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GLOBAL ENERGY AND CLIMATE CHANGE: PLAUSIBLE ROLE OF NUCLEAR ENERGY

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At the threshold of the 21st century, humanity is trying to formulate with faith and concern the major features of future existence. The necessity for changing the approach to the definition of human development is explained by the growing crisis in the interaction between humanity and nature, by ever increasing contradictions between rich and poor nations, by improvements in human consciousness and by the reevaluation of the attitudes towards the prospects and real outcomes of technological progress. Problems waiting for their resolution at the beginning of the next century are multiform. Many of them are only appearing, their impacts are still unclear. Others have already emerged on a full scale. For some, the difficulties and critical situations are well-known, but for others we must still look for workable solutions with the cooperative efforts of all nations with different levels of economic development and political systems. One thing is quite evident now: international cooperation and consensus will be an effective mean for saving humanity. The complexity of the overwhelming majority of global problems grows very fast (the rate of this process can be compared - if not more - with technological progress itself). Many problems appear simultaneously, stimulate each other and produce new problems.

The evolution of natural systems that feed and sustain human populations, and indeed the evolution of modern society, has occurred in the context of a moderate and stable climate. A stable climate system has always been taken for granted in the evaluation of the prospects for human progress. Therefore, recent trends in climate changes, caused by increasing CO2 concentrations and other radiative active trace gases in the atmosphere, and as a result expected global warming, are now of major concern to humanity. Carbon dioxide is the major contributor to the total increase in climate forcing during the 1980s, amounting to 55% or about 8.2 bln.t C of which 67% are connected with fossil fuel combustion[1]. Many other greenhouse gases (e.g., CH4, N2O, etc.) are also released in large quantities by energy systems. Therefore, it is naturally that energy systems are addressed in the first order in all strategies preventing climate change and environmental degradation.

Many believe that the energy remains over a long time ahead an essential element of human existence and a moving force of material culture, which is the basis of our civilization. The energy problems will hardly dominate in the next century, however, they will keep their place of the highest priority among

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[1] IPCC (1990). Policymakers Summary of the Scientific Assessment of Climate Change. Report to IPCC from Working Group 1, June, p.17; Beaver, R. (1990). Summary of Major Sources of Anthropogenic Greenhouse Gas Emissions, EMF 12, September.

the human problems . At the same time, we can assume that after reaching some level of human development, the importance of material culture will start to decline making place for mental wealths and goods. This means that the gap between the rates of economic development and energy consumption will become normal rather than a temporal event. This tendency can now be observed in some of the developed countries and will be a general trend for the next century. The economic progress with stabilizing or even decreasing energy consumption may be a reality in the near future. This factor will help in finding solutions to the global energy problems. On the other hand, inexhaustible energy sources exist already or are known, in principle, and their development depends on the cost and time of penetration. Once cheap and limited energy sources are exhausted, new technologies based on inexhaustible resources will find their application.

All that affirms that humanity will not be perished by the lack of energy over the foreseen future. The problem is how to provide the energy supply in an optimal way, with a minimum of burden for the economy and the environment and with a minimum of risks for humanity and the biosphere. This optimized approach requires the application of social cost concepts, including all externalities reflecting direct and indirect impacts on humanity, biosphere and climate over the whole technology life-cycle to the development of global/regional/local energy strategies or to the selection of energy technologies. The long-term energy prospects will be based only on such a conceptual approach.

After the first energy crisis in 1973, global energy projections were oriented towards the transition from existing energy systems, based on limited resources of fossil fuels, to systems on practically inexhaustible resources (e.g., fission and fusion, renewable energy). The resource availability played a major role in those studies. Although many (if not all) projections of those years turned out to be far from reality, these studies provided a strong stimulus for the development of energy research activities all over the world, resulting in a wider knowledge of existing fossil fuel resources (especially for crude oil and natural gas), in elaborating and demonstrating new technologies for energy production, based on such "infinite" energy sources as the Sun, Ocean, Earth, and in realizing the large energy savings potential, associated with the "negative" costs, i.e., when the costs for energy savings are less than for energy production. In the 1980s, the central point in long-term energy analyses shifted more and more towards environmental issues, and over the last years the climate change problems with increasing carbon dioxide concentrations in the atmosphere are the focus of long-term studies.

Consensus exists that further environmental pollutions and climate changes could be prevented if energy systems emissions are significantly reduced. Scientists and politicians worldwide are involved in studying ways of transition from current energy system, which are to 90% based on fossil (carbon) fuels to systems based on non-carbon fuels and inexhaustible resources. The Intergovernmental Panel on Climate Change (IPCC) stated recently that in order to stabilize the carbon concentration in the atmosphere, the CO_2 releases should be reduced by 60% to today's level[2]. As being the major contributor to the atmospheric carbon stock, energy systems in developed countries must reduce their emissions 3-4 times and in developing countries - 30-40% to reach the level defined by the IPCC. The fulfillment of this requirement is linked with tremendous changes in energy systems and immense energy cost increases. However, a final decision on the necessity and depth of these changes can be taken only after a careful evaluation of the damages caused by global warming. A global abatement strategy must be really global in its nature and include, besides energy systems, other sources of greenhouse gas emission and sinks (e.g., deforestation and aforestation, land use, CO2 disposal, etc.). The importance of finding intelligent ways of global warming mitigation now defines the problems which are central in all approaches to energy system projections and scenarios today.

In general, the global situation of energy systems on the eve of the 21st century can be summarized as follows:

* Mankind takes its first steps towards 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 are the central point of all future energy systems development concepts;

* Global energy demand is likely to continue to grow over the next century (at least during the first half) because of increasing population and further development of material production in developing countries, though this 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 (end of next century) at a level 2 to 5 times higher than that of today's. Energy consumption increases will be justified by social and environmental goals and priorities put forward by human society over the next century. However, one thing is evident: the share of developing countries in global energy consumption, which is today equal to 1/5 of the total, will steadily increase and will probably reach 70-80% of the total energy consumption in the second half of the next century. This means that the central point in global energy issues will shift from developed to developing countries over the next several decades and could result in new political tensions on the global scene if not properly taken into account now;

* In case of relatively low energy demand growth rates, fossil fuel resources at any rate (even such as hydrocarbons) will continue to play a leading role in energy supply until the middle of next century (only if no special measures or regulations will constrain the use of fossil fuels because of their links climatic impacts);

* 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

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[2] Intergovernmental Panel on Climate Change. Policymakers Summary of the Scientific Assessment of Climate Change, June 1990, p.8.

needs. (The situation might change, of course, if fossil fuels use is limited because of climate changes and if new technological breakthroughs and improvements in the safety of nuclear reactors are achieved);

* Electrification will keep its importance for productivity and social improvements. For many countries, the electricity growth rates will be higher than those for GNP. In view of this growth, the share of steam and hot water and, especially, of direct fuels use at the end-consumer will steady decline. This tendency may even increase if ecological or climatic aspects will constrain their usage;

* Capital intensities of energy supply will increase but will keep the share of energy systems in total investments at a constant level (or even declining 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 will grow).

In total, the global energy situation over the next century will not be critical if humanity follows a reasonable long-term strategy for energy systems development. However, in order to avoid critical situations in the future, it will be necessary now to find new concepts of energy development which, on a broader scale as today, take into account social, economic and environmental impacts of energy development.

These ideas are the background for IIASA's global energy and climate change study undertaken in collaboration with CRIEPI of Japan.

Analytical Framework. The analytical framework of the study is based on three different models (Fig. 1).

The energy projections are accomplished in two stages:

at the first stage, the MEDEE-2 model[3] is applied for detailed simulations of final energy demand for ten world regions:

North America, Australia and New Zealand
Western Europe
Eastern Europe
Japan
ex-USSR
Latin America
North Africa and Middle East
Pacific
China and other Asian CPCs
Other less-developed countries (LDCs).

at the second stage, the aggregated results for two major world regions (developed and developing Countries) produced at the first stage are used by the LEAP model[4] for the evaluation of primary energy projections and required changes in energy

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[3] Chateau, B. and B.Lapillonne (1982): Energy Demand: Facts and Trends, Springer-Verlag, Wien-New York.

[4] Raskin, P.(1986): LEAP: A Description of the LDC Energy Alternatives Planning System, Bejer Institute/Scandinavian Institute of African Studies, Uppsala, Sweden.

conversion sectors as well as in primary energy productions and trade. CO_2 emissions are calculated on the basis on the results of the second stage. The analysis of output indicators (e.g., primary energy or electricity per capita or GNP, elasticities, GNP per capita) in time dynamics and by region helps in the verification of results and in making them more practicable and compatible. This process requires also several iterations to produce meaningful and reasonable energy projections. An auxiliary spreadsheet model is used for calculating cost/investments required by a scenario/ option.

The results of energy projections are used for the evaluation of energy saving potentials by region and cost-effectiveness of its implementation until 2010. The MARS model[5] helps in identifying optimal global CO_2 abatement strategies under given constraints for energy systems and CO_2 reduction goals. The model belongs to the class of discrete problems (the most known examples of this family are the problem of optimal assignments and the travelling salesman problem). Since none of exact algorithms can be applied for tasks with more than 15-20 variables, the heuristic algorithm has been developed for practical usage which enables to obtain a plausible approximation for the optimal solution within a reasonable calculation time. The two-step approach exploits the additive structure of the objective function to decompose at the first step the initial problem on few independent subproblems and to use them for the synthesis of the "optimal" solution on the second step. A combinatoric algorithm of induced sorting with rejecting infeasible or less-effective solutions is used at the stage of the decomposition. The method generates at each iteration a new feasible solution and compare the value of the objective function for it with the best value achieved at the previous iterations. Finally, a finite set of mutually excluding solutions for subproblems is generated. At the second step, the Bellman's dynamic programming is used to get the "optimal" solution on the set obtained at the first step with taking into account possible constraints on some common variables. Such a procedure can help in finding practical solutions for problems with hundreds of variables

Therefore, the measures which can be applied to reduce CO_2 emissions or CO_2 accumulation in the atmosphere in developed and developing countries are considered as an initial set of possible options (often mutually excluded) on which the optimal solution is to be found. This step finishes the modeling process though sometimes several iteration loops may be required to reach the reasonable and practical solutions.

<u>Definition of Global Scenarios</u>. Long-term social and economic projections for the development of such complex systems as the energy sector are aimed primarily at the clarification of major trends and tendencies which will prevail in the foreseeable

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[5] The MARS model is a modification of the CLAIR model used in Russia and some other ex-Soviet republics for investigating environment protection policies at the regional and local level (CLAIR: An Environmental Decision Support System for Atmospheric Air Pollution Simulation and Control, System Handbook, February 1990).

future and which must help in clarifying some bottlenecks neglecting which might create large difficulties for the future development. Numerical results are of less importance if they do not drastically change the nature of the long-term policy based on the evaluations of major trends and tendencies. Long-term projections have different implications, however, the issues of the exhaustion of cheap fossil fuel resources and the impacts of energy systems upon the environment and global climate are of most interest in the study.

The most productive approach to long-term projections for man-made systems under study is based on scenario analyses with varying some limited number of exogenous parameters. Such approach helps in the evaluations of systems responses at the different combinations of initial assumptions and data. Meanwhile, the scenario approach has at least one, but essential drawback which is connected with expressing each time subjective views of certain experts involved in the study or group of them. No doubts that this study as well as many similar (if not all at all) pretending to be a scientific research, but not a prophecy, suffers from this handicap.

Two major scenarios which differs by the efforts and effectiveness of energy conservation policies are selected for the detailed analysis of final energy demand:

- Dynamic-as-Usual Scenario - where the rate of social, economical and technological changes worldwide stays the same over the whole time period and the competition between fuel and energy forms is based primarily on market mechanisms;
- Enhanced Efficiency and Conservation Scenario - where special measures additionally to the conditions specified by the Dynamic-as-Usual Scenario are applied to promote and improve energy efficiency in all regions and economy sectors.

Several options within each final energy scenario reflecting structural changes in primary energy supply have been proposed for the further analysis:

- Base Case - with no special constraints on energy systems development,
- Nuclear Moratorium - with practically freezing nuclear energy at the level projected for the year 2005-2010, i.e. assuming that all nuclear power plants currently available in-construction will be finished and no new construction will be allowed except replacement of old and obsolete plants,
- Accelerated CO2 Abatement - with enhanced energy systems restructuring. The marginal case (enhanced energy conservation and the whole range of CO2 abatement measures) assumes CO2 emission reductions until 2050 of about 60% below the current human-made carbon dioxide emissions level, which are, as stated in a recent IPCC report, required to stabilize concentrations. The second case supposes antropogenic releases of CO2 at levels close to the sustainability state and no further increases in the CO2 concentration in the global atmosphere by the middle of the next century.[6]

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[6] The earlier this nature state is achieved, the lower global temperature increase is projected. It means that postponing the policy actions to prevent global warming for some time in the future will result in higher and higher temperature level at which the concentration stabilization will be at last attained.

The study horizon is divided in three large subperiods: first (1980-1990) for model calibrations and verifications[7], second (1990-2010) with two 10-year subperiods to justify in more details mid-term projections; and third (2010-2050) with two 20-year subperiods to understand better the long-term trends and policy measure responses.

Final Energy Demand. Final energy demand assessments are the central point of long-term energy projections based on the simulation approach. In this study, final energy demand includes feedstock and non-commercial fuels which often in official statistics are treated separately. Besides that, only centralized heat supply options are specified in the MEDEE-2 model. That means that decentralized heat suppliers are included in direct fuel usage with corresponding efficiencies.

Final energy projections are based on the analysis of different factors, major of which are as follows:

- population projections,
- GNP growth,
- industrial activities,
- transportation requirements,
- households and service sector expansions,
- energy efficiency improvements,
- social behavior changes.

Population projections and the GNP growths are the same for both scenarios, but other factors vary between scenarios. UN population prospects until 2030 are used in the study, and the author's assessments afterwards until 2050 (Table 1). Economic activity outlooks are based on the input assumptions agreed by the Energy Modeling Forum (EMF-12 Working Group, 1990-1991)[8] for its current joint study on energy and climate change with some author's corrections, mainly related to former socialist countries (the ex-USSR and Eastern Europe) (Table 2). Energy prices over the next decades are assumed to be still under the strong influence of crude oil market projections for which we took the median of the poll responses provided by the International Energy Workshop jointly organized by the Stanford University and IIASA (Fig.2).

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[7] This stage helps in tuning the models because there are no enough input statistical data for some regions to run models effectively. Therefore, the "unavailable" data have been "restored" or reproduced by analogues with other similar regions or based on the available statistics for some state-representatives. The results of model runs have been compared with the available aggregate statistics to be assured that models can describe satisfactorily the past changes in energy systems. This tuning process required usually several iterations.

[8] The Energy Modeling Forum (Stanford University, USA) organized an international group of scientists in 1990-1992 for studying energy sector impacts of greenhouse gas emission control strategies. The group discussed and agreed upon some initial assumptions and scenarios which make the results more transparent and compatible.

Summarizing final energy demand projections made for ten world regions, it is necessary to point out that global final demand will increase from 6400 mln.toe today to around 7365 mln.toe in 2000 and further to 8-13 bln.toe in the middle of the next century (Table 3). Today, 2/3 of final energy is consumed in developed countries. However, their role in the future will strongly decline reaching about 40% (Dynamic-as-Usual Scenario) or only 1/3 (Enhanced Efficiency and Conservation Scenario) in 2050. Depending on the scenario applied, final energy demand in developed countries can either continue to rise by 25%, if moderate efforts in energy efficiency improvements are made, or decline by almost 1/3 compared to today's level if enhanced conservation policy is implemented. The further growth of final energy in the regions of developed countries is unlikely and more probable that final energy demand will continue to decline. Therefore, in both cases the developing countries will be responsible for the major part of global final energy demand growth and this will continue until the end of the next century and presumably beyond it.

The consequences for shifting the burden of global energy problems from developed to developing countries should be evaluated in advance to avoid new complications and tensions around energy resources and environmental degradations in the future.

Electricity Generation. Electricity sector remains one of the most dynamic in the future as a bridge to solving many environmental and social problems of humanity.

Over the time period under study the electricity generation in developed countries will practically double reaching 18000-20000 TWh in 2050 (9100 TWh in 1990). It means that per capita electricity consumption will increase from 7100 kWh to 11000-13000 kWh. The share of non-fossil technologies in electricity generation will steady increase, however, the rate of shifts in the electricity generation will strongly depend on the necessity to overcome these changes under the pressure of environmental and climatic constraints.

In case of accelerated CO2 abatement, the share of non-fossil technologies will increase from 36% today to more than 80% in the long-term. Especially fast growth rate is expected for nuclear energy which must contribute about 60% of all electricity generated in the region (today's level of nuclear energy is about 21%). The further growth is projected for gas-fired technologies (both for base, intermediate and peak load zones) which output will more than double until the end of the first quarter of the next century (and the share of this technology will increase from 20% today to about 30% in that time), however, afterwards in the accelerated CO2 abatement option fossil-fuel modes of electricity production will decline to reach the goal of sustainable CO2 emission around the middle of the next century. In this case the share of fossil fuel technologies shall not exceed 18-20% of which practically all will be met by natural gas-fires power plants (primarily combined-cycle and cogeneration). Strong reduction of coal-fired generating capacities will be required after 2010-2020 with practical elimination of this technology as giving too much carbon emissions until the middle of the next century.

If the consequences of global warming are less dangerous than we can imagine today, then the changes could be less dramatic and the share of non-fossil technologies can reach only less than 45% of which about 32% belongs to nuclear. In this case the electricity produced by coal-fired power plants will double until 2050 and by natural gas will even triple.

In view of the total economic growth in less developed countries, where GNP will increase almost 7 times over the next several decades, the strong exceeding growth for electricity demand is projected. It is expected that the electricity demand will rise from 2050 TWh (only 18% of the current world electricity production) to about 20000-30000 TWh in the middle of the next century (50-60% of a total for the world) (Table 7).

The share of fossil fuel power plants will steady increase until 2010-2020 reaching 70-75% (68% in 1990) in both scenarios. However, in the Dynamic-as-Usual Scenario with moderate efforts in energy conservation this level will be practically stabilized until 2050. Especially strong growth is expected for coal-fired electricity which share will rise from 16% today to 48% in 2050. The share of natural gas will also increase, however, less than for coal (from 15% to 24%),primarily because of less natural gas availability than of coal in this region. But in Enhanced Conservation Scenario with the accelerated CO2 efforts the share of fossil fuels must be drastically reduced after 2020 with reaching to not more than 10% of which the major part is met by natural gas. Both scenarios and options assume the increase in the share of non-fossil technologies which contributions must reach about 90% in 2050 to fulfill the sustainability goal. However, these projections look strongly unlikely and impossible without good world cooperation and earlier understanding of the problem and undertaking joint actions.

In general, the world electricity generation will grow with an average growth rate of 2-2.5% annually over the time period under study reaching 40000-45000 TWh in 2050 (11150 TWh in 1990) (Table 4). The structure of generating technologies will strongly depend on the scenario applied. It is expected that in the extreme case the renewable energy technology could contribute not more than one third of required electricity in the middle of the next century. From the other hand, the CO2 emission constrains in the case of a sustainable scenario will allow for fossil fuel technologies not more than 10% of which all are practically on the basis of natural gas. Therefore, the difference (about 55%) should be met with non-carbon technologies (e.g., nuclear or renewables). Of course, the changes are much less in the case of Dynamic-as-Usual Scenario in which the share of non-carbon technologies will increase only to one third until 2050 (with only 15% contributed from renewable sources and the rest from nuclear and alike).

Nuclear Energy. The approximate estimates for conventional uranium resources, which are equal to about 20 mln.t or 85 bln.toe in fossil fuel equivalent case of the conversion of uranium in light water reactors and which approximately 5500 bln.toe if breeder reactors are used (Table 5). However, these resources will be able practically to satisfy only about 850 GWe of nuclear over the next hundred years (assuming that 160 t of natural uranium with a cost less than $80/kg U is used annually to run 1 GWe). The introduction of breeder-reactors can expand the resource base manifolds (about 50-60 times) and practically eliminate the problem of the resource base for nuclear energy. These estimates do not include uranium in shales and in sea phosphate depositions (about 7 mln.t U). There are much more deposits of uranium in sea water and in granites, however, the cost of its extraction is much higher than $130/kg shown in the table, the cost at which nuclear power plant equipped with light water reactors can still compete with fossil fuel power plants. If breeders are applied on a broad scale, the cost of uranium will be of less importance because the uranium is used in these reactors 60-70 times more efficient than in case of light water reactors. It means that the resource base for advanced reactors will be expand manifold.

The future of nuclear energy is one of the most controversial points in all energy projections presented today. Therefore, several options related to nuclear have been analyzed in the study. Base Case assumes steady but declining growth rates for nuclear over the whole time period; Nuclear Moratorium is based on practical freezing nuclear after the completion of all existing nuclear power plants under construction and late projections (practically, after 2005-2010), and Accelerated CO2 Abatement when the necessity for nuclear is determined by the request of reaching CO2 emission levels as it is stated by IPCC to stop further increase in the carbon atmospheric concentration. Table 6 contains nuclear projections. The prospects for this energy source over the next 15-20 years are extremely uncertain: from one side, risk and safety problems make nuclear unpopular among the population in many countries already having this technology, and from other side, the idea that the ecological and climatic problems could be solved only by having some niche for nuclear becomes more and more popular. In all scenarios without the limits on nuclear the share of this energy will increase from 5.4% in 1990 to 6.3% in 2000 and 6.3-8% in 2010. However, the nuclear development after 2010 will depend on the improvements in the technology and in our perception of nuclear as a measure to alleviate global warming: in the middle of the next century the share of nuclear in the total energy demand may rise slowly to 11% (Dynamic-as-Usual Scenario, Base Case) or even to more than one third if the constraints on CO2 emissions are imposed and the goal to achieve sustainable level until 2050 is needed[9]. Total installed capacity of nuclear power plants must increase from 318 GW(e) today to almost 400 GW(e) in 2000 and 1300-3650 GW(e) in 2050[10]. These projections mean that the average annual increments in nuclear installed capacity over the whole time period should be about twice lower than in the 1980s (if Dynamic-as-Usual Scenario is addressed) or at least twice higher (if Energy Efficiency and Conservation Scenario and Accelerated CO2 Abatement path is selected).

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[9] Of course, in case of constraints on nuclear during the first halve of the 21st century the share will decline slowly after 2010 reaching 4-5% in the middle of the century.

[10] We assume here that nuclear energy includes, except nuclear itself in the form of fission and fusion, other non-carbon technologies which have not been already embraced within renewable energies. But it is clear that nuclear is of the first priority in this list because of its maturity, however, still requiring further solid improvements.

Large contribution of this energy form in total energy supply is expected for developing countries. The share of this region in today's nuclear installed capacity is less than 6%; it will reach 7% in 2000 and 25-60% in 2050 depending on the scenario applied.

Of course, such a policy will create many new problems for which there are no acceptable solutions today:

* fuel reprocessing to expand the resource base for nuclear energy,
* safety improvements by at least two orders of magnitude to reach acceptable safety levels,
* nuclear waste disposal to prevent radioactive contamination on a broad scale,
* Pu utilization.

Before this problems are not settled, and the public changes its negative attitude towards nuclear (it presumably takes several decades), there are still keeping large uncertainties about the future for nuclear energy. Meanwhile, as concerns carbon emission reduction, nuclear remains one of the most effective preventive measure for the foreseeable future.

Global/Regional Energy Balances. Primary energy demand in developed countries will be increasing in the future with a steady declining growth rate. Therefore, the energy demand is projected to raise by 10% until 2000 as compared to the 1990 level reaching 6.8 bln.toe. In the new century two ways are analyzed: with a further growth under the assumptions of the Dynamic-as- Usual Scenario, or with a practical stabilization of energy demand over the whole first part of the century in case of the Enhanced Efficiency and Conservation Scenario. As a result of these two approaches the energy demand will reach about 6500-7300 mln.toe in 2010 and will further grow up to 8700 mln.toe if the Dynamic-as-Usual path is selected. However, if enhanced efficiency improvement measures and policies are applied and started immediately, then the results will be seen already at the beginning of the next century and the energy demand will be close to stabilization at the level close to that reached until 2000.

Large changes in primary energy mix are expected. Crude oil demand will decline from 38% in total energy demand currently to 32% in 2000 and further to 10-13% in the middle of the next century. The role of natural gas will steady increase: its share will raise from 25% today to 29% in 2000 and 30-32% in 2010, but afterwards the demand will strongly depend on the policy chosen: at moderate efforts in energy conservation and CO2 abatements the further growth in absolute terms is expected (however, the percentage of natural gas in total energy demand will remain practically unchanged), or if enhanced policy measures to cope with global warming are applied, then the decline of demand for carbon-content fuels will be inevitable (of course, less for natural gas than for coal or crude oil) and the share of this fuel will keep less than 20% in 2050. Coal will hold its position about 23% until 2000, but afterwards either small growth will be anticipated with reaching 28% in the middle of the next century (Dynamic-as-usual Scenario, Base Case) or the coal demand will be sharply declined because of CO2 emission reduction goals established to achieve over the time period under study (Enhanced Efficiency and Conservation Scenario, Accelerated CO2 Abatement). The non-carbon contribution will increase in all cases, but with much higher rate in case of CO2 reduction strategy. The share of nuclear which is equal now to only 7.1% in the primary energy demand will increase to 8.3% in 2000 and further to 15-40% in 2050 depending on the policy in energy conservation and CO2 abatement. Renewables contributions will also expand from 5.8% today to 6.3% in 2000 and 10-35% in the long-term.

Changes in the demand for electricity will result in the increase of the share of primary energy resources used for electricity generation: from 35% today to 39% in 2000 and 50-70% in 2050. The expected contribution from non-carbon technologies will steady grow from 36% currently to 45-85% in the middle of the next century. The lower level is projected for the Dynamic-as-Usual future, and the highest one for the case with Enhanced Energy Conservation and Accelerated CO2 Abatement.

Per capita energy consumption will still increase over the current decade reaching 5-5.15 toe per capita, however, afterwards this indicator will likely continue slow growth or start to decline, of course, with a different rate for various scenarios. The per capita energy demand will reach about 8 toe/capita for Dynamic-as-Usual future if no special measures to stop CO2 emissions are applied or rocket even to 11 toe/capita if accelerated growth of non-carbon technologies is required. Under the pressure of enhanced efficiency improvements it will be able to reduce to about 3.3-4.6 toe/capita (less than 4.9 toe currently). The energy/GNP ratio will steady improve reaching 0.15-0.25 toe/10^3 \$ in 2050 compared to 0.52 toe/10^3 \$ today (average annual decline 1.2-2% per year). In spite of remarkable improvements in energy use the efficiency in this region will remain lower than in Japan over the whole time period.

Strong changes are projected for the energy system in developing countries. First, total primary energy demand will grow by a factor of 4-5 until 2050. In total, the primary energy demand in the region of developing countries in the middle of the next century is expected to be equal to 7-12 bln.toe per year.

Crude oil is the most important energy carrier in this region with a contribution to total energy demand of 48% nowadays. In the future this fuel keeps its leading position but in the next century the role of crude oil will inevitably decline reaching 15-30% until 2050. A large portion of this decline will be substituted by natural gas which utilization will double over the next decade (140 mln.toe in 1990) and will grow by a factor of 2.5 over the another decade reaching 650-700 mln.toe in 2010. In 2050 natural gas consumption is projected of 700-1500 mln.toe. However, the share of natural gas after reaching its maximum at about 15-20% will start to decline and attain 10-15% in the middle of the next century. The coal consumption will be extremely sensitive to the scenario applied, especially in the long-term. In Dynamic-as-Usual future the coal consumption will steady increase reaching 755 mln.toe in 2000, 1100-1200 mln.toe in 2010 and about 3000 mln.toe in 2050 (540 mln.toe in 1990). The request to substantially drop in the CO2 emissions will result in strong declining coal production and use after 2000 with practical elimination of this fuel form from the application until the middle of the next century what seems today hardly realistic if you treat seriously all the factors and effects followed-up. The share of non-carbon fuels will expand: from less than 9% now to about 25-80% in the long-term future depending on the scenario selected.

The share of electricity generation in total primary energy consumption will raise from 25% in 1990 to 33% in 2000 and further to 45-65% in 2050.

In spite of the large expansion of the energy demand in this region per capita energy demand will change less pronounced because of the much higher growth rate for the population (0.8-1.3 toe in 2050 compared to 0.6 toe today). That will result in a slow progress in the improvement of living standards for the population of many developing countries, though some of them will surpass the current level of well-being achieved in many developed countries. Meanwhile, remarkable improvements in energy use are expected resulted in the energy/GNP ratio decline over the next 60 years from 0.7 toe/10^3 $ in 1990 to 0.3-0.5 toe/10^3 $ in 2050. However, the efficiency of energy usage will remain still at least twice lower than in developed countries.

In the light of these trends in developed and developing regions, the world energy consumption will increase from 8.6 bln.toe today to 10-11 bln.toe in 2000 and further to 13-24 bln.toe in 2050. Energy demand in developed counties can remain approximately at today's level over the whole time period or slightly even reduce until the middle of the next century. The energy demand growth will be caused primarily by the requirements of developing countries (including Asian centrally planned economies) to solve their social and economic problems. The projected growth of energy demand in this region will 2-5 times exceed today's level. As a result, the share of developing countries in the world energy balance will increase from 30% in 1990 to 55-60% in 2050. These changes mean that over the next several decades the burden of the global energy problems will shift from developed to developing countries what can create new "hot" issues in world energy supply if no in-time measures are undertaken.

The primary energy mix will strongly dependent on the strategy of energy system development. At "normal" (dynamics-as-usual) conditions coal production will increase to 4-5 bln.toe in 2050, crude oil to 4-4.2 bln.toe and natural gas to 2-4 bln.toe. The share of non-carbon technologies (nuclear and renewable energies) will expand to 25-30%. However, if the strategy of CO2 abatement with achieving sustainability level until the middle of the next century is selected, then the share of fossil fuels should be drastically reduced (according to our estimates, down to 15-25% of total energy supply in 2050), and the most remarkable reduction should be achieved, first of all, in coal and liquid fuel uses. If nuclear moratorium is imposed at the beginning of the next century, then to compensate this fall additional production of fossil fuels (primarily, coal) will be required with a followed-up CO2 emission increase.

Table 7 contains the summary of world energy projections. World energy consumption will increase from 8.6 bln.toe currently to about 10 bln.toe in 2000 and 10-12 bln.toe in 2010. With lower efforts in efficiency improvements the resulted consumption until the middle of the next century will projected to be 18-25 bln.toe. But enhanced efforts in energy savings will be able to reduce primary energy demand to 12-17 bln.toe[11]. The most remarkable is the fact that the share of developing countries which is equal to about 30% today (including non-commercial fuels) will reach 55-65% in the long-term future. It means that during the several next decades the burden of the world energy problems will shift from developed to developing countries.

<u>CO_2 Emission.</u> The analysis of CO_2 emissions arose by fossil fuel combustions is the major component in global warming projections. The expected levels of CO_2 emissions produced by energy systems all over the world during the coming several decades are presented at Fig.3. The conversion coefficients used for recalculating fossil fuels into carbon dioxide emissions are given in Table 8[12].

CO_2 concentration assessments have been made by calculating the CO_2 accumulation in the atmosphere taking into account the world energy balance described by the scenario applied. It was assumed that only 60% of carbon released with emissions remain in the atmosphere as an air-borne concentration[13]. The results of these calculations are summarized in Table 9. The results show that even in spite of large efforts in energy conservation and primary mix changes to transfer to CO_2 energy sustainable system until the middle of the next century (60% CO_2 reduction compared to currently observed levels) the further increase in CO_2 atmospheric concentration will take place over the whole tome period. Quite naturally, that nuclear moratorium cases will cause the maximal concentration increase, however, only insignificantly

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[11] Nuclear moratorium case shows less level of energy demand because of the constant conversion factor used for nuclear equal 0.33 over the whole time period compared to changing (and improving) efficiency for coal-fired power plants which are assumed to replace nuclear. The same reason is behind the higher levels of the primary energy demand projections for Accelerated CO_2 Abatement cases in which the larger percentage for nuclear and renewables (enhanced by the higher share of electricity in final energy to reach CO_2 reduction goals) results finally in higher primary energy demands for these cases compared to others considered in the study.

[12] The values for specific emissions are borrowed from a book "Schutz der Erdatmosphere. Eine Internationale herausforderung", Deutscher Bundestag, Bonn, 1988, p.489.

[13] According to CO_2 concentration records since 1860 and up to the benign of the 1970s and estimates of the cumulative fossil fuel consumptions over the same time period, it follows that approximately 40% of the carbon released has remained in the atmosphere. However, more precise instrument observations provided in 1959-1973 has shown that the air-borne part was equal to 56% (see "Energy and Climate", NAS, Washington, D.C., 1977, pp.140-158). Today majority of climate models assumes this share as 60%. The last estimate is used in our approach to the evaluation of CO_2 concentration changes in the long-term future. However, there are expectations that the value of CO_2 sunk by the Nature will strongly depend on the temperature increase and the biomass expansion followed by natural processes as well as man-made aforestation.

higher than for base cases because at the moment of moratorium introduction (somewhere around 2005-2010) the nuclear energy contribution to the total world energy balance will be still at the level of several percents. Meanwhile, the concentrations are projected to increase 1.3-1.5 times until 2050 (Dynamic-as-Usual Scenario) or 1.25-1.35 times (Enhanced Efficiency and Conservation Scenario). It means that the concentrations will be at least 100 ppm higher than today's level even in case of applying very severe measures in the energy conservation and primary mix change. If we assume that CO2 contribution to global warming remains only 50% over the whole time period as we observe it today, then total effect equal to doubling CO2 concentration will be observed already around 2050.

CO2 concentration projections show that though the carbon accumulation will continue, but its growth rate can be remarkably reduced if reasonable policy based on enhanced energy savings and fossil fuel use reductions applied.

If in parallel with enhanced energy system restructuring, a reforestation program will be deployed on a broad scale then the greenhouse effect could be substantially lessened. Some simplified calculations show that if forest areas could be increased by 20-40% until the middle of the next century, then the quantity of carbon accumulated in the atmosphere could be reduced by 35-80%. It means that the enhanced energy conservation and CO2 abatement policy applied to energy systems themselves and enhanced reforestation programs started immediately both could help in achieving the current CO2 concentration level sometime in the second part of the next century[14]. Though the effect of reforestation is very much uncertain and plausible and the appraisals are based on a simplified approach, the reforestation hopefully can substantially compensate negative effects of the CO2 accumulation in the atmosphere and alleviate global warming. The most radical measures applied within energy systems will not be able to stop the process of carbon accumulation in the atmosphere (at least, the period of doubling CO2 concentration will be extended beyond 2050 for a couple of decades). Parallel efforts in other spheres of the human activity are required (first of all, urgent stopping deforestation and starting enhanced restoration of forests, especially those in tropical zones as well as reducing the emissions of other greenhouse gases which contributes totally to not less than 50% of global warming and which quantities released are much lower compared to carbon dioxide). The research on global warming impacts on the humanity

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[14] The total area estimated to be available for reforestation is about 865 mln.ha (Houghton, R. (1990). The Future Role of Tropical Forests in Affecting the Carbon Dioxide Concentration of the Atmosphere, Ambio, vol.19, no.4, pp.204-209). If we assume that the carbon fixation rate in growing trees is equal to 5 t C/ha/year (managed and tropical forests) and the growing time period is 20 years (see, e.g., Farnum, P., R.Tomas and J.Kulp (1983): Biotechnology of Forest Yield, Science, 219:694-702), then growing biomass can fix about 80 bln.t C over the next 50-75 years, which corresponds to about 40% of carbon accumulated in the atmosphere in the case of the most effective scenario with CO2 abatement measures in energy systems or much less in the case of other less effective energy policies.

and the environment should start now to help as soon as possible in selecting the optimal (or at least reasonable, non-regret) path in global energy development.

Costs for the Implementation of CO2 Reduction Policy. It is quite natural to assume that the transition from a "normal" development to that characterized by accelerated CO2 abatement will result in different efforts. For simplicity, we can presume that those efforts could be measurers by the fraction of the GNP spent on the energy systems including cumulative investments in energy production, conversion, transportation and distribution, end-use and energy conservation over the time period under study. The results of the MEDEE and LEAP modeling runs have been used for the assessment of cumulative investments required over 1990-2050 for the realization of the described scenarios (with taking into account the life-time for different technologies). Table 10 shows in a summarized form the results of calculation. The conclusions on the efforts can be summarized in the following way:

* total investments required by energy systems differ very little by scenarios (in spite of the common believe that a CO2 abatement policy will inevitably result in increased costs)[15]. The options with enhanced energy savings and efficiency improvements have, as a rule, lower capital demand than the dynamic-as-usual scenario/options (by 7-9%),

* as usual, total global investments spent on the reconstruction of energy systems over the next several decades will keep, on the average, within 4-5% of global GNP produced over that time period. However, in dynamics the share is expected to decline for all regions as a result of steady progress in efficiency improvements,

* the structure of the capital expenditure is strongly dependent on the scenario/option adopted: first, the investments in energy conservation in the Dynamic-as-Usual Scenario do not exceed 10% of total investments but in the Enhanced Efficiency and Conservation Scenario the share of this issue must be much higher (25-28%); second, CO2 accelerated abatement policy in both cases requires much more investments in energy conversion (primary, in the electricity sector) for two major reasons - higher rate of electrification and larger share of non-carbon (but more expensive and energy less-effective) technologies; and third, as a result, the fraction of total investments spent on fossil fuel production must be remarkably reduced, especially if we want follow a policy of enhanced energy conservation and CO2 accelerated abatement;

* there is a large difference in the fractions of investments spent on the energy systems between regions: 2.5-3.5% of cumulative GNP for developed countries with already existing infrastructure and 7-9% for less-developed counties. The latter seems alarming because it means that about 40-50% of the total capital available in developing countries over the next decades must be invested into energy system reconstructions which will be

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[15] It would be true if we have tried to apply CO2 abatement measures without any or little efforts in energy conservation, but applied together both policies will be able to keep costs at the reasonable level.

hardly done in the view of large uncertainties existing around global warming. It means that the energy can be a constraint for development in spite of its energy resource availability. Therefore, the main task of industrially developed countries is to provide enough assistance and aid to LDCs which will make easier for them to bear the burden and help in affecting, at a minimum, their economic and social development. Only such a policy can be fruitful, effective and will be met with understanding.

CONCLUSIONS:

1. Energy as one of the most active driving forces of social and economic progress will keep its leading position among the global issues over the whole 21st century. This predetermines the necessity and expediency for long-term energy studies. Uncertainties in many essential parameters and different views on social and philosophical concepts of humanity progress require miltidisciplinary approaches to energy systems development and periodical revisions of energy projections .

2. Global energy system have started recently the transition path from that, based on fossil fuels with practically limited and exhaustible resources, to systems using inexhaustible or renewable energy resources (fission and fusion, solar, wind, biomass, geothermal, etc.). It is difficult to foresee exactly how long this transition period will last, because the rates of transition will depend on many factors, of which the most important will remain to be energy costs at end-user and its safety for humanity, biosphere, and natural environment.

3. The progress in the global energy system over the next several decades (at least, until the middle of the next century) will be characterized by the following events:

* further energy demand growth, primarily in developing countries,

* the role and importance of energy savings and conservation at all stages of energy chain from primary energy production to end-use will steady increase,

* strong constraints on nuclear energy, especially in the near future (at least, until new generations of nuclear reactors with much higher safety than today and with better economics, are developed, demonstrated and publicly accepted),

* limited contributions from renewable energies to the energy supply because of their low reliability and poor economics,

* good positions for fossil fuels to keep their role in global energy supply for a long time from resources' availability and economics point of view, however, ecological and climate factors may force humanity to restrict the use of fossil fuels, starting with the ecologically most dangerous.

Since the mid-1980s the ecological and climate factors play a more active role in shaping energy policies in many developed countries, slowly phasing out economic and political factors at the second position. This tendency will continue to gain on power in the future with logical results in changing the methodologies of energy technology selections and energy policy compilations which will be followed with the appearance new concepts of long-term energy developments primarily oriented towards environmentally benign and less risky concepts and options.

4. In view of expected trends and changes within the global community over the first half of the next century, the world energy consumption will increase from 8.6 bln.toe in 1990 to about 10 bln.toe in 2000 and further to 13-24 bln.toe in 2050. Energy demand in developed countries will likely to stay at the current level over the whole time period or may even slightly decline (it is quite possible that in some countries with very high per capita energy demand the reduction of primary energy consumption will start even in the near future). The major part of the growth in world energy demand will be justified by the needs of developing countries to improve their economic and social position. It is expected that the primary energy demand in developing countries will increase by a factor of 3-5 compared to today's level. The share of developing countries in world energy demand will double from 28%, currently, to 55-60% in 2050. These changes mean that within few decades the burden of the global energy problems will shift from developed to developing countries creating new burning points on the world energy scene if no proper measures and steps are undertaken now.

5. The world primary energy mix will strongly dependent on development strategies applied over the next 50-60 years. In the case of Dynamic-as-Usual development, i.e. without special constraints on fossil fuels or nuclear energy), coal production can reach 5-6 bln.toe in 2050, crude oil production will practically remain at the same level (however, with strong changes in the structure of oil sources) and natural gas production will more than double compared to today's level. The share of non-carbon primary energy resources (nuclear and renewables) will increase from 12% in 1990 to about 25% in 2050. However, if the strategy for global warming prevention is to be followed, then the share of fossil fuels in primary energy consumption must be strongly reduced (even down to 25% in the middle of the next century in the case of the strategy with 60% CO2 emission reductions until the middle of the next century). Naturally, that the most remarkable decrease is expected for coal and crude oil production, having much more carbon release in comparison with natural gas. A nuclear moratorium or even elimination of this energy form in the future will require an increase in fossil fuel production even if some decreases of energy demand due to energy savings and conservation is projected.

6. Electricity keeps its position as a most universal energy carrier in all sectors of end-use, including transportation. The environment protection goals can be achieved with the most effective and less expensive ways though applying electric technologies. Therefore, a strong growth rate for electricity generation is projected in both regions - developed and developing countries. Total electricity generation will increase from about 11 TWh in 1990 to 14-14.5 TWh in 2000 and further to 40-45 TWh in 2050. The developing countries, which contribute now about 19% to total world electricity, will increase their share to 50-60% in the long-term. The share of nuclear energy is expected to keep its level of 18% over the next couple decades (or even slightly decrease). However, later on some revitalization of nuclear is expected and nuclear electricity will increase its production severalfold in absolute terms. As concerns nuclear proportions within total electricity generation, its share can either keep practically very close to the current level or strongly increase up to 50%, if CO2 abatement policy is implemented by the world community. The share of renewable

energies in electricity generation which now is equal to 17% either keep its position (even with small tendency to decline rather than to increase), but the CO2 accelerated abatement will require more non-carbon electricity and the share of renewables can reach 30-35% until the middle of the next century.

7. In spite of the most radical steps to prevent the impact of energy systems on global climate, the CO2 accumulation in the atmosphere will not be stopped. At the best, we can speak only of postponing the doubling of carbon concentration in the atmosphere for a couple of decades in the longer future. Parallel efforts within other spheres of human activity are required, first of all - to stop deforestation of tropical forests, enhance reforestation, and reduce emissions of other greenhouse gases which in total contribute about 50% to global warming. Studies on the assessments of the consequences of possible climate change must be started immediately and the optimal strategy based on cost-benefit analysis must be suggested to the world community.

8. The transition to accelerated CO2 reduction policy will require about 4-5% of the world GNP spent on investments within energy systems, which is not significantly higher than today. However, the structure of the investments must be drastically changed from energy producing sectors to energy conservation and savings. In the most effective case with 60%-CO2 emission reduction the share of energy final-use and energy conservation may reach about 1/3 of all investments in energy sector. Large increases in investments are expected in energy conversion sectors, especially for electricity generation, with a share reaching almost 50% of total investments over the next decades.

9. In the view of the existence of large uncertainties around global warming, "non-regret" energy strategy for the next couple decades could be suggested based on the utilization of the huge energy savings potentials in both developed and developing countries, which, if properly addressed, can reduce energy consumption with simultaneous decreases of energy costs. The analysis based on the results of modeling approaches used in the study has shown that developed countries could reduce their carbon emissions by about 1.6 bln.t C per year in 2010 with a negative net-cost compared to a "hypothetical" case with no improvements within energy systems and continuing current supply-oriented energy policy. The carbon emissions reduction potential for developing countries is less, but still remarkable (about 0.5 bln.t C per year). These results in CO2 emission reductions can be achieved by wider use of many existing energy saving technologies, economics restructuring, and shifts in the primary energy mix to less- or no-carbon content fuels. Meanwhile, this "non-regret" policy can only stabilize CO2 emissions in 2010 what is not really enough to prevent global warming. The requirements to reduce CO2 emissions globally until 2010 below the current level will inevitably require hundreds of billions new investments what may be unjustified before the phenomena and its consequences are finally resolved. However, in the long-run, such requirements may be necessary to accomplish. Therefore, the earlier we start the preparation to these changes, e.g. by implementing at the first stage "non-regret" approach, the less final expenditure will be required to come over from the current path of development to new one with much lower CO2 emission levels and aiming at 60%-CO2 emissions reductions as it is stated by IPCC to stabilize global climate changes.

10. It would be a naive to think that global energy and climate change policy can be introduced without strong obligatory measures at the national and global levels. These measures should include policy actions, marketing guidelines, educational programs, financial mechanisms, and technology transfer. The realization of this policy will require a creation of a new institutional frameworks bringing in a concert all the players at the international and national energy markets.

11. Many unsettled questions remain in the global warming issue and finding effective response strategies. Therefore, the research of the problem and its links with energy systems will have to continue at the global as well as regional/national levels. Special attention in these studies should be given to the elaboration of complex climate models including all potential contributors to global warming. New approaches to technology selections should be suggested with more orientation towards social cost concepts, accounting for human, environmental, climate externalities including direct and indirect impacts over the whole life-cycle of technology. Ways of solution for energy problems should be studied in more details, paying more emphasis to life-style changes required in developing countries to cope successfully with their economic and social problems and to prevent copying the western-type life-style which would be a disastrous for the humanity. Scenarios with strong CO_2 emission reductions assume, as a rule, larger decrease in the use of fossil fuels. Therefore, new concepts of world energy supply must be studied assuming the existence of two principally different approaches (this is especially important for the electricity sector): one, based on the concept of the centralization, and the other, based on decentralized energy technologies (today the first concept prevails, however, decentralized solutions from a point of view of the environment contamination and safety in some cases seem more attractive). Long-term choices for global energy system developments and transformations should receive justified quantifications within a scientific discussions and be a root for prioritizing of R&D projects for the near future.

Table 1 General population projections (million).

Region	1990	2000	2010	2030	2050
North America	296	318	336	365	390
Western Europe	497	524	545	570	590
Eastern Europe	96	100	104	107	110
Japan	122	127	130	126	121
USSR	288	308	326	360	380
Latin America	448	540	630	770	850
Pacific	405	487	565	765	965
North Africa and Middle East	218	284	359	485	580
China and other Asian CPCs	1225	1397	1513	1710	1775
Other LDCs	1706	2195	2630	3795	5100
Total	**5301**	**6274**	**7140**	**9053**	**10861**
Developed	1299	1378	1441	1528	1591
Developing	4002	4896	5699	7525	9270

Source: World Population Prospects (1988; 1989), Population Studies No. 106, United Nations, N.Y. (until 2020); and author's assessments (after 2030).

Table 2 Economic activity assumptions (GNP, billion $ 1980).

Region	1990	2000	2010	2030	2050
North America, Australia and New Zealand	3690	4725	5760	8555	11525
aagr, %[a]		2.5	2.0	2.0	1.5
Western Europe	5250	6850	8350	12400	16700
aagr, %[a]		2.7	2.0	2.0	1.5
Eastern Europe	495	550	705	1555	1900
aagr, %[a]		1.0	2.5	2.5	2.5
Japan	1510	2100	2590	3125	3650
aagr, %[a]		3.4	2.0	1.0	0.8
USSR	1640	1730	2215	3630	5950
aagr, %[a]		0.5	2.5	2.5	2.5
Latin America	1087	1460	1965	3545	6400
aagr, %[a]		3.0	3.0	3.0	3.0
Pacific	540	725	1095	2890	3235
aagr, %[a]		3.0	3.0	3.0	2.5
North Africa and Middle East	630	850	1140	2050	3700
aagr, %[a]		3.0	3.0	3.0	3.0
China and other Asian CPCs	722	1120	1160	3635	7235
aagr, %[a]		4.5	4.0	4.0	3.5
Other LDCs	480	695	960	1835	3185
aagr, %[a]		3.8	3.3	3.3	2.8
Total	**16044**	**20805**	**27110**	**42820**	**63480**

[a]aagr = average annual growth rate.

Source: National Accounts Statistics: Main Aggregates and Detailed Tables (1989), United Nations, N.Y.; Energy Modeling Forum, EMF–12 Working Group (1990-1991), University of Stanford, Calif.; and author's assessments.

Table 3 Final energy demand projections by regions (million toe).

Region	1980	1990	2000	2010 Dynamic as Usual	2010 Enhanced Efficiency and Conservation	2050 Dynamic as Usual	2050 Enhanced Efficiency and Conservation
North America, Ausralia, and New Zealand	1567	1702	1865	1910	1580	1950	885
Western Europe	1045	1165	1265	1290	1165	1330	775
Eastern Europe	264	274	264	283	243	350	200
Japan	257	305	375	400	360	300	210
USSR	812	1010	998	1073	968	1470	770
Latin America	335	419	530	660	590	1250	745
Pacific	140	185	240	310	305	665	560
North Africa and Middle East	124	181	261	366	331	946	596
China and other CPCs	423	660	915	1190	1135	2870	1925
Other LDCs	407	503	650	780	715	1770	1260
Total (rounded)	**5375**	**6400**	**7365**	**8260**	**7390**	**12900**	**7926**

Table 1 Electricity generation projections for the world.

				2010		2050	
	1980	1990	2000	Dynamic as Usual	Enhanced Efficiency and Conservation	Dynamic as Usual	Enhanced Efficiency and Conservation
Total generation (TWh)	8042	11152	14230	18450	16880	39120	44900
By fuel type							
coal	2601	3303	4504	6760	5390	14605	1160
liquid	1939	1716	1115	660	555	505	130
gaseous	1192	2257	3860	5460	5095	10205	5370
nuclear	706	1994	2500	2960	3070	8450	22660
hydro	1604	1842	2105	2300	2360	3215	4150
other renewables	0	40	146	310	410	2140	11430

Table 5 World uranium resources (10^3 tons).

Production Costs ($/kg U)	Proven Reserves	Undiscovered Resources[a]
25–40	85	355
40–80	1505	12135
80–130	875	6392
Total	2465	18885

Source: Bourrelier, P.-H., de la Tour, X.B., Lacour, J.-J., op. cit.
:[a]Generation of 1 GWe/yr in LWR-type nuclear power plants requires 225 tons of natural uranium; with breeders the efficiency is 60–65 times higher.

Table 6 Nuclear Energy (GW(e)).

	1980	1990	2000	2010	2050
Total capacity	135	318	396	480–540	1295–3665
Developed	133	300	368	425–465	990–1465
LDCs	2	18	28	55–75	305–2200
Average annual increment (GW(e)/yr)					
(at NPP life time = 40 years)					
Dynamic as Usual Scenario			25		35
Enhanced Conservation and CO_2 Abatement Scenario			60		75

Reference: in the 1980s about 30 GW(e)/yr

Table 7 Primary energy consumption by fuel type, Mtoe

	1990	2000	2010	2050
Dynamic-as-Usual Scenario				
Base Case	8580	10025	12015	18795
coal	1970	2370	2815	5455
oil	3540	3630	3715	4030
gas	1660	2235	3015	3995
nuclear	483	655	970	2045
reneables	552	705	1040	2940
non-commercial	375	430	410	330
Nuclear Moratorium	8580	10025	12065	18990
coal	1970	2370	3165	6975
oil	3540	3630	3765	4030
gas	1660	2235	3015	3975
nuclear	483	655	670	745
reneables	552	705	1040	2940
non-commercial	375	430	410	325
Acc. CO_2 Abatement	8580	10025	12655	24025
coal	1970	2370	2300	1340
oil	3540	3630	3705	3795
gas	1660	2235	2715	2690
nuclear	483	655	2195	7665
reneables	552	705	1365	8380
non-commercial	375	430	375	155
Enhanced Efficiency and Conservation Scenario				
Base Case	8580	9775	10480	12405
coal	1970	2305	2400	3050
oil	3540	3510	3325	2400
gas	1660	2190	2460	2615
nuclear	483	655	940	1660
reneables	552	695	970	2435
non-commercial	375	420	385	245
Nuclear Moratorium	8580	9775	10385	12105
coal	1970	2305	2595	3800
oil	3540	3510	3325	2405
gas	1660	2190	2460	2615
nuclear	483	655	655	705
reneables	552	695	965	2435
non-commercial	375	420	385	245
Acc. CO_2 Abatement	8580	9775	11150	17185
coal	1970	2305	2540	125
oil	3540	3510	3185	1955
gas	1660	2190	2665	2025
nuclear	483	655	1170	6205
reneables	552	695	1250	6800
non-commercial	375	420	340	0

Table 8 · CO_2 emissions from burning fossil fuels.

Type of Fuel	$\frac{tCO_2}{tce}$	$\frac{tCO_2}{toe}$
Solid	3.0	4.5
Liquid	2.3	3.45
Gaseous	1.5	2.25

Source: Deutscher Bundestag, Schutz der Erdatmosphäre. Eine internationale Herausforderung. Bonn (1988).

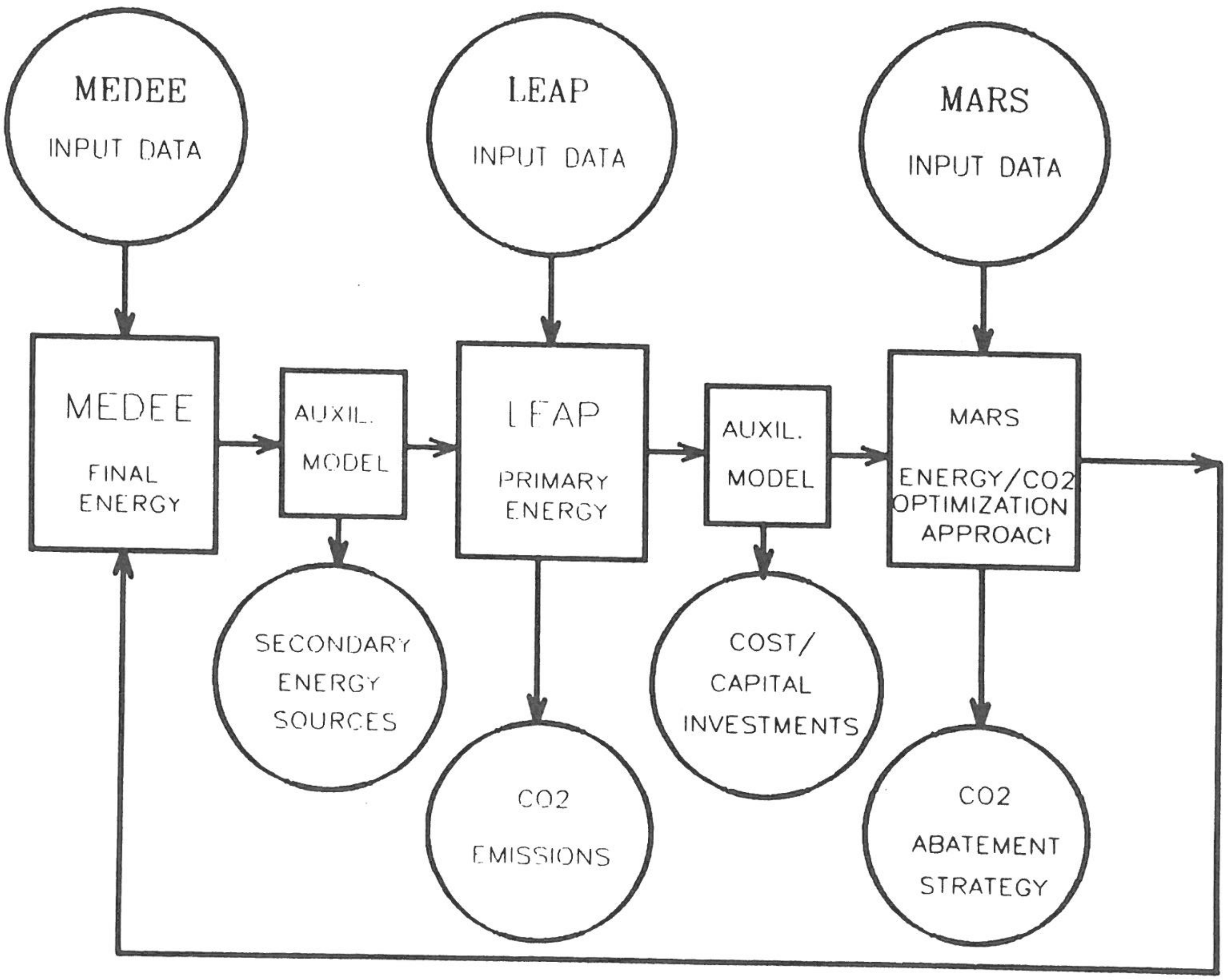
Table 9 · CO_2 air-borne fraction until 2050 .

	bln. t C	ppm
Dynamic-as-Usual-Scenario		
Base case	345	530
Nuclear moratorium	355	535
Accelerated CO_2 abatement	225	470
Enhanced Efficiency and Conservation Scenario		
Base case	240	480
Nuclear moratorium	275	495
Accelerated CO_2 abatement	200	460

Table 10 Investments required for the energy scenarios and options, 1980–2050 (billion US$).

	Developed Countries (w/o Japan)	Japan	Less Developed Countries	Total
Dynamic as Usual Scenario				
Base Case	41235	3873	56745	101853
production	10135	3	25815	35953
conversion	20785	3130	21915	45830
final use	4315	210	5655	10180
conservation	6000	530	3360	9890
% of GNP	2.7	2.3	8.5	4.3
Nuclear Moratorium	40735	3733	56730	101198
production	10210	3	25815	36028
conversion	20200	3005	21900	45105
final use	4325	195	5655	10175
conservation	6000	530	3360	9890
% of GNP	2.7	2.3	8.5	4.3
Accelerated CO_2 Abatement	49510	3853	59980	113343
production	8555	3	16620	25178
conversion	29635	3110	32000	64745
final use	5320	210	8000	13530
conservation	6000	530	3360	9890
% of GNP	3.3	2.3	9.0	4.8
Enhanced Efficiency and Conservation Scenario				
Base Case	44475	3688	46145	94308
production	8300	3	1600	24303
conversion	16535	2530	17450	36515
final use	2810	180	4340	7330
conservation	16830	975	8355	26160
% of GNP	2.9	2.2	6.9	4.0
Nuclear Moratorium	44305	3700	46935	94940
production	8415	3	16390	24808
conversion	16275	2530	17850	36655
final use	2785	192	4340	7317
conservation	16830	975	8355	26160
% of GNP	2.9	2.2	7.0	4.0
Accelerated CO_2 Abatement	47530	4173	53615	105318
production	7515	3	12515	20033
conversion	19510	2970	27145	49625
final use	3675	225	5600	9500
conservation	16830	975	8355	26160
% of GNP	3.1	2.5	8.0	4.5

FIG.1. MEDEE--LEAP-MARS INTERACTIONS



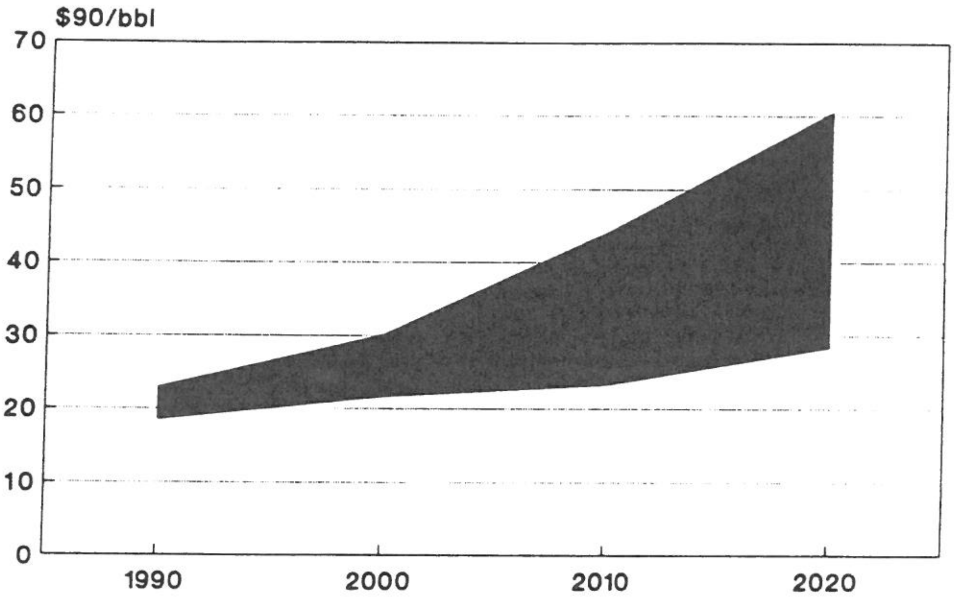


Fig. 2 Crude oil price projections (Source: IEW Pool Responses, 1991)

FIG.3.

CO2 EMISSIONS by GLOBAL ENERGY SYSTEMS