300
	E	9	37	123	200	380	725	1230	3100	5600
Latin America	P	117	222	416	630	930	1325	1815	2745	3630
	E	69	153	374	555	975	1700	2830	5600	8050
Soc.Countries	P	820	2105	3300	4770	6165	7510	8630	10125	10500
	E	481	1137	2070	3690	6165	9210	12100	17600	20500
World (rounded):										
bln. t c.e.		3.56	6.79	9.06	11.5	14.1	17.0	20	25	32
TWh		2.30	4.73	7.78	11.0	15.9	22.8	30	46	62

B) Enhanced Energy Saving Scenario

Regions		Actual Data 1960	1970	1980	1990	Projections 2000	2010	2020	2040	2060
North America	P	1552	2434	2619	2750	2810	2810	2780	2670	2500
	E	940	1640	2355	2920	3440	4210	4790	5140	5100
Western Europe	P	784	1322	1581	1725	1815	1850	1850	1795	1660
	E	602	1176	1800	2215	2640	3050	3390	4300	4000
Pacific Region	P	136	401	529	595	620	620	610	550	475
	E	145	428	696	800	970	1115	1325	1370	1200
North Africa	P	31	69	155	240	345	430	510	635	725
and Mid.East	E	8	30	114	150	280	520	730	1295	1600
Africa south	P	46	82	142	235	375	580	825	1435	2130
to Sahara	E	30	78	155	235	400	705	945	2390	3945
South Asia	P	54	89	164	295	485	750	1070	1855	2650
	E	23	73	164	245	490	950	1500	3100	4900
South-East Asia	P	26	66	158	255	395	565	745	1100	1345
	E	9	37	123	200	365	645	975	1800	2300
Latin America	P	117	222	416	625	930	1225	1535	2025	2300
	E	69	153	374	555	975	1575	2400	4125	5170
Soc.Countries	P	820	2105	3300	4770	6045	6945	7520	7830	7830
	E	481	1137	2067	3695	6045	8515	10530	13625	15365
World (rounded):										
bln. t c.e.		3.56	6.79	9.06	11.5	13.7	15	17	20	21
TWH		2.30	4.73	7.78	10.9	15.4	21.0	26	36	42

Note: P - primary energy consumption, mln. t c.e.
E - electricity generation, TWh.

global problems and political tensions, for which solutions should be found now to prevent critical situations in the future.

- The absolute levels of primary energy demand in socialist and developing countries will systematically grow, although it is quite possible that energy demand in developed countries could stabilize by the beginning of the next century. After several decades of stabilization, this tendency is likely to be replaced by an absolute reduction in energy demand in the regions of developed countries. Per capita primary energy demand in developed countries, after reaching a maximal level of 5.9–6.0 tce/cap beginning in the next century, will start to decline to 4.5–5.0 tce/cap in the second half of the next century. Per capita demand in developing countries will increase from 0.6 tce/cap in the mid-1980s to 1.7–3.0 tce until 2060; this will be much lower than in developed countries and far from the saturation level. Average energy consumption in socialist countries will grow from the present 2.9 tce/cap to 3.7–5.0 tce in 2060 and will be practically equal to that of developed countries.
- Electricity generation will increase with growth rates higher than that of total primary energy demand. Electricity generation in the world as a whole will grow by a factor of 2.0 until 2000, a factor of 1.7–1.9 by 2000-2020, and a factor of 1.6–2.2 by 2020–2060 (from 7.8 TWh in 1980 to 15–16 TWh in 2000, 25–30 TWh in 2020, and 40–60 TWh in 2060, the upper levels refer to the scenario excluding enhanced energy-conservation measures).

Therefore, global primary energy demand is expected to increase two to three times, depending on the future energy-conservation scale implemented. These energy demand levels turn out to be much lower than those projected in the early 1980s, when energy savings were treated with less attention and assumed much higher inertia in the reconstruction of energy systems. It is quite possible that this projection also overestimates the energy demand levels (especially for the base scenario). More radical energy demand projections even today [see, for example, Lovins *et al.* (1981)] foresee the technical availability (but not economically valid) to reduce global primary energy demand in the year 2020 to that of the mid-1980 level. However, such marginal projections are seen as illustrations of the capabilities of technological progress achieved until now, rather than reflect the real social and economic situation of the world.

4.4 Projections of Global Primary Energy Supply

The primary energy production structure will depend heavily on the ways and options of global energy systems development. The following approach is used in this study: first, the assumptions of the future contribution of renewable energies are considered on the basis of some assessments of renewable energy potentials; then nuclear energy input is calculated based on the scenario assumptions of nuclear penetration; finally the rest is met by fossil fuels, taking into account their resources and technical, economical, and ecological attractiveness.

Renewable energy potentials (feasible from technical and economic points of view) and assumptions of their utilization at the end of 2060 are presented in *Table 4* [3]. The table shows that the total potential of renewables is calculated at about 20 billion tce per year. By 2060, the rates of utilization of the potential is assumed as follows: for the business-as-usual scenario (without any control measures) 25%, and for all other scenarios (with some special regulations) 50% (today this rate does not exceed 4% to 5%).

For nuclear energy, the following assumptions are used in scenarios: for business-as-usual options, 20% to 25% of the world energy demand by 2060 is met by this energy source; in nuclear moratorium options, 7% (the 2010 level); in nuclear elimination options, 0; and in fossil fuels limitation options, 25% to 40% (depending on the scenario).

Possible assessments for meeting global energy demand for the above scenarios are presented in *Table 5*.

Under normal technological progress in the energy sector, and without special measures or restrictions to regulate primary energy consumption or mix, it is expected that fossil fuels' share

Table 4: Renewable energy potential and its utilization

	Bln.tce/year	% utilization in 2060	
		low	high
Hydro[1)]	1.2	50	75
Organic wastes[1)]	4.4	30	67
Wind[2)]	3.2	20	40
Solar photovoltaics[3)]	9.0	15	30
Solar collectors[4)]	2.8	20	40
Total (approxim.)	20	25 (5 bln.)	50 (10 bln.)

Notes: 1) Goldemberg J. et al., 1985.
2) Haefele W., 1981.
3) Assuming that 2% of the global desert area is covered with photovoltaics arrays.
4) Assuming that 5 m^2 of solar collectors per inhabitant with an average energy saving about 70 kg ce/m^2/year are used and 8 bln. of population.

Table 5: Primary energy mix (billion tce/year).

Options	1980	1990	2000	2010	2020	2040	2060
A) Base Scenario	9.06	11.5	14	17	20	25	32
- business-as-usual							
coal	2.63	3.3	4.2	5.3	6.2	7.7	9.9
oil	3.90	4.1	4.2	4.2	4.4	4.5	4.2
natural gas	1.72	2.5	3.2	4.1	4.4	4.5	4.8
nuclear	0.23	0.6	1.1	1.7	2.8	5.0	8.0
other	0.58	0.9	1.3	1.7	2.2	3.3	5.1
- nuclear moratorium							
.coal	2.63	3.3	4.2	5.1	6.2	8.2	10.6
oil	3.90	4.1	4.2	4.4	4.6	4.5	4.2
natural gas	1.72	2.5	3.2	4.1	4.8	5.0	5.1
nuclear	0.23	0.6	1.0	1.2	1.4	1.8	2.2
other	0.58	1.0	1.4	2.2	3.0	5.5	9.9
- nuclear reduction							
coal	2.63	3.3	4.3	5.3	6.6	9.5	12.8
oil	3.9	4.1	4.2	4.4	4.6	4.5	4.2
natural gas	1.72	2.5	3.1	4.1	4.8	5.0	5.1
nuclear	0.23	0.6	1.0	1.0	1.0	0.5	0.0
other	0.58	1.0	1.4	2.2	3.0	5.5	9.9
- fossil fuel reduction							
coal	2.63	3.3	4.1	4.4	4.2	3.3	2.2
oil	3.90	4.1	4.2	4.3	4.2	4.0	2.2
natural gas	1.72	2.5	3.1	3.9	4.6	4.8	4.5
nuclear	0.23	0.6	1.3	2.2	4.0	7.4	13.1
other	0.58	1.0	1.4	2.2	3.0	5.5	10.0
B)Enhanced Energy Saving Scenario	9.06	11.5	13.7	15	17	20	21
- business-as-usual							
coal	2.63	3.3	4.1	4.4	4.6	5.2	5.3
oil	3.90	4.1	4.1	4.0	3.9	4.0	3.2
natural gas	1.72	2.5	3.0	3.3	3.9	4.0	3.4
nuclear	0.23	0.6	1.1	1.5	2.0	2.8	4.1
other	0.58	0.9	1.4	1.8	2.6	4.0	5.0
- nuclear moratorium							
coal	2.63	3.3	4.1	4.5	4.8	4.6	3.2
oil	3.90	4.1	4.1	4.0	3.9	3.6	2.9
natural gas	1.72	2.5	3.0	3.3	3.9	4.2	3.8
nuclear	0.23	0.6	1.0	1.1	1.2	1.4	1.5
other	0.58	0.9	1.5	2.1	3.2	6.2	9.6
- nuclear reduction							
coal	2.63	3.3	4.1	4.4	4.9	5.6	4.4
oil	3.90	4.1	4.1	4.0	4.0	3.6	2.9
natural gas	1.72	2.5	3.0	3.5	4.0	4.2	3.8
nuclear	0.23	0.6	1.0	0.9	0.8	0.4	0.0
other	0.58	1.0	1.5	2.2	3.3	6.2	9.9
- fossil fuel reduction							
coal	2.63	3.3	4.1	4.0	3.4	2.4	1.5
oil	3.90	4.1	4.1	3.9	3.1	2.6	1.1
natural gas	1.72	2.5	3.0	3.5	3.7	4.0	3.4
nuclear	0.23	0.6	1.0	1.3	3.4	4.8	5.1
other	0.58	1.0	1.5	2.3	3.2	6.2	9.9

will go down from the present 87% to 56%–59% by the end of the projection period. Coal production will increase to 5.5–9.9 billion tce annually (though its share in the global energy balance will change from 29% to 25% in the enhanced energy-conservation scenario and to 31% in the base case scenario). Crude oil production will remain at the level of 3.3–4.2 million tce (2.3–2.9 billion tons) by the end of the period, and its share will decrease sharply from 36% to 13%–15%. The peak of global crude oil production is expected between 2000 and 2010 (in the enhanced energy-savings scenario) or 2040 (in the base case scenario). Natural gas production will reach 3.5–4.8 billion tce (2.9–4.0 trillion m^3) with its share going down from 22% to 15%–16%. Nuclear energy production will systematically grow in all options except nuclear reduction, supplying almost 20%–25% of the global energy demand until 2060, and the renewable energy share will increase to 16%–24%, depending on the scenario.

In the scenarios with delayed global warming, fossil fuels consumption is strongly reduced (down to 28% in 2060), due to the intensive development of non-carbon energy technologies (e.g., nuclear and renewables). Simultaneously, a decline of the absolute consumption of fossil fuels will take place, especially in the enhanced conservation scenarios. The most remarkable reduction will be expected for coal and crude oil the shares of each decreasing to 7%. The share of natural gas will be between 14%–16%. Nonfossil eneregy sources will produce over 70% of the primary energy by the end of the projection period; the share of renewable energies will be 30%–45%.

In the scenarios with limited nuclear energy (moratorium or even reduction), it is assumed that in the near future (15 to 20 years) nuclear energy production will still increase because nuclear power plants now under construction will be operating. After 2010, the nuclear program might stabilize at the achieved level (approximately 7% in the nuclear moratorium scenario) or decrease to zero until 2060 (in the nuclear reduction scenario). In the former case, nuclear energy will be able to contribute 1.5–2.2 billion tce (the low level for the enhanced energy-conservation scenario and the high level for the base case scenario). Naturally, such severe restrictions on nuclear energy development will be followed by higher production of fossil fuels. In this case the fossil fuels share will reduce only to 47%–62% as compared to the present 87%, but the absolute volumes of fossil fuels production will practically decline to today's level after reaching its peak between 2010 and 2020 in the enhanced energy-conservation scenario or continue to grow by almost two times in the base case scenario.

4.5 Fossil Fuel Resources in the 21st Century

Table 6 shows an assessment of the expected cumulative use of global fossil fuel resources from 1980 to 2060. As can be seen from the table, under moderate energy-savings efforts (base scenario) large shares of conventional crude oil and natural gas will be extracted until the end of the projection period, and there will be needs for developing unconventional hydrocarbon resources (*for crude oil*: oil shales, heavy oils, oil sands, synthetic crude from coal; *for natural gas*: gas from tight formations, geopressure zones, gas hydrates, substitute natural gas from coal). For coal resources, the exhaustion rate will remain very low even for economically recoverable coal resources (less than 15%). In the enhanced energy-savings scenarios, the level of fossil fuel resources utilization will be 15%–20% lower.

In total, it should be pointed out that even in the limited fossil fuels use scenarios the wide-scale production of unconventional crude oil should start circa 2025, and in some countries the same will be true for natural gas. This means that within that time period the technologies for liquid and gaseous synthetic hydrocarbon production, including coal conversion, should be tested and put on on line.

Table 6: Fossil fuel resources use in 1980–2060.

Scenarios	Coal (bln. t c.e.)	Oil (bln. t)	Natural gas (trln.m³)
1) Base Scenario:			
- business-as-usual	495	242	265
- nuclear moratorium	510	245	280
- nuclear reduction	565	245	280
- fossil fuel reduction	285	220	265
2) Enhanced Energy Saving Scenario:			
- business-as-usual	365	220	230
- nuclear moratorium	332	215	235
- nuclear reduction	365	215	240
- fossil fuel reduction	245	175	230

Notes: Coal recoverable resources - 3500 bln. t c.e.
conventional crude oil - 257 bln. t.
conventional natural gas - 295 trln.m^3
(Energy in a Finite World. Paths to a Sustainable Future, W.Haefele, Program Leader, Ballinger Publishing Co., Cambridge, Mass., 1981)

4.6 CO_2 Emissions by Energy Systems

The analysis of CO_2 emissions caused by burning fossil fuels and processing in energy technologies and installations and related climate changes due to the greenhouse effect is an essential element of energy forecasting.

CO_2 emission assessments of concentrations in the atmosphere were carried out on the basis of cumulative carbon release calculations for the primary energy mix scenarios for different future energy system developments (*Table 7*). It is assumed that only 60% of the carbon released remains in the atmosphere (the rest is absorbed by the oceans). According to some observations of CO_2 concentrations in the atmosphere from 1960 to 1970 and assessments of cumulative consumption of fossil fuels, it follows that about 40% of the anthropogenic carbon remained in the atmosphere. However, more accurate observations from 1959 to 1973 show that the share of carbon remaining in the atmosphere was equal to about 56% (see National Academy of Sciences, 1977). Many modeling approaches assume the share to be 60% (see, for example, Rogers, 1990). The same assumption is also applied in this study. The CO_2 absorption rate depends on many factors, of which the main ones are temperature gradient and biomass expansion. Edmonds and Reilly (1983), for example, use a different airborne ratio for atmospheric CO_2 concentration, ranging from 40% to 70%.

The following CO_2 outputs were used for CO_2 emissions (in tons of CO_2 per 1 ton of tce): for coal, 3.0; oil, 2.3; and natural gas, 1.5 (Deutscher Bundestag, 1988). The results of calculations are given in *Table 7*. Analysis of the results with CO_2 emission shows that in spite of remarkable efforts in energy conservation and changes in the primary energy mix (enhanced energy-savings and limited fossil fuels scenarios), there are still no fundamental changes in CO_2 releases combined with a reduced atmospheric concentration during the whole period under consideration. Of course, this cannot be achieved in the next 15 to 20 years as it was recommended by the 1988 Toronto Protocol with the goal to reduce CO_2 emissions by 20% by 2005. Moreover, first signs of an effective CO_2 reduction policy will only start to be noticeable after 2010.

Restricting the use of nuclear energy will naturally result in a substantial growth of CO_2 concentrations (by a factor of 1.5 to 1.6) as compared with the fossil fuels limitations option in which CO_2 concentrations growth will be minimal (only by a factor of 1.3 to 1.4). However, if one assumes that the CO_2 contribution to total global warming will remain close to 50% during the whole period (this ratio exists now and will most likely stay unchanged in the future), then by 2060 a doubling of total atmospheric CO_2 concentrations is expected. More distinct differences in global energy development scenarios should be expected beyond the projection period.

Results of CO_2 concentration forecasts show that, although CO_2 accumulation in the atmosphere will take place during the whole period, the concentration growth could, however, essentially slow down if a reasonable policy of energy conservation and reduced fossil fuels use is followed. The negative impacts of global warming might substantially reduce with an active policy of reforestation parallel to CO_2 abatement measures.

Rough estimates show that increasing the forestal areas of the world by 40% [4] until 2060 could reduce atmospheric CO_2 concentration growth by almost 255 bln. t C (*Table 8*), and with reduced fossil fuels use and enhanced energy savings it could substantially compensate the expected CO_2 release from fossil fuel burning over the projected period.

Despite the fact that these are very simplified calculations, the effects of enforced reforestation depend on the scenarios applied: practically eliminating the negative impacts produced by fossil fuels and delaying global warming or only somewhat compensating for global warming. This means that energy conservation coupled with reforestation should be considered as primary measures for CO_2 abatement.

Table 7: CO_2 Projections by energy sources (billion tons).

A) Base Scenario

Options	1980	1990	2000	2010	2020	2040	2060	Total
Business-as-Usual								
Total releases	0	53.4	63.0	73.5	83.8	193.2	221.2	688.2
Remaining in the atm.	0	32.1	37.8	44.1	50.3	115.9	132.7	412.9
Concentration, ppm	340	355	373	395	417	470	535	
Nuclear Moratorium								
Total releases	0	53.4	63.0	73.5	85.0	201.7	233.1	709.5
Remaining in the atm.	0	32.1	37.8	44.0	51.0	121.0	139.8	425.7
Concentration, ppm	340	355	373	394	417	475	540	
Nuclear Reduction								
Total releases	0	53.5	63.3	74.3	87.1	214.5	259.6	752.1
Remaining in the atm.	0	32.1	38.0	44.6	52.3	128.7	155.8	451.3
Concentration, ppm	340	355	375	394	419	480	553	
Fossil Fuel Reduction								
Total releases	0	53.5	62.2	69.2	72.6	140.7	114.3	512.4
Remaining in the atm.	0	32.1	37.3	41.5	43.5	84.4	68.6	307.4
Concentration, ppm	340	355	375	392	412	453	485	

B) Enhanced Energy Saving Scenario

Options	1980	1990	2000	2010	2020	2040	2060	Total
Business-as-Usual								
Total releases	0	53.4	62.7	70.2	72.4	148.6	150.4	557.7
Remaining in the atm.	0	32.1	37.7	42.1	43.4	89.1	90.3	334.6
Concentration, ppm	340	355	373	393	413	455	500	
Nuclear Moratorium								
Total releases	0	53.4	62.7	70.2	73.0	143.8	128.3	531.4
Remaining in the atm.	0	32.1	37.7	42.1	43.8	86.3	77.0	318.8
Concentration, ppm	340	355	373	393	413	454	490	
Nuclear Reduction								
Total releases	0	53.4	62.7	70.3	74.2	153.4	145.7	559.7
Remaining in the atm.	0	32.1	37.7	42.2	44.5	92.0	87.4	318.8
Concentration, ppm	340	355	373	393	414	457	500	
Fossil Fuel Reduction								
Total releases	0	53.4	62.8	68.7	63.6	105.1	79.0	432.6
Remaining in the atm.	0	32.1	37.7	41.4	38.2	63.0	47.4	259.5
Concentration, ppm	340	355	373	392	410	440	462	

Table 8: Effect of reforestation on CO_2 reductions.

	% Reforestated	Mln.ha	CO2 absorbed (bln.t C)
2000	5	100	7
2010	10	200	14
2020	25	500	27
2030	45	900	48
2040	65	1300	55
2050	85	1700	55
2060	100	2000	48
Total			254

Note: Maximal area of reforestation = 2000 mln.ha (25% of the global forest-free area)
Average biomass growth rate = 6.85 t/ha/yr
Average growth time = 20 years

5 Comparative Analysis of Global Long-Term Energy/ CO_2 Studies

Recently, long-term energy projections have become an essential part of global economic and social planning because of the long lead times of new energy technologies' penetration and their high capital intensities. Several years ago the long-term approach to energy projections was stressed. At that time it was discovered that increasing amounts of atmospheric CO_2 concentrations were causing global warming; atmospheric CO_2 concentrations to a large extent are caused by fossil fuels use. For this reason global, long-term energy projections are again the focus of many research studies being carried out over recent years.

There is a multitude of global, long-term energy projections published worldwide. Most appeared in the late 1970s and early 1980s, and a new wave occurred in the late 1980s, when the threat of global warming started to be considered a real and serious global problem. These studies use different assumptions, methodological approaches, and time periods and are based on different sets of input data: global/regional economic and population growth, costs and efficiencies of energy technologies evaluations, availability of conventional and renewable energy sources, and so on. Strictly speaking, the diverse features of these studies makes comparisons practically impossible. Here we will attempt to analyze the quantitative results of a few selected studies without trying to clarify why and how such results came about. Such a simplified approach makes it possible to notice the evolution of long-term energy projections over time.

To review global energy/CO_2 projections, we use original publications as well as summaries of global/regional studies presented at IIASA's International Energy Workshop in June 1989. We have chosen the following studies (in order of their appearance) for further analysis from a long list of available publications:

Nordhaus, W.D., Strategies for the Control of Carbon Dioxide (1977).

WCG (Working Consulting Group) of the President of the USSR Academy of Sciences, Long-Term Global Energy Projections, Moscow (1978)(in Russian).

Colombo, U. and O. Bernardini, A Low Energy Growth Scenario and the Perspectives for Western Europe, Report prepared for the Commission of the European Communities, Panel on Low Energy Growth (1979).

Rotty, R. and G. Harland, Constraints on Carbon Dioxide Production from Fossil Fuels Use (1980).

Häfele, W. *et al.*, *Energy in a Finite World: A Global Systems Analysis.* Report by the Energy Systems Program of the International Institute for Applied Systems Analysis. Cambridge, Mass: Ballinger (1981).

Lovins, A., L. Lovins, F. Krause, and F. Bach, Energy Strategies for Low Climatic Risk. Report to the German Federal Environment Agency (1981).

Nordhaus, W. and G. Yohe, Future Paths of Energy and Carbon Dioxide Emission. In *Changing Climate*, Report of the Carbon Dioxide Assessment Committee. Washington, DC: National Academy Press (1983).

Edmonds, J. and J. Reilly, A Long-Term Global Energy-Economic Model of Carbon Dioxide Release from Fossil Fuel Use. *Energy Economist* **5**:74–88 (1983).

Rose, D., M. Miller, and C. Agnew, Global Energy Futures and CO_2-Induced Climatic Change. Report MITEL 83-015. Cambridge, Mass. (1983).

Goldemberg, J., T. Johansson, A. Reddy, and R. Williams, An End-Use Oriented Global Energy Strategy. *Annual Review of Energy* **10**:613-688 (1985).

Edmonds, J. and J. Reilly, *Global Energy: Assessing the Future.* New York: Oxford (1985).

Frisch, J.-R., Long-Term Energy Alternatives to Hydrocarbons, Presented at the 12th World Petroleum Congress, Houston, TX (1987).

AMOCO Corporation, Lower and Upper Price Cases, Presented at the International Energy Workshop, IIASA, Laxenburg, Austria, June (1989).

Centre for International Energy Studies, Erasmus University, High, Low, and Mid-Point Demand Growth, Presented at the International Energy Workshop, IIASA, Laxenburg, Austria, June (1989).

Ashby, A. and D. Dreyfus, Global Outlook for Service Sector Energy Requirements, Presented at the International Energy Workshop, IIASA, Laxenburg, Austria, June (1989).

14th Congress of the World Energy Conference. Conservation and Studies Committee, World Energy Horizons 2000–2020, Paris (1989).

Häfele, W., Energy Systems Under Stress, Invited paper, 14th World Energy Conference, September 1989.

Starr, C. and M. Searl, Global Projections of Energy and Electricity. American Power Conference, Annual Meeting, Chicago, Ill., April (1989).

Sinyak, Y., Global Energy/CO_2 Projections, Unpublished report, IIASA, Laxenburg, Austria (1990).

US EPA and US DOE, Atmospheric Stabilization Framework (1990).

From a methodological viewpoint, these studies can be divided into four groups:

1. Studies based on reasonable judgments and assumptions without the application of mathematical models and tools or detailed calculations [see, for example Häfele (1989)].

2. Studies with collective views based on initial assumptions and an iterative process of finding a consensus. (A good example of such an approach is the study prepared for the 14th World Energy Conference by a group of experts with Dr. J.-R. Frisch as Project Director. An extensive information exchange between experts and the central team was used to produce final, consistent results.)

3. Studies directed at the detailed analysis of energy end-consumers and assessments of efficiencies of new energy technologies, using a normative approach to global energy problems [see, Goldemberg *et al.* (1985) and Lovins *et al.* (1981)].

4. Studies with modeling approaches for solving global energy problems — from simplified models of energy/economy interactions [WCG (1978) and Sinyak (1990)] to complicated sets of mathematical optimization models [Häfele *et al.* (1981) or Rotty and Harland (1980)] to complex computer modeling systems using simulation procedures (Edmonds and Reilly, 1985).

The analysis of available studies shows that the majority of the projections predict a further growth in global energy demand (*Table 9*), but several prognoses deviate from this overall trend: Goldemberg *et al.* (1985), for example, assume an energy demand stabilization until 2020, Lovins *et al.* (1981) are convinced that global energy demand could even be reduced to early 1980 levels by the year 2030.

It is interesting to see the evolution of projections. The average global energy demand estimate in 200 pre-1985 studies is equal to 17 billion tce annually, whereas after 1985 the average estimate is already remarkably lower: only 13 billion tce. The same trend but with pronounced deviations downward can be seen for subsequent time periods: the average estimate of pre-1985 studies for 2025 is above 25 billion tce as compared with only 17 billion tce estimated in studies

Table 9: World energy demand projections (billion tce).

Reference Sources	2000	2010	2020-2030	2030-2040	2050-2060
WCG (1978)	18.3–21.2		30.9–38.3		43–55
Colombo and Bernardini (1979)				15.4	
Häfele *et al.* (1981)					
(Low scenario)	15.8			23.5	
Lovins *et al.* (1981)				5.5	
Nordhaus and Yohe (1983)			26.2		
Edmonds and Reilly (1983)			20.2–28.5		
Rose *et al.* (1983)			12.9–19.4		
Goldemberg *et al.* (1985)			12.0		
Edmonds and Reilly (1985)	16.5		31.3		56.0
Center for International Energy Studies, Erasmus University (1988)		20.8–23.4			
Frisch (1987)	12.0	17.1	23.2	27.7	31.8
AMOCO (1989)		19.2–19.5			
Ashby and Dreyfus (1989)		18.6			
WEC-14 (1989)	13.6–14.7		16.5–19.3		
Starr and Searl (1989)					18.4–29.2
Sinyak (1990)	13.7–14.1		17.1–20.0	20.0–25.0	21.0–32.0
US EPA/DOE (1990)		18.2	17.0-23.0		

conducted after 1985. Even more striking is the reduction in global energy-demand assessments for the middle of next century: about 50 billion tce for 2050 in pre-1985 studies as compared with 25 to 27 billion tce for 2060 in studies published after 1985. All these changes indicate a drastic shift to assessing the role future energy systems will play and to using the huge energy conservation potential that exists in all economic sectors of developed and developing countries. It has become evident that energy savings are real long-term factors in energy systems development which provide further economic growth with minimal risks to the environment, mankind, and resource exhaustion and, moreover, with less capital and operation and maintenance costs.

Most interesting is the comparison of three studies: Sinyak (1990); Edmonds and Reilly (1985); and Frisch (1987). All of them have almost the same time horizon; deal with global/regional aspects of energy demand evolution; and, moreover, consider energy demand not only in total but by primary energy forms. Furthermore, they try to link energy systems development to global climate changes resulting from increased CO_2 concentrations.

The projections show a steady growth in global energy demand until the middle of the next century but with different growth rates. According to WEC-14 projections, annual growth rates will decline from 1.5% in 2000–2020 to 0.7% in 2040–2060. Edmonds and Reilly (1985) assume rather high annual growth rates for primary energy demand during the first half of the next century (2.5% per year), which result in an overestimation of primary energy demand and CO_2 emissions.

Concerning the different primary energy demand forms, there are large discrepancies among the different projections (*Table 10*). Edmonds and Reilly (1985) expect a doubling of crude oil production from 2000 to 2050, reaching 10.2 billion tce (more than 7 billion toe), including unconventional liquid fuels resources like oil shales, heavy oils but without synthetic oils produced from coal. According to projections by Frisch (1987), global crude oil production will reach its peak in 2000 and then will slightly decrease until 2060. Projections by Sinyak (1990) assume a sharp reduction in crude oil production in case of regulatory constraints of strategies directed to a delay in global warming, and a stabilization over the whole period if the consequences of global warming turn out to be less severe and no special regulations are applied. The magnitude of existing crude oil projections can be explained by the different treatment of unconventional oil resources in the studies. For example, Edmonds and Reilly (1985) assume that two-thirds of the crude oil production in 2050 will be from unconventional sources with lower costs than in the case of synthetic oils production from coal.

Just the opposite is the case with natural gas production. According to Edmonds and Reilly (1985), after 2025 natural gas demand will decline because of the rapid exhaustion of conventional natural gas resources which will be replaced at a very slow pace by unconventional resources with extraction costs much higher than that of substitute natural gas production from coal. Frisch (1987) assumes a steady growth in natural gas production until 2060. Sinyak's (1990) projections support Edmonds and Reilly's projections and Frisch's projections: with minimal fossil fuel consumption (limited fossil fuels use options) they are close to Edmonds and Reilly's projections; with maximal fossil fuels use, they are close to the projections of Frisch (nuclear moratorium or nuclear reductions options).

The situation of coal prospects remains very uncertain. It is quite evident that in the case of restrictions for fossil fuel consumption, because of the many environmental, economic, and societal factors, the use of coal has to decline. If nuclear energy, in turn, is constrained or substantially reduced, then only coal will be able to fill the gap in expected primary energy demand which will be followed by increased CO_2 emissions. Therefore, depending on initial assumptions, the long-term coal projections could differ by an order of magnitude. Coal's share (including biomass) is, according to Edmonds and Reilly (1985), at the highest level in 2050 (45%), with coal production of more than 25 million tce (almost eight times more than in the mid-1980s). They assume that after 2025 synthetic liquids and gaseous fuels from coal will vastly expand, and according to their estimates one-third of the coal produced will be used for this purpose. Meanwhile, the synfuels from coal have ever higher CO_2 emissions per unit of energy than those produced by liquid gaseous fuels from natural sources (e.g., three times more than that for natural gas).

Assessments of the future role of nuclear energy show the biggest deviations. Edmonds and Reilly's projections for 2050 are almost three times that of Frisch's but very close to the level predicted in Sinyak's limited fossil fuels use option in the base scenario. However, this level could be reduced by half in the case of enhanced energy saving accompanied by global-warming regulations. Edmonds and Reilly build their projections on the assumption of a higher economic efficiency for nuclear energy together with growing crude oil and natural gas prices and far-reaching consequences of environmental pollution. They predict a 5.6% growth rate for nuclear energy between 2000 and 2025 and 3.4% between 2025 and 2050. But they could not account for the consequences of Chernobyl and the resulting negative public opinion for nuclear energy. This is the main reason for their overestimates in nuclear projections. At the same time it is necessary to understand that without nuclear energy the global-warming problem can hardly be solved in the next century, even with enhanced energy-savings policies. This position is also supported by the World Energy Conference (WEC, 1989), Häfele (1989), and many others.

The future role of renewable energy sources is in all studies evaluated as modest, although the absolute volume of this energy form will increase by several factors. Only Sinyak (1990) projects the share of renewables to be at a very high level (maybe even too high!) in the limited fossil fuels use scenarios.

In summary, one could point out some common tendencies in energy systems development concerning energy demand growth, conventional crude oil and natural gas resources exhaustion, production of unconventional crude oil, and, to a lesser extent, unconventional gas production and the penetration of nuclear and renewable energy sources in the global energy balance. However, the future structure of primary energy supply and production levels of different energy forms remains very uncertain, which shows that further research in this field in necessary.

Table 10. World energy supply by energy sources (billion tce).

Resource	Reference	1985	2000	2020–2030	2030–2040	2050–2060
Crude	Edmonds and Reilly (1985)		5.2	6.2		10.2
Oil	Frisch (1987)		5.2	4.9	4.5	3.5
	Sinyak (1990)	4.3	4.1–4.2	3.1–4.6	2.6–4.5	1.1–4.2
	WEC-14 (1989)		4.2–4.4	4.6–5.1		
	Häfele (1989)				4.1	
	US EPA/DOE (1990)			4.9–5.2		
Natural	Edmonds and Reilly (1985)		2.8	3.8		3.0
Gas	Frisch (1987)		2.9	4.0	4.6	5.2
	Sinyak (1990)	2.2	3.0–3.2	3.7–4.8	4.0–5.0	3.4–5.1
	WEC-14 (1989)		2.5–2.8	2.9–3.4		
	Häfele (1989)				4.6	
	US EPA/DOE (1990)			3.1–3.6		
Coal	Edmonds and Reilly (1985)		5.2[a]	11.9[a]		25.4
	Frisch (1987)		4.5	7.1	8.9	10.8
	Sinyak (1990)	3.2	4.1–4.2	3.4–6.6	2.4–9.5	1.5–12.8
	WEC-14 (1989)		3.6–4.0	4.6–5.8		
	Häfele (1989)				1.7	
	US EPA/DOE (1990)			5.4–9.4		
Nuclear	Edmond and Reilly (1985)		1.4	5.4		12.3
	Frisch (1987)		1.2	2.6	3.5	4.3
	Sinyak (1990)	0.5	1.0–1.1	0.8–4.0	0.4–7.4	0–13.1
	WEC-14 (1989)		0.8–0.9	1.2–1.6		
	Häfele (1989)				4.3	
	US EPA/DOE (1990)			2.5–3.4		
Others	Edmond and Reilly (1985)		1.9	4.0		5.1
	Frisch (1987)		3.2	4.6	6.2	8.0
	Sinyak (1990)	1.8	1.3–1.5	2.2–3.2	3.3–6.2	5.0–10.0
	WEC-14 (1989)		2.5–2.6	3.2–3.1		
	Häfele (1989)				3.9	
	US EPA/DOE (1990)			1.0–1.5		
Total	Edmond and Reilly (1985)		16.5	31.3		56.0
	Frisch (1987)		17.1	23.2	25.0	32.0
	Sinyak (1990)	12.0	13.7–14.1	17.1–20.0	20.0–25.0	21.0–32.0
	WEC-14 (1989)		13.2–14.7	16.5-19.0		
	Häfele (1989)				18.6	
	US EPA/DOE (1990)			16.0–23.0		

[a]Including biomass.

In recent projections, many authors consider CO_2 emissions as the major element in expected global warming. First, burning fossil fuels to provide society with useful energy forms produces large quantities of CO_2 released into the atmosphere. Second, CO_2 emissions and their related global-warming effect have a global character unlike many other air pollutants with only regional/local impacts. Third, the negative consequences of global warming might be noticed soon (within the next decades: the lifetime of energy equipment built now). All this makes the CO_2 problem an essential element of global energy projections.

Many studies forecast a steady increase in global CO_2 emissions (see again *Table 10*). However, a few projections predict reductions in CO_2 emissions: for example, Rotmans *et al.* (1989) show that annual CO_2 emissions could be reduced by a factor of two by 2050 as compared with today's levels.[5] The dynamics of this indicator provides two distinct periods: the first from 2020 to 2025, when the majority of projections expect modest growth, and the second after 2025, when a sharp growth occurs because of changes in primary energy mix connected to the higher use of coal for synthetic fuel production as well as to high levels of crude oil production from oil shales, both of which are accompanied with high CO_2 emissions. The diverging CO_2 emission assessments in the studies can be explained by the different evaluations of specific emissions caused by burning fossil fuels.

When calculating CO_2 concentrations in the atmosphere, many studies use different assessments of the share remaining in the atmosphere after part of the CO_2 is absorbed by the oceans. This share ranges from 40% to 70% (naturally, the wide magnitude of estimates produced highly different results). The expected CO_2 emissions are shown in *Table 11*.

Table 11: Expected annual CO_2 emissions (billion C/yr).

Reference Sources	1985	2000	2020-2030	2030-2040	2050-2060
Nordhaus (1977)		11	18[a]	40	45
Rotty and Harland (1980)		9	13		15
Häfele *et al.* (1981)		9	16		
Edmonds and Reilly (1985)	5.5	6.9	12.3		26.3
Lashof (1989)		5.4[a]	6–11[a]		7–15[a]
EPA (1989)		5–11			4–18
Rotmans *et al.* (1989)		4–7[a]	4–13[a]		3–21[a]
Sinyak (1990)		6.2–6.3	6–8	5–11	4–13
WEC-14 (1989)		7.2	9.1	8–10	11–14
Häfele (1989)		6–7	4.1		
US EPA/DOE (1990)			10–13		

[a]Including other CO_2 sources besides fossil fuels and other trace gases.

All studies indicate increasing CO_2 concentrations until the middle of next century (see *Table 12*), but it will be hardly double that of the preindustrial period. Sinyak (1990) predicts increasing CO_2 concentration levels up to 460–550 ppm by 2060 (this only accounts for burning fossil fuels and not for anthropogenic and other natural factors). Rotmans *et al.* (1989) show a possible stabilization of CO_2 concentrations during the next century if drastic preventive measures are initiated immediately to reduce fossil fuels use and to control other emissions from trace gases.

In conclusion, it is necessary to note that there are common trends in all studies for future development. But at present, differences in numeric results are still significant. These differences demand additonal efforts in energy/CO_2 research with improvements in projection methodologies and in studying the causes for global warming (either natural or anthropogenic).

Table 12: CO_2 concentration projections (ppm).

Reference Sources	1985	2000	2020-2030	2030-2040	2050	2060
Edmonds and Reilly (1985)		380	445		575	
Häfele *et al.* (1981)		350–370	410–490			
Minzer (1989)		350–380[a]	360–490[a]		400–630[a]	
Rotmans *et al.* (1989)	340	360[a]			370–530[a]	
Sinyak (1990)		373	410–420	440–480		460–550
WEC-14 (1989)		348	372-377	395–410		423–456
Häfele (1989)		410	440	460	470	475

[a]Including CO_2 sources besides fossil fuels and other trace gases.

6 Conclusions

1. Energy as a driving force of social and technological progress will keep its leading role among major global problems during the 21st century. This calls for necessary and expedient elaborations of long-term energy projections. The many forms of energy development, uncertainties in input assumptions and parameters, and differences in socio-philosophical concepts of societal development explain the diversity in approaches to solving global energy problems and periodic reevaluations of long-term forecasts.

2. Today's energy systems have entered a period of transition from systems based on exhaustible fossil fuels resources to systems based on practically inexhaustible resources (nuclear fission and fusion, renewables). The duration of this transition period will depend on many factors. The main factors certainly are the significance of climatic and environmental degradations associated with the different energy systems and technologies and the social costs of various energy sources. The global-warming issued could speed up the pace of this transition.

3. The next decades (at least until the middle of the next century) of global energy systems development will be characterized by the following:

   - Further energy demand growth (mainly in socialist and developing countries).
   - Growing importance of energy conservation and savings in all areas of energy production and consumption.
   - Severe limitations in nuclear energy development (especially during the next couple of decades) until new generations of nuclear reactors are installed with much higher safety rates.
   - Limited contribution of renewable energy sources to the global energy balance which is due to their unfavorable economics, often negative impacts, and unreliability.
   - Fossil fuel will keep its leading role in the global energy supply from the viewpoint of resources availability and production costs, although ecological and climatic factors will greatly influence its future use.
   - The influence of ecological and climatic factors in compiling energy strategies will increase, while the impact of political and economic factors, presently dominating the energy-related decision-making processes, will decrease.

4. In light of these anticipated tendencies, global energy demand might increase from the current levels of 11.5 to 13–14 billion tce in 2000 and up to 20–30 billion tce in 2060. Moreover, energy demand in developed countries will remain stable or even start to decline

after that period (it is quite probable that the absolute level of energy demand in some developed countries will start to decrease in the near future). The largest growth in global energy demand will take place in developing countries (including China and other socialist countries). The expected energy demand growth in developing countries with market economies will be six- to tenfold and in socialist countries 1.7–2.2 times that of mid-1980 levels. At the same time the share of developing countries with market economies will increase from 11.5% in 1980 to 42%–52% in 2060 and the developed countries' share, which now exceeds 50%, will decrease to 16%–12% in 2060. Such drastic changes in the global energy demand structure indicate the shift of global, energy-related problems to the regions of developing countries in the coming decades. This will be followed by new "hot" points in solving global, energy supply problems if reasonable measures are not taken in time.

5. The primary energy supply structure in the next 70 to 80 years will be strongly dependent upon the applied energy development strategies. In the business-as-usual scenario (without any constraints on fossil fuels or nuclear energy), coal production will increase to 5–10 billion tce annually until the end of the projection period, conventional crude oil to 3.2–4.2 billion tce, and natural gas to 3.4–4.8 billion tce. The total share of nuclear and renewable energy will reach 40%–45%. However, in the case of the global-warming prevention strategy, the share of fossil fuels must be substantially reduced (in our assessments to 25%–28% in 2060), with coal and crude oil production – because of CO_2 emissions – declining more than natural gas. A freeze or even limits on nuclear energy production could only be compensated by a growth in fossil fuels production (of course, parallel to enhanced energy savings) by at least 1.4–2.6 times that of today's level, but this will be accompanied by a proportional rate of CO_2 emissions.

6. In spite of many radical measures that could be taken to stop the negative impacts on the global climate, it is unlikely that increasing atmospheric CO_2 concentrations can be avoided during the period under consideration (the most we can expect is a possible delay in global warming for a couple of decades). Parallel to these measures other efforts have to be taken. (First of all intensive global reforestation and reduction of other trace gase emissions, which contribute up to 50% to global warming.) Broad-scale investigations on the phenomenon of global warming and its consequences must be started, and preventive measures must be evaluated in order to choose the optimal strategy for social and economic development worldwide. The climate-change issues should be treated as a real and essential global problem that requires the collective efforts by all nations looking for the optimal path to global/regional energy development (especially for the next several decades in view of the high uncertainty and remote consequences).

7. The probability and consequences of global warming still remain highly uncertain and call for further studies on energy-ecology-climate interaction at the global as well as regional levels. Special attention should be devoted to elaborate the complex mathematical model sets, describing all the aspects of future global warming produced by natural and anthropogenic systems (including energy systems), and to assess the socioeconomic results and costs of preventive measures. Therefore, it is imperative to resume a new round of global-energy-related studies with new goals and approaches.

Notes

[1] This statement may be too optimistic but the acceptance of environmental considerations, the understanding of the importance of the risk analysis, and many other factors serve as examples of this controversial statement.

[2] This statement is valid until per capita GNP and energy consumption reach some minimal levels ensuring their entering into the group of industrially developed countries.

[3] In fact, the total potential may be several times more if we assume much higher rates for solar energy utilization than those given in *Table 6*. Therefore, the levels of renewable energies utilization assumed in this study should be considered as rather conservative which might be several times more in case of special governmental promotions.

[4] Total global solid area covered with forests of all types is about 75 million km^2 today; the remaining noncultivated area (savanna, deserts and semideserts, tundra, etc.) spreads over more than 60 million km^2 (Leemans, 1990). Cultivating one-third of the forest-free area will give almost 2000 million hectares of new forests or more than the 25% growth of the global forest area. This is hardly an exaggerated assumption if we take into account that the Tropical Forestry Action Plan of 1987 identifies the need to rehabilitate 1.6 million km^2 of forest and woodland for erosion and flood control alone (United Nations Development Programme, 1990). Assuming an average productivity of the new forests attributable to intensive plantation management at the level of 3–4 t C/ha/year for moderate latitudes and of 6–8 t C/ha/year for wet tropical forests (Marland, 1988) and applying two-thirds of the efforts on growing new forests to the tropical zone, we find that over the next 70 years the total quantity of the carbon absored from the atmosphere will reach about 255 billion t; this corresponds to some 50% to 100% of CO_2 remaining in the atmosphere due to burning of fossil fuels. Until now less ambitious programs of reforestation are considered (e.g., the IPCC study contemplates only 400 million hectare as a target for CO_2 reduction which could give only 80 million t C over 100 years, (IPCC, 1990).

[5] The investigation by Rotmans *et al.* (1989) deserves special attention because it treats many factors influencing global warming.

References

AMOCO Corporation, Lower and Upper Price Cases, Presented at the International Energy Workshop, IIASA, Laxenburg, Austria, June (1989).

Ashby, A. and D. Dreyfus, Global Outlook for Service Sector Energy Requirements, Presented at the International Energy Workshop, IIASA, Laxenburg, Austria, June (1989).

Centre for International Energy Studies, Erasmus University, High, Low and Mid-Point Demand Growth, Presented at the International Energy Workshop, IIASA, Laxenburg, Austria, June (1989).

Colombo, U. and O. Bernardini, A Low Energy Growth Scenario and the Perspectives for Western Europe, Report prepared for the Commission of the European Communities, Panel on Low Energy Growth (1979).

Deutscher Bundestag, Schutz der Erdatmosphere. Eine internationale Herausforderung, Bonn, (1988).

Edmonds, J. and J. Reilly, A Long-Term Global Energy-Economic Model of Carbon Dioxide Release from Fossil Fuel Use. *Energy Economist* 5:74-88 (1983).

Edmonds, J. and J. Reilly, *Global Energy: Assessing the Future*. New York: Oxford (1985).

EPA, Environmental Protection Agency's Report to Congress. Policy Options for Stabilizing Global Climate. Expert Group Meeting on Methodologies and Analytical Tools, Paris, April 10-11 (1989).

Frisch, J.-R., Long-Term Energy Alternatives to Hydrocarbons. 12th World Petroleum Congress, Houston, Tex. (1987).

Goldemberg, J., T. Johansson, A. Reddy, and R. Williams, An End-Use Oriented Global Energy Strategy. *Annual Review of Energy* **10**:613-688 (1985).

Häfele, W. *et al.*, *Energy in a Finite World: A Global Systems Analysis.* Report by the Energy Systems Program of the International Institute for Applied Systems Analysis. Cambridge, Mass: Ballinger (1981).

Häfele, W., Energy Systems Under Stress, Invited paper, 14th World Energy Conference, September (1989).

Harvey, L. D. Danny, *Managing Atmospheric CO_2: Policy Implications*, *Energy*, **15**(2):91–104 (1990).

IPCC (International Panel on Climate Change), Policymakers Summary of the Formulation of Response Strategies, Report prepared for IPCC by Working Group III, June (1990).

Lashof, D., Expert Group Meeting on Methodologies and Analytical Tools, Paris, April 10-11 (1989).

Leemans, R., Possible Changes in Natural Vegetation Patterns due to a Global Warming, WP-90-08, International Institute for Applied Systems Analysis, Laxenburg (1990).

Lovins, A., L. Lovins, F. Krause, and F. Bach, Energy Strategies for Low Climatic Risk. Report to the German Federal Environment Agency (1981).

Marland, G., The Prospects of Solving the CO_2 Problem through Global Reforestation, DOE/NBB-0082, February (1988).

Minzer, I., Reducing the Risks of Rapid Climate Change: Energy Choices for Developing Countries. Expert Group Meeting on Methodologies and Analytical Tools, Paris, April 10–11 (1989).

National Academy of Sciences, Energy and Climate, Washington, DC (1977).

Nordhaus, W.D., Strategies for the Control of Carbon Dioxide (1977).

Nordhaus, W. and G. Yohe, Future Paths of Energy and Carbon Dioxide Emission. In *Changing Climate*, Report of the Carbon Dioxide Assessment Committee. Washington, DC: National Academy Press (1983).

Rogers, P., Climate Change and Global Warming, *Environ. Sci. Technol.* **24**(4):428–430 (1990).

Rose, D., M. Miller, and C. Agnew, Global Energy Futures and CO_2-Induced Climatic Change. Report MITEL 83-015. Cambridge, Mass. (1983).

Rotmans, J., H. de Boois, and R. Swart, An Integrated Model for the Assessment of the Greenhouse Effect: The Dutch Approach. Expert Group Meeting on Methodologies and Analytical Tools, Paris, April 10–11 (1989).

Rotty, R. and G. Harland, Constraints on Carbon Dioxide Production from Fossil Fuels Use (1980).

Starr, C. and M. Searl, Global Projections of Energy and Electricity. American Power Conference, Annual Meeting, Chicago, Ill., April (1989).

Sinyak, Y., Global Energy/CO_2 Projections, unpublished report, IIASA, Laxenburg, Austria (1990).

United Nations Development Programme, "The Tropical Forestry Action Plan 1987" (1990).

US EPA and US DOE, Integration of the EIS Country Studies: US Approach and Comparative Analysis, Summary paper (draft), January 29 (1990).

WCG, Working Consulting Group of the President of the USSR Academy of Sciences, Long-Term Global Energy Projections, Moscow (1978)(in Russian).

WEC, (World Energy Conference), 14th Congress, Conservation and Studies Committee. World Energy Horizons 2000–2020, Paris (1989).