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The Concept of Sustainable Energy Development

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Abstract—Problems of sustainable energy development are considered. A brief analysis of the present state of producing and consuming energy and organic fuel resources and environmental problems of the industrial world are given. Much attention is devoted to defining the concept of sustainable development, its criteria, and, in particular, criteria concerning energy supply.

Energy resources have always played an important role in the development of human society [1]. The development of new technologies, energy consumption, and the growth of the population are interdependent; however, this tie is ambiguous and diversified. In the 20 century, a sharp rise in both energy consumption and the world population were observed. However, if the growth of industrial production and the corresponding consumption of energy absolutely and relatively (per capita) took place in the developed countries, a sharp increase in the population occurred in the developing countries [2]. In the past few decades, the actual development of thickly populated regions required a considerable increase in energy production. The problems associated with the impact on the environment of growing energy consumption will become even more acute in the near and distant future. Interdependence of the human population, the sustainable development of the economy of individual countries and regions at the present-day technological and civilized level, and environmental protection (that is, preservation of the habitat for human beings on Earth) have become more implicit.

The history of life on Earth is based on photosynthesis and evolution [3]. The history of our planet relies on capturing solar energy and conversion of this energy by photosynthesis into organic substances.

Boltzman, one of the founders of modern physical chemistry, wrote in 1884 [4] that the struggle for life is not a struggle for elements that form living organisms or for energy but a struggle for negative entropy available in energy transfer from the hot Sun to the cold Earth. In fact, life on Earth requires a continuous flux of negative entropy as a result of the solar energy captured by photosynthesis. The Sun is an enormous machine that produces energy and offers the Earth the possibility of receiving large quantities of negative entropy. Every year, the Sun sends 5.6×10^{24} J of energy to the Earth and produces 2×10^{11} tons of organic matter by photosynthesis. This is equivalent to 3×10^{21} J of energy per year. Throughout the billions of years since the Earth was created, this process has led to the accumulation of an enormous amount of different hydrocarbons. The energy resources that are available to people are to a great extent connected with chemical energy stored in fossil fuel [5]. Quantitative data on confirmed resources of fossil fuel are given below (in 10^9 tons of oil equivalent—t.o.e.):

Oil	95
Natural gas	85
Coal	530

The abundant energy resources in the early days of industrial development of modern society stipulated that the strategy for the development of our civilization be based on the concept of unlimited energy resources. However, even then, it was clear that the pattern of energy-resource usage strongly depends on technological development [6, 7].

Figure 1 shows the actual change in world-wide usage of primary resources since 1850, and the corresponding forecast for the future [6]. In this figure, F is the fraction of the market taken by every primary-energy resource at given times. We may note that two main factors affect the pattern of energy consumption. One is related to the development of technologies, while the other, to the availability of the respective energy resource. Moreover, the total level of energy consumption, the availability of alternative energy sources, the social structure of society, and several other factors also affect this process [8, 9]. Figure 2 shows the dynamics of world energy consumption [10].

Fossil fuel is a nonrecyclable, exhaustible natural resource. In this respect, it is interesting to determine, how long available sources of fossil fuel will be the main source of energy for our civilization. The report of the Club of Rome "Limits of Growth" [11] was among the first to point out the finite nature of fossil fuel. After the first and the second energy crises, the world community at large became aware of the possibility of physical exhaustion of fossil fuel. Figure 3 shows a forecast for the amount of fossil fuel available based on its yearly consumption for the year under consideration [12]. From here we see that coal will be available for the next 250 years and gas for 50 years. Evidently, as long as fuel consumption increases, new technologies for discovering new resources will be developed. Therefore, the time until all available energy sources will become completely exhausted is slowly increasing. Newly discovered deposits of oil and natural gas counterbalance the increased consumption of these resources. During the last 30–35 years, the calculated period for their complete exhaustion has hardly changed at all. Nevertheless, it is clear that, in the future, mankind will meet the problem of the disbalance between oil and natural gas consumption and the availability of these resources.

It is known that energy consumption depends on two main parameters, namely, the amount of energy consumed per capita and the growth of the population. There is a correlation between the gross domestic product (GDP) and energy consumption per capita. Figure 4 shows this dependence for several countries in 1990 [12]. We see that, on the whole, the higher the per capita energy consumption, the greater the GDP. However, note that Japan, Germany, France, the United States, Canada, and Norway have approximately the same GDP per 1000 people; however, in the last three countries, the per capita consumption of energy is more than two times higher. This shows that the relationship between the per capita energy consumption and the GDP is not simple and unambiguous. Several other factors affect this dependence. Among them are the climatic and geographic conditions, social factors, traditions in the structure of energy consumption, cultural traditions, and others. Presently, these additional factors are not well recognized. Nevertheless, an analysis of these factors may lead to a better understanding of the specifics of energy consumption in the highly developed countries.

There are a number of scenarios which are used for forecasting world economic development. If we assume that the recent trends for economic growth existing today will keep on in the next 50 years and the growth of the population will be as in Fig. 5 [13], the energy consumption anticipated will be as shown in Fig. 6 [14]. We may expect that, in the near future, our civilization will face the problem of depleted natural resources. The methods of forecasting and the models for the growth of energy consumption existing today do not allow us to determine exactly when this will happen. However, mankind should take certain measures to be ready for this.

The limited accessibility of natural resources and economic growth are fundamentally in opposition to each other. The answers to the following questions are quite important [15]:

can the scarcity of energy resources be mitigated in the future as it could in the past;

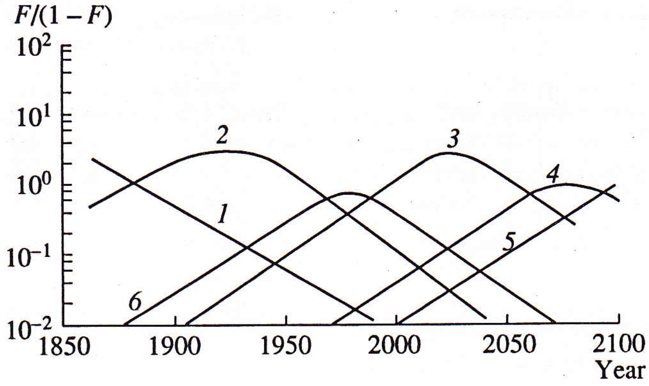

Fig. 1. Market penetration of primary energy sources. (*1*) Wood; (*2*) coal; (*3*) natural gas; (*4*) nuclear energy; (*5*) solar and fusion energy; (*6*) oil.

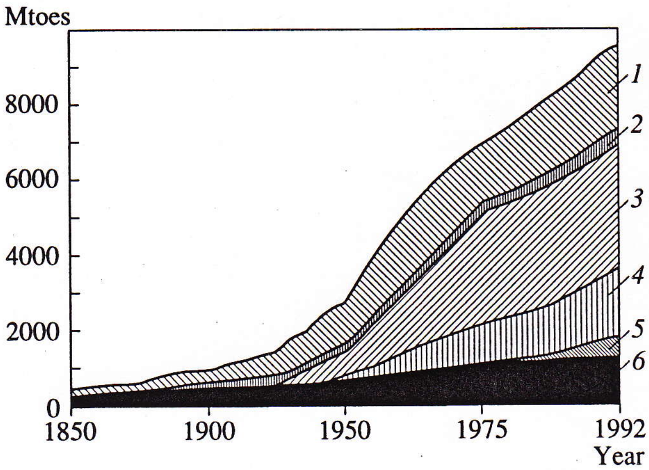

Fig. 2. World energy consumption. (*1*) Coal—23.2%; (*2*) hydro-geo—5.8%; (*3*) oil—33.4%; (*4*) natural gas—19.7%; (*5*) nuclear—6.3%; (*6*) biomass—14.6%.

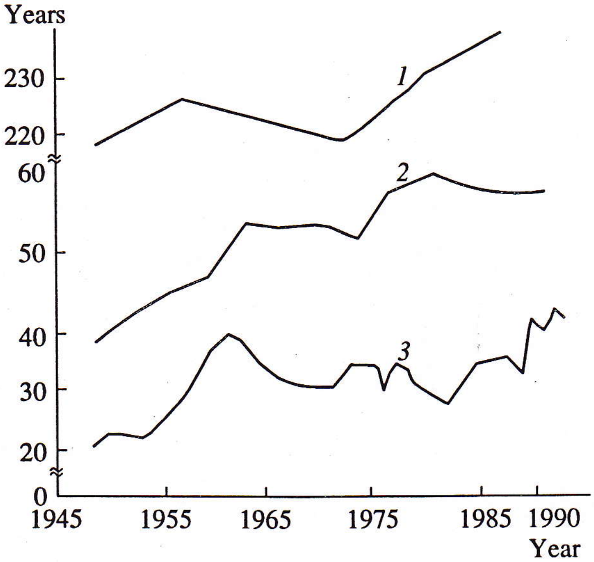

Fig. 3. Residual life forecast of energy resources. (*1*) Coal; (*2*) natural gas; (*3*) oil.

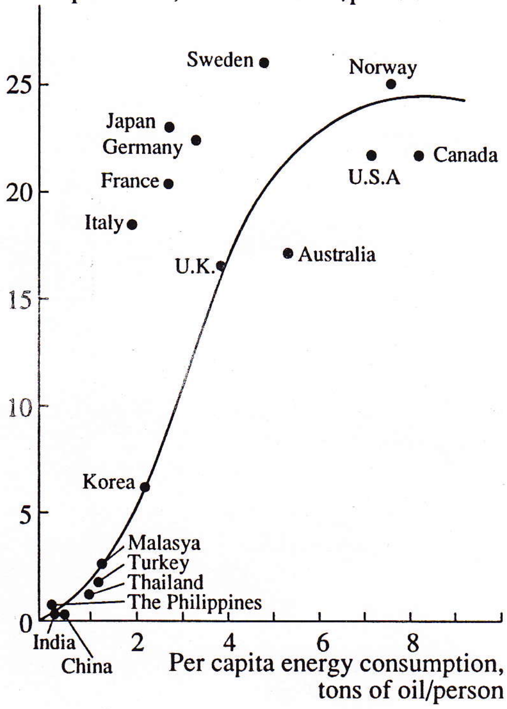

Fig. 4. Economic growth and energy consumption.

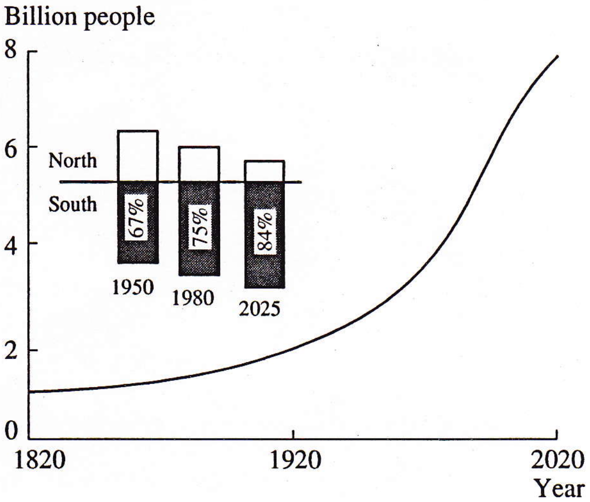

Fig. 5. Demographic forecast.

did this scarcity de facto impede economic growth.

An appropriate analysis was conducted in [16] for the conditions in the United States. This analysis based on relative energy prices and unit costs concerned natural gas, bituminous coal, anthracite, and crude oil. The dynamics of their scarcity was considered. Figure 7 shows the results obtained. The data for the United States can to some extent be an indication of the future trend for the world. We see that every one of the energy resources became much more scarce in the 1970s. A reverse situation arose in the 1980s. The economy of the country remained sustainable. This fact is of great importance for forecasting the prospects of economic growth. It was not proved that short-term fluctuations in the availability of energy resources can considerably affect long-term economic growth. Thus, clearly, a comprehensive study of the potential influence of the scarcity of nonrenewable energy resources on economic growth is needed.

THE ENVIRONMENT

The consumption of primary energy resources is a major source of harmful emissions [17–19]. Recently, for economic reasons, more than 88% of the primary energy in the world has been generated from fossil fuel. The exhaust gases from the combusted fuel have accumulated to an extent that can inflict serious damage to the global environment. The amount of CO_2 accumulated in the atmosphere is estimated to be approximately 2.75×10^{12} tons. Figure 8 shows the trend for global warming [20]. We see that, in the second half of the past century, global warming became much more intensive than in the second half of the present century, despite the fact that the main increase in the consumption of fossil fuel and in CO_2 emissions took place just in the second half of the 20th century (Fig. 2). The average temperature in the 20th century increased by 0.2°C, as compared to 0.4–0.5°C in the previous century. Possibly, the time scale of atmospheric processes does not allow us to make correct conclusions from the above data of temperature measurements. However, clearly, the complex natural processes have been poorly studied and the problem of global warming requires more sophisticated analysis to make justified conclusions regarding the extent of the influence of CO_2 emissions on global warming.

Figure 9 shows a curve for the CO_2 concentration in the atmosphere [20]. From a comparison of Figs. 2 and 9, we can see that, in the period from 1860 to 1990, the increase in consumption of hydrocarbon fuel was not accompanied by a proportional growth in the CO_2 content in the atmosphere of the Earth. Nevertheless, clearly, a further increase in emissions of CO_2, as well as of SO_2, NO_x, and of particulates, will considerably affect the environment. Many developing countries, such as China and India, will continue to use inexpensive abundant indigenous coal to meet growing domestic needs [21, 22]. Since China is the third largest energy producer in the world, after the United States and Russia, its contribution to the CO_2 accumulated globally will be substantial, if a proper strategy of mitigation is not adopted.

SUSTAINABILITY

As is known, energy resources are bricks for building our civilization [23] and the basis for the growth of human prosperity. However, the production and con-

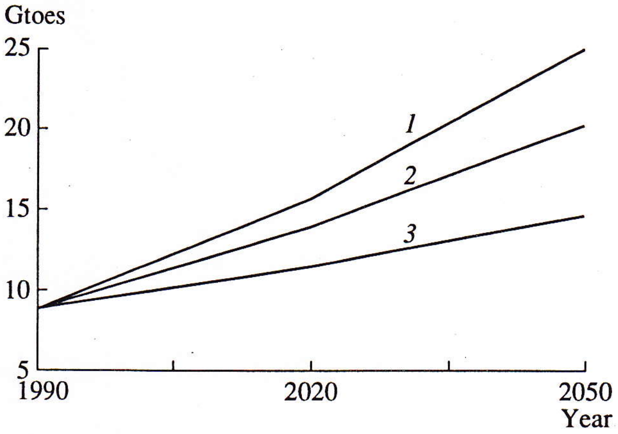

Fig. 6. Future energy consumption forecast. (*1*) Optimistic; (*2*) middle; (*3*) ecologically driven.

sumption of energy go hand in hand with the less welcome side effects. This is a reason why society has recognized the importance of intelligent, clean, and efficient use of energy, as much as this is possible. Energy occupies the central place in debates surrounding one of today's main dilemmas: how to combine economic development with a healthy habitat in a world that is undergoing rapid change as a result of the growth of the population and economic development of the developing part of the world.

The term "sustainability" has become a popular buzzword in discussions on using resources and environment policy. Therefore, a more exact definition of this term is needed. Below are given interpretations that are most often adopted.

(1) The definition of the World Commission on Environment and Development (the Brundtland Commission) [24]: "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

(2) The definition from the Agenda 21, Chapter 35 (the Program for the 21st Century) [25]: "Development requires taking long-term perspectives, integrating local and regional effects of global change into the development process, and using the best scientific and traditional knowledge available."

(3) The definition of the Council of Academies of Engineering and Technological Sciences [26]: "It means the balancing of economic, social, environmental, and technological consideration, as well as incorporation of a set of ethic values."

(4) The definition from the Earth Charter [27]: "The protection of the environment is essential for human well-being and the enjoyment of fundamental rights, and as such requires the exercise of corresponding fundamental duties."

(5) Thomas Jefferson's definition [28, 29]: "The Earth belongs to each generation during its course fully, and in its right no generation can contract debts greater than may be paid during the course of its existence".

All five definitions stand for the emphasis of specific aspects of sustainability. Definitions (1) and (5) imply that each generation must bequeath enough natural capital to permit future generations to satisfy their needs. Even if there is some ambiguity in this definition, it means that we should leave our descendants the ability

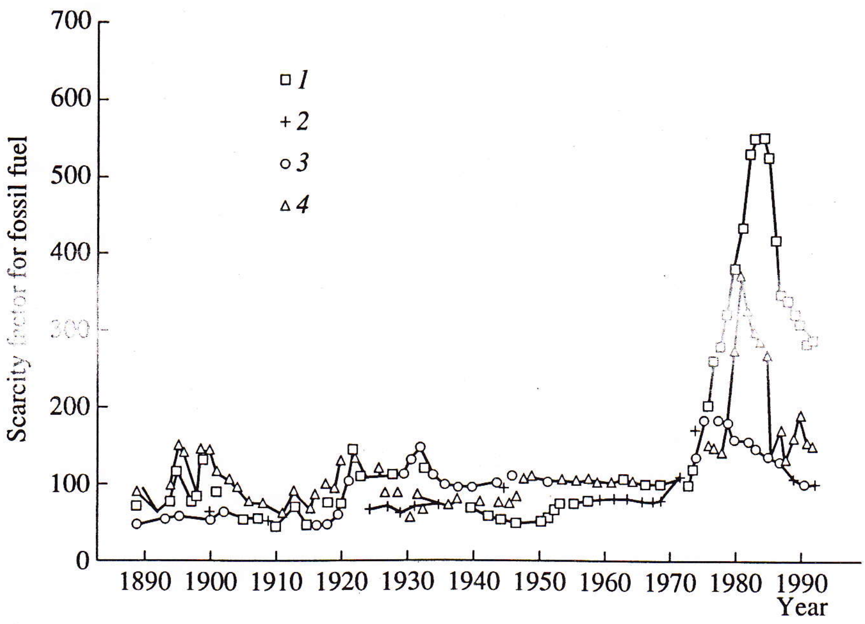

Fig. 7. Scarcity factor for fossil fuel. (*1*) Natural gas; (*2*) bituminous coal; (*3*) anthracite coal; (*4*) crude oil.

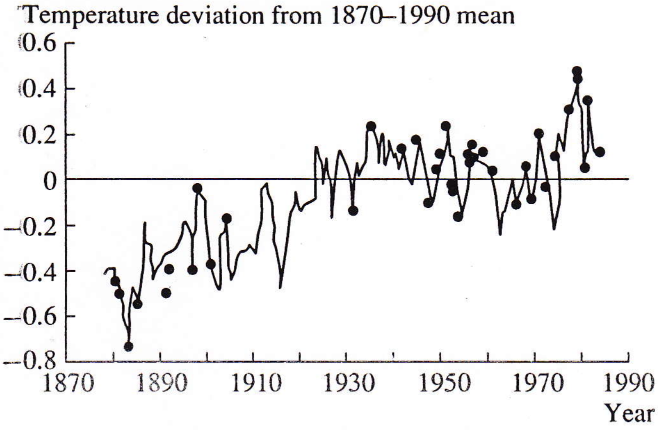

Fig. 8. Global warming trend.

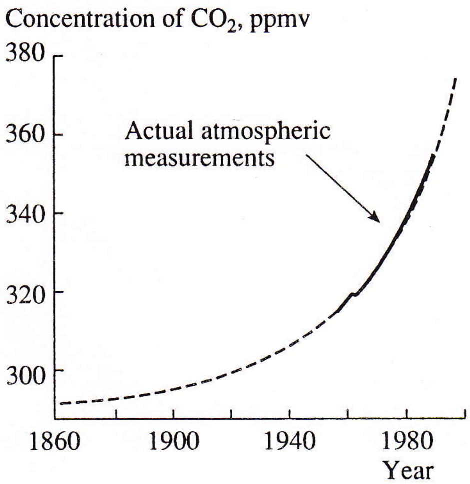

Fig. 9. Carbon dioxide concentration change.

to survive and meet their own needs. However, these definitions do not specify in what form resources are to be left and how much is needed for the future generation, because it is difficult to specify future scenarios.

The definitions (2) and (3) are more political. They appeal for coordinated actions to be taken at global, regional, and local levels in order to stimulate the United Nations, Governments, and Local Authorities to plan development programs in accordance with scientific and technological knowledge. According to definition (3), the ethical aspect of future development actions should be taken into account.

The definition (4) is based on religious beliefs paying responsibility toward nature and the Earth.

PROVISION OF SUSTAINABLE DEVELOPMENT

Since the Brundtland Commission in its 1987 report "Our Common Future" warned of the growing threat to the Earth from pervasive world poverty, environment degradation, disease, and pollution, it has become indispensible for the scientific community to pay more attention to subjects related to these problems. Five years after the commission the United Nation Conference on the Environment and Development was held in Rio de Janeiro. An unprecedented number of world leaders met to discuss and map the road to sustainable development. Among the documents adopted at the Rio Conference was "Agenda 21," a blueprint on how to make development socially, economically, and environmentally sustainable. Agenda 21 calls on governments to adopt national strategies for sustainable development. Sustainable development focuses on the role and the use of science in supporting the prudent management of the environment and for future survival development of humanity [30–33]. Scientific knowledge should be applied to articulate and support the goals of sustainable development. In harmony with conclusions and recommendations of this International Conference, the following areas of activity can be identified:

(a) strengthening of the scientific basis for sustainable management;

(b) enhancing scientific understanding;

(c) improving long-term scientific assessments;

(d) building up scientific capacity and capability.

It is essential for implementation of this program that it be focused on long-term perspectives and global changes of survival systems. An active role is to be played by scientists from the developing countries in realizing the program. Since most of the increase in the population is expected in the developing part of the world, the participation of scientists from the developing countries will bridge the deficiency in dealing with specific problems, which are immanent to the protection of the environment of these countries alone due to the academic approach. The strength of the movement for sustainable development is promoting the idea that the Earth is the only place for our human civilization.

ENERGY SUSTAINABILITY CRITERIA

Several attempts have been made to define the criteria for assessing the sustainability of market products. In this respect, the Working Group of UNEP on Sustainable Development has come out with qualitative assessment criteria for assessing new product design [34]. We would like to similarly use these criteria as a specific application in the design of the energy-supply system. In this case, the design of the energy system is taken to be an entity which should comply with the set of sustainability criteria, that is, strategy, optimization, dematerialization, longevity, and the life cycle.

The strategic or entity criterion. The strategic design criterion requires holistic planning that meets and considers all interrelated impacts; for example, logistic, space planning, and resource planning. As to the energy system, it may be interpreted as total optimization of local resources, urban and industrial planning with transport optimization, and assessment of the possibility of using renewable energy sources.

The optimized design criterion. The design optimization of the energy system means selection of the structure and the design parameters of a system to minimize energy costs under conditions associated with available material and financial resources, protection of the environment, and government regulations, together with safety, reliability, availability, and maintainability of the system.

The criterion of dematerialization (level of intelligent provision) of a design. This implies that the energy system, as a whole, the plant, and the equipment are designed with optimal use of information technology in order to exclude duplication, to prevent operational malfunctioning, and to ensure rational maintenance scheduling. Dematerialization in the design may be regarded as the introduction of knowledge-based systems, the use of virtual libraries, digitized video, online diagnostic systems, and new sensors and measurement devices.

The criterion of longevity of the design. A complex energy system is usually composed of different subsystems and individual elements of equipment. The lifetime of these subsystems and elements is not the same. In this respect, optimal selection of the life cycle of the elements and subsystems may lead to the procedure of retrofitting or modernization. Examples of this criterion can be seen as the modular design of subsystems, standardization of elements, lifetime monitoring and residual lifetime assessment, and coordination of suppliers and consumers.

The criterion of life-cycle design. This means that the energy system and its subsystems should meet sustainability at every stage of the life cycle, that is, they should respond to daily and seasonal changes in the load, external climatic conditions, and social (domestic) demands of the population. Typical time scales of these cyclic changes should be accounted for.

SUSTAINABLE ENERGY DEVELOPMENT

As was said above, energy sustainability is a complex process that involves availability of resources, efficiency of energy production and consumption [35, 36], and global processes in nature and human society. Several problems that are of fundamental importance when considering sustainable energy development are considered below.

Controlling the depletion of energy resources with the aid of the scarcity index. Energy resource scarcity is directly related to the output of social production no matter what scarcity model is used. In this respect, the efficiency of using resources and the development of technologies is of fundamental importance. Obviously, the efficiency of using energy resources is a short-term factor, which may return benefits in the near future [37]. As regards the development of technologies, lengthy research and development is needed. In some cases, it will require appropriate social adjustment in order to understand the need for using new energy sources.

The availability of new energy sources is limited by two factors: capital for investments in prospecting for new resources and the development of new technologies for their extraction. From recent experience we learned that there is a direct correlation between the capital invested for prospecting and the amount of resources available. It was proved that 18 USD have to be invested per one t.o.e. of new energy reserves (1 t.o.e. = 10^7 kcal). In many developing countries, this is a factor limiting the availability of energy resources.

Assessment of the efficiency of energy conversion. Potential improvement of the energy conversion process is a driving force for its development [38]. In assessing the conversion process, a promising tool is the exergy analysis of a certain energy conversion system; this allows us to determine how efficiently the potential of the energy source is used. At the same time, Carnot's principle gives the absolute limit for any transformation of a free energy deposit [39, 40].

The development of clean-air technologies. There are several technologies that make it possible to reduce emissions of harmful substances; among them are catalytic combustion, fluidized bed combustion, low NO_x burners, and new designs of boilers.

The development of intelligent energy systems. There are the following ways for realizing intelligent systems: the development of expert systems to improve the quality of operation of energy plants; the creation of new control systems on the basis of fuzzy logic; the design of a thermal system with the aid of the principle of artificial intellect.

New and renewable energy sources. Besides the possibilities offered by improving the efficiency of processes in power-generating units, there is a great challenge to increase the efficiency of the energy system by introducing hybrid energy systems, which use renewable energy sources that meet the energy sustainability requirements. Therefore, we expect that the long-term energy strategy will rely on renewable energy sources [41–43].

THE CAPACITY OF THE ENVIRONMENT FOR COMBUSTION PRODUCTS

Sustainability is closely related to the capacity of the environment of our planet. It has been shown that the natural processes in the biosphere possess the maximal rate of change, which exceeds by several orders of magnitude present rates of change of the parameters that define the anthropogenic impact on the environment and by four orders of magnitude the mean rate of change of the parameters that define geophysical pro-

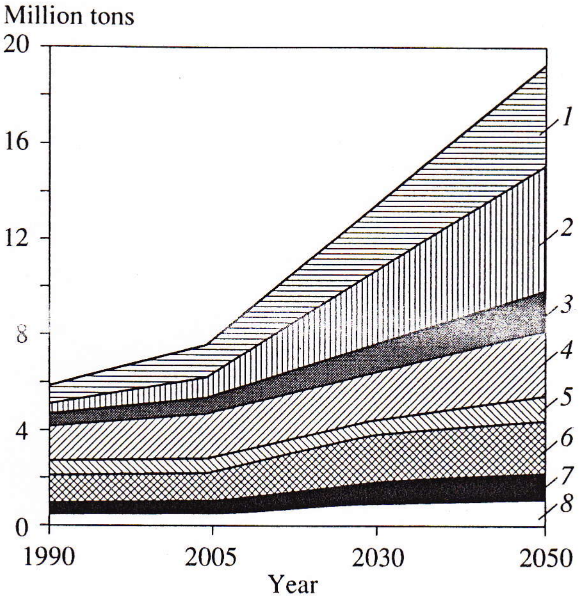

Fig. 10. CO_2 emission forecast. (*1*) Developing countries; (*2*) China; (*3*) India; (*4*) USA; (*5*) Japan; (*6*) CIS; (*7*) Eastern Europe; (*8*) Western Europe.

cesses [44]. The concentration and the rate of change of chemicals involved in biochemical cycles may be characterized by changes in the amount of organic and inorganic carbon. The amount of biologically active organic and inorganic carbon chemical species in the environment is about the same; it is ten times greater than their annual primary production. Therefore, in principle, we may expect that this resource of environment capacity can be used for ten years if only synthesis or decomposition of organic matter takes place. This means that all processes of life will end.

The fluxes of organic material produced by synthesis and decomposition in the biosphere are equal with an accuracy of one hundredth of a percent of anthropogenic perturbations. Apparently, in the geological time scale, the slow change in the environment can be compensated for by biological processes in the biosphere, which controls its own chemical composition.

From Le Chatelier's principle we know that any external perturbation of the equilibrium state of a system will induce a process to compensate for these perturbations. Compensation for perturbations in the environment can be obtained by synthesis and decomposition in the biosphere. Since preservation of the biosphere affects the biodiversity of our planet, it is of primary interest in long-term evolution to have control over the organic processes in the biosphere. For this reason, the preservation of the biosphere is the principal requirement for global ecological security and, as a consequence, for the sustainable development of our planet.

Energy use is a major source of emissions. At the same time, it is essential for economic and social development and an improved quality of life. Several adverse threats have been recognized as a signal for the potential hazard to the environment. Among them are the increasing pressure of greenhouse gases to change the climate and of chemicals on the ozone layer.

The emissions of gases into the atmosphere lead to global warming due to the presence of greenhouse gases and to the depletion of the ozone layer in the stratosphere. The change in the CO_2 concentration in the atmosphere during the last one and a half centuries correlates, on the whole, with the global change in the atmospheric temperature. This has led many specialists in the field to conclude that the damage is irreversible.

MITIGATION OF THE NUCLEAR POWER THREAT TO THE ENVIRONMENT

Nuclear power plants (NPP) have substantial advantages over power plants burning fossil fuel in the light of the greenhouse effects, because they do not exhaust greenhouse gases and do not create the greenhouse effect [45]. However, it is known that the design of present-day nuclear power reactors makes it potentially possible for the latter to become an enormous source of radioactive emissions. Beside the effect on the immediate surroundings of the NPP, such hazardous events may lead to a threat to the environment regionally and globally. The small probability of such an event is the only argument why this disaster does not spread to the global environment. The recent accidents at NPPs require a different approach to assessing the risk involved. Human society should not allow its very existence to depend on possible fatal accidents made by people without having the power to correct such events.

The opponents of nuclear power engineering point to two circumstances that are crucial in their opinion: the possibility of a high level of radiation following accidents and the strong inheritance of long-living radioactive waste in future generations. Undoubtedly, both these points are very relevant for the sustainability of development of this form of energy. To exclude these adverse factors, the strategy of multistaged defense of NPPs was developed.

Present-day reactor design in the second line of defense has many active safety systems and few passive ones. Active systems require external energy supply for intervention, whereas passive ones are based on physical phenomena like natural convection, thermal dilatation, and others [46, 47]. Designers presently tend to increase the percentage of passive safety systems to counteract possible accident chains. This trend is also due to the preference given to the deterministic approach over the more scientific probabilistic one.

Designs of second-generation nuclear reactors with a 100% passive safety system already exist. The Multipurpose Advanced Inherently Safe Reactor (MARS) [48] is an example of such a reactor.

The problem of long-living wastes is still open for interesting solutions. It is possible to separate the long-living radionuclides from other radioactive fission products. The actinides may be recycled in "ad hoc" reactors and converted into radionuclides of the second category. These radionuclides having a long lifetime can be converted into short-living isotopes by mutation through particle interaction in high-energy accelerators. There will be much less wastes, and they can be conveniently buried in suitable geological formations.

More advanced solutions have been proposed since the 1960s, such as the proposal for a subcritical reactor fed by spallation neutrons generated by a beam of protons accelerated up to 1 GeV and more. A fast reactor of such a type, which is cooled by natural circulation of liquid lead, was proposed in [49].

The present energy strategy requires adaptation to new criteria, which are in line with future energy system development. Undoubtedly, there is a link between consumption of energy and consumption of environment capacity. This is an alarming indication, which recently has become the leading theme for our near and distant future.

Engineering science today has to be oriented to areas, which may directly assist in our future energy development. There is a demanding necessity that our attention be oriented to global aspects of energy development. Modern technologies will help us adapt to the essential principles of sustainable energy development. With the appropriate introduction of renewable energy resources in our energy future and with relief of the nuclear energy threat, it will be possible to embody the main principles of the strategy of sustainable energy.

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