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TOPICAL PROBLEMS

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Can the future world energy system be free of nuclear fusion?

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Contents

Abstract. The available information on the dynamics of world population growth as well as global statistical data on today's energy production, consumption and distribution are presented. Natural restrictions on the modern world's fossil combustion energy system are discussed along with possible climatic and biospherical impacts for its part. Alternative energy sources capable of replacing the existing energy system are considered and prospects for controllable nuclear fusion are discussed.

1. Introduction

When Academician L A Artsimovich was asked when the first fusion reactor would be built he answered: "The fusion reactor will be built when mankind needs it, but hopefully a little bit earlier". Is fusion needed today? If not, then when will they be needed if they are needed at all? People working in this area of research are confident they are working for a very important goal — the creation of a practically inexhaustible and clean energy source. The latest results from the biggest experimental nuclear fusion device — the European tokamak JET — show that the goal is very close [1]. JET has almost reached the breakeven condition, when the fusion power produced in the fusion reaction is equal to the energy consumed by the reactor.

Unfortunately, progress in the fusion program has not been as fast or easy as was expected many years ago when the program started. This area of research requires formidable long term financing which sometimes seems too expensive, especially in Russia living through the hard times of lost long term goals. In attempt to answer the above questions, I have collected statistical data which are presented below.

The layout of the paper is as follows. It will start from data on the world population and energy production, and its consumption and distribution among the different regions of the world (Sections 2 and 3). In Sections 4 and 5, I shall discuss the environmental limitations for the present global energy system based on the burning of fossil fuels. In the following Section 6 I shall discuss the alternative energy sources available which could contribute to the future energy system. Section 7 is devoted to controlled nuclear fusion energy. Finally, in the Conclusions I shall try to give my answer to the question which was addressed to Academician Artsimovich.

2. The world population and historical energy systems

Whether or not we want it, the world population will continue to grow for a long time. Figure 1 shows the world population vs. time in the past forty years and its projection to the future.

In sixties, when the world population was under 3 billion, the prediction that the population would double and reach 6 billion by the year 2000 sounded like scientific fiction. The prognoses proved to be surprisingly accurate — the world population is 5885 million today. The same models predict that by the year 2050 it will reach 9 billion. The population growth occurs mostly because of the increase in life expectancy and hence we cannot do much to slow it down — our moral principles aim for the extension of human life up to natural genetic limits and hence any solution based on the control of life expectancy is not acceptable.

"Feed and breed!" — God commanded our ancestors 12000 years ago, when the ice caps of the last ice age rapidly

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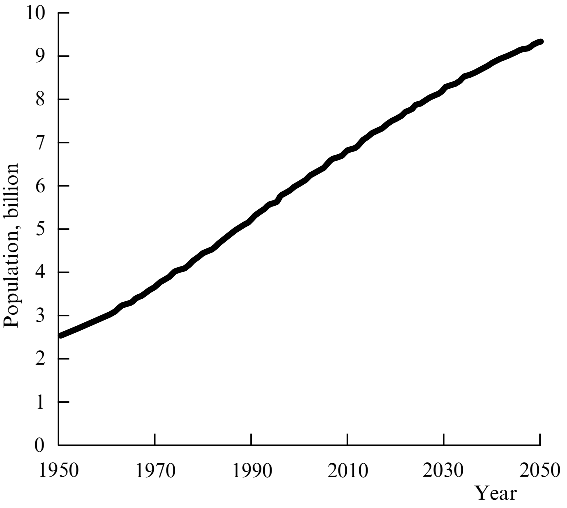

Figure 1. World population growth [4].

moved north opening new territories and vast grassy pastures capable of feeding numerous herds. And they complied.

It is difficult to predict what is the limit of growth and what would be dynamics of the population after the maximum (closed ecological systems have a tendency to a rapid decrease in the population of a biological kind after it reaches the level which destroys the habitat). What is clear from the present projections is that the population will continue to grow during the next 50 years at a rate approximately the same as the last 50 years.

The next 12000 years after the end of the last ice age and the start of the history of civilization, people fed on the primary producer on the Earth — green plants which directly consume solar energy in the chemical reaction of photosynthesis:

$$6CO_2 + 6H_2O + h\nu \Rightarrow C_6H_{12}O_6 + 6O_2 \,. \quad (1)$$

A living green plant (a primary consumer of solar energy) consumes atmospheric carbon dioxide during its growth, builds up organic material and produces oxygen. Reaction (1) is reversed when the green plant is consumed by secondary consumers (herbivores, insects, microorganisms, etc.) or burned in the chemical reaction of oxidation. This renewable energy source sustains almost all levels of the global ecological system and was able to maintain a human population of a few million people. The approach of New Stone Age or transition from hunting and gathering to agriculture and rearing of domestic animals did not change the energy source — it was the creation of a union of people and certain animals and plants (man – pig – crop), which resulted in a mutual well-being and a rapid growth of the population of this community.

The Industrial Revolution, which occurred about three hundred years ago, was something essentially different and extraordinary for the millions years of existence of the natural world — this was presumably the first change of the energy source from solar energy to the chemical energy of fossils (coal, oil and natural gas). The cheap and vast new energy source colossally changed the present appearance of the world and greatly benefited the 'man – pig – crop' community, causing an explosive growth of inhabitants exemplified in Fig. 1.

The main chemical reaction which produces energy during fossil burning, viz.

$$C + O_2 = CO_2 + 94 \text{ kcal/mol}, \quad (2)$$

is now the primary source of energy in the industrial world.

3. Energy production and consumption

3.1 The structure of the present energy system

Figure 2 shows the structure of energy production and consumption in US as an example of energy flows in an industrial country. Similar energy flows are typical of any other industrial countries, including Russia which is at the top of the list among the European countries.

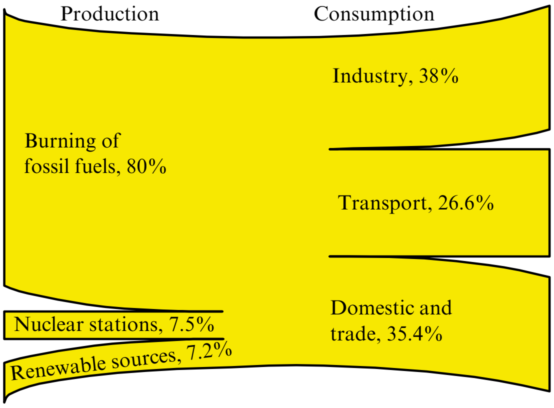

Figure 2. Energy flow in US in 1996 [5].

Most of the energy in an industrial country (80% in US) is produced by burning fossils — coal, oil, and natural gas. Nuclear energy contributes to the total production at the level of ~ 7.5% (also in US). About the same amount of energy is produced by all the renewable energy sources such as hydroelectric, solar, wind and others.

Approximately 40% of the net energy produced is used in industry, about 25% — in transport (cars, planes, ships, and trains) and the rest is employed in our houses for heating, lighting and cooking. The division is somewhat artificial but gives an idea of energy resources needed for *homo industrial*.

3.1.1 Food production. It is interesting to look at the energy consumption in agriculture for the example of an industrially developed country. Table 1 shows the energy used at the different stages of the food path from field to table in the US [2].

The growing process including soil preparation, planting, fertilization, and harvesting requires 3% of the total energy produced in the US. At 0.95×10^{20} J/year of the total energy consumption and US population of 2.63×10^8 people this is equivalent to 344 W per person. However, growing is only a small part of the total energy consumption. The food must be processed, transported to the shop, sold, and cooked before it appears on a table. If one includes all the energy expenses, then the mean power expended increases to almost 2 kW per capita or 16.5% of the total energy produced in the country. Assuming that an average person consumes 1 kg of food a day (or 2 kcal), one can estimate that the mean power (in the form

Table 1. Energy consumption in agriculture in the US. The percentage was taken from Ref. [2] and per capita energy expenses were recalculated from the US population of 263 million and total annual energy consumption of 0.95×10^{20} J [5].

Energy used for:	In percentage of total energy consumption	Absolute magnitude, 10^{18} J/y	Average power per capita, W
Growing	3.0	2.85	344
Processing and transportation	5.9	5.61	676
Sale	2.6	2.47	298
Preparation	5	4.74	571
Total	16.5	15.69	1889
Consumption of power in form of food			100

of food) required to sustain life of the average person is about 100 W, which is a small part of the total power spent on the food production. Because most of the auxiliary energy is produced from the fossils we can say that the diet of the *homo industrial* consists of more than 90% fossils.

The cheap and vast energy sources allowed drastical reduction of the number of people working in the food industry. In the pre-industrial era almost 100% of population was busy with food production. It is still the case in some poor countries such as Nigeria where 97% of inhabitants work in agriculture [2].

On the contrary, in the US only 7% of the population are farmers and average family spend 18% of their income on food [2].

3.1.2 Transport. Transport is one of the largest energy consumers in the industrial world. For example, it accounts for ~ 27% of total energy consumption in US. About 97% of the energy used in transport comes from petroleum combustion in engines [2]. Automobiles and trucks use 80% of all transport energy. It is unlikely that number of cars will be reduced in developed countries such as US — the infrastructure of these countries is largely based on automobile transport. While there has been an impressive improvement in the efficiency of gasoline engines — by a factor of 2–3 over the last 20 years — the total petroleum consumption will continue to grow due to the growing number of cars especially in the developing countries such as China.

Most industrial countries have similar distribution of energy production and consumption with some regional variations. As of integral over the whole world, the relative contribution of fossil fuels to the energy production is even larger as compared to the United States. The energy resources contribute to the world energy systems as shown in Table 2. In 1994, the contribution of fossil fuels to the global energy system was as large as 86%.

3.2 Regional distribution of energy consumption

It is well known that the distribution of energy production and consumption among different regions is very nonuniform. The best way to illustrate it is to introduce in the usual way a distribution function $N(P)$, which gives a number of people $\mathrm{d}N$ in the world with a power production P per capita:

$$\mathrm{d}N = N(P)\,\mathrm{d}P\,.$$

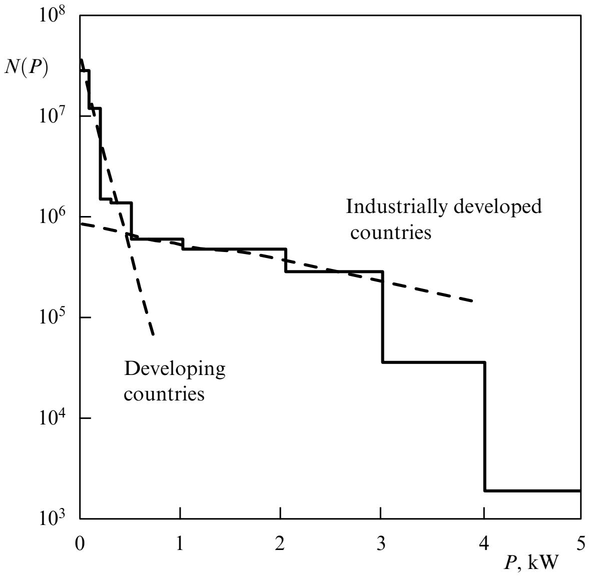

Figure 3. Distribution of the world population by electrical power production per capita.

The distribution function for electrical power could be easily derived from the data on electrical energy production in different countries [6] and population of these countries [7]. Such distribution function $N(P)$ is shown in Fig. 3.

The distribution clearly consists of two components: industrial and so-called developing countries. The separation of the world into rich and poor countries can be seen by the difference in the slope of $N(P)$ below 500 W and above 500 W per capita. The industrial countries such as US, Japan, most European countries, Russia and others have more than 500 W of electrical power per capita. In these countries live about 20% of the world population enjoying an average electrical power per capita of about 2000 W. The rest of the world, i.e. 80%, in 1995 had, on average, less than 100 W electrical power per capita.

Not all industrially developed countries are rich. For example, Russia is one of the largest primary energy producers and has about 1400 W electrical power per capita but at the same time its people have relatively low personal incomes. On the other hand, it is clear that a country with 100 W electrical power per capita can hardly provide a decent life for its population in the *homo industrial* manner.

For the present it is difficult to predict how the distribution function shown in Fig. 3 will evolve. The kinetic equation for this distribution function has not yet been written. What is known is that the population of industrial world and its mean energy production per capita are almost stabilized. The evolving part is the poor world. It gives the major input to the total growth of the world population as well as to the growth of the total energy production. It is also clear that the

Table 2. World primary energy production in 1994 [6].

	Coal	Natural gas	Crude oil	Nuclear power	Hydroelectric	Others	Total
Total power, 10^{12} W	3.00	2.81	4.39	0.75	0.81	0.05	11.81
In percentage of total power, %	25.40	23.74	37.15	6.37	6.88	0.46	100

development of communications (globalization) increases the coupling between the two components of the world. The flow of investment into the developing countries (such as China) will lead to an increase of the energy production in the developing world and will 'cool down' the hot component of the distribution function (relocation of the energy consuming industries, increase of efficiency in industry and transport, etc.).

Figure 3 gives the consumption distribution of electrical power whose contribution to the global energy production is only 24% of the total energy. However, the level of consumed primary energy is more or less proportional to the electrical energy and hence one can expect a similar distribution.

In conclusion, an energy production of a few kW per capita is a necessary (but not sufficient) condition for the well-being of *homo industrial*. The total energy production will continue to grow as a result of the population growth and increase of per capita energy consumption in developing countries. The projection for the future growth of energy production predicts a 2–3 fold increase in energy production which will reach $(25-30)\times10^{12}$ W by the year 2050 [1].

4. Natural limits on the global energy system

In this section we review the natural restrictions on the global energy production. We will not discuss the availability of resources† but rather look at the environmental consequences which may limit the energy production on a much shorter time scale [1].

4.1 Global energy balance

It is well known that the present anthropogenic energy source is too small to affect the global climate by direct heating of the Earth. A comparison of the solar energy with the primary energy production is given in Table 3. The present total energy production is less than $\sim10^{-4}$ of the solar energy reaching the Earth surface and less than $\sim10^{-2}$ of its periodical variations which are believed can affect the climate. Hence, the anthropogenic energy source adds only 0.01% to the solar power and is obviously too small to have any direct effect on the climate. More dangerous could be a change in the chemical composition of the atmosphere, which could modify the carbon cycle and in turn could affect the global climate by the greenhouse effect.

Table 3. Comparison of the present energy production with the solar power [1, 3].

Total primary energy production (1994)	1.2×10^{13} W
Solar constant	1370 W/m^2
Total solar power on the Earth	1.8×10^{17} W
Total solar power reaching the Earth surface (70%)	1.3×10^{17} W
Amplitude of variation of solar luminosity in 11-year cycle	0.1%
Change of insolation due to long-term [$(20-40)\times10^3$ y period] variation of Earth's orbit (Milankovitch mechanism for ice ages [9, 10])	3%

As was shown above, the major part of the total energy (86%) is produced by burning fossils or in other words exploiting chemical reaction (2), which has a by-product — carbon dioxide. In this way almost all carbon burned at power stations is emitted into the atmosphere in the form of carbon dioxide. Doing this we directly affect the natural carbon cycle — the major cycle of life on the Earth based on the chemical reaction of photosynthesis (1). Emission of CO_2 by the present energy system has already led to a shift in the natural balance of carbon and at some level may produce irreversible changes in the biosphere. The greenhouse effect from CO_2 produced by burning fossils was predicted more than 100 years ago by S Arrhenius [11]. It was purely theoretical estimation because at that time it was not known whether CO_2 would be accumulated in the atmosphere or absorbed by the oceans and geological structures. 100 years after this prediction we know much more about balance of carbon dioxide in the atmosphere.

4.2 The balance of carbon dioxide in the atmosphere

The amounts of carbon in different forms involved in the carbon cycle and its content in the atmosphere and oceans are shown in Fig. 4. The total amount of carbon in the atmosphere (in form of CO_2) is about 750 Gt (1 Gt $=10^9$ metric tons). Each year land green plants absorb approximately 100 Gt of carbon from the atmosphere for photosynthesis and growth [12] (this corresponds to an average productivity 2 kg/m^2/y on 10% of the Earth surface). Approximately the same amount of carbon is released each year back into the atmosphere during consumption of the green plants by secondary consumers, chemical decomposition, fires and other natural causes. The total amount of carbon in biomass including soils is estimated at the level of about 2200 Gt, which corresponds to an average lifetime of biomass of about 20 years (close to the typical lifetime of a tree). The food chain of the man–pig–crop community contributes to the carbon cycle at the level of only 1 Gt/y. Marine green plants (plankton and other algae) in shallow ocean water, where sunlight can penetrate and where photosynthesis is possible (depth less than 100 m), exchange with the atmosphere an additional 90 Gt C per year. This is almost equal to the surface plant carbon exchange [12]. Oceans contain a huge amount of carbon, 40000 Gt [9], which enters carbon dioxide dissolved in deep water, but the exchange of CO_2 between deep and shallow waters is very slow — it takes about 500–1000 years [1]. With the present CO_2 concentration in the atmosphere the net absorption by oceans is estimated to be only 2 Gt C per year.

Geological sources and sinks of carbon dioxide seem to be small. For example, the average volcano plus weathering

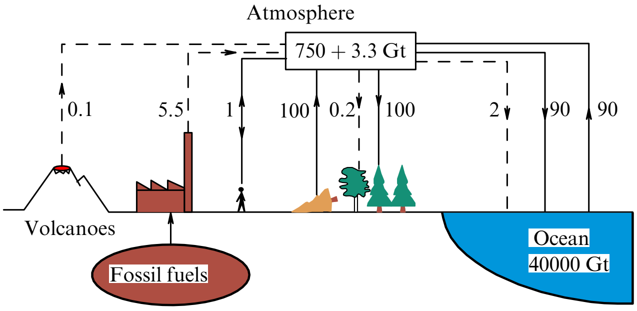

Figure 4. Simplified carbon cycle in the biosphere [1, 12]. The fluxes are given in Gt of C per year. About 2 Gt out of 5.5 Gt emitted from burning fossils is absorbed by the oceans and 0.2 Gt is the net absorption by land plants (including the effect of deforestation). The net accumulation of CO_2 in the atmosphere is 3.3 Gt C/y.

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† A detailed analysis of the energy resources can be found in the paper [8].

source was estimated in Ref. [3] to be less than 0.1 Gt C per year, which is much smaller than the biogenic fluxes.

One can make interesting observations from Fig. 4. Firstly, the land and marine green plants could absorb all CO_2 from the atmosphere in four years. This means that a carbon atom in the form of CO_2 lives in the atmosphere only four years on average until it is absorbed by a green plant during photosynthesis. The atom will spend the next 20 years in the organic mass of the plants and after plant decomposition returns to the atmosphere. Therefore, the full turnover of the C atom in the carbon cycle takes about 25 years. For example, carbon from a tree which died 100 years ago has already been recycled by plants and animals three times. Secondly, the amount of carbon in the atmosphere is several times smaller than the amount of carbon in the biomass. This means that the atmospheric CO_2 is indeed in a state of a dynamic balance with the animate nature and evaluation of the effect of anthropogenic activity should be done in the context of the total biomass balance. The notorious greenhouse effect is clearly only one side of many attacks and it might be that we are not aware of many critical aspects of this interaction.

4.3 Effect of the global energy system on the carbon cycle

Figure 4 shows that the anthropogenic source of carbon dioxide due to burning fossils is equivalent of about 5.5 Gt C per year and is significantly larger than all nonbiogenic sources such as volcanoes. It is clear that the biosphere, which has existed for billions of years, has a natural feedback control system which among other aspects keeps the concentration of carbon dioxide in the atmosphere at a constant level. Indeed, about 2 Gt of this additional source of 5.5 Gt is absorbed by the oceans. The land plants could absorb 1.8 Gt but deforestation of tropical forests is believed to lead to an additional emission of 1.6 Gt, so the net absorption by the land biomass is only 0.2 Gt C/y. Thus, the industrial pollution markedly exceeds the capacity of the feedback response and about 3.3 Gt C/y is accumulated in the atmosphere in the form of CO_2. It can be seen in Fig. 5, which shows the actual concentration of CO_2 in the atmosphere over the past 1000 years [1]. The early points were obtained from analysis of air bubbles in the ice of Antarctica. Starting from 1958, there are regular direct measurements of atmospheric CO_2 in Hawaii. There appears a clear correlation between the start of massive burning of fossils at the beginning of the 18th century and the sharp increase in CO_2 concentration. The present growth rate is in good agreement with the sources and sinks described above.

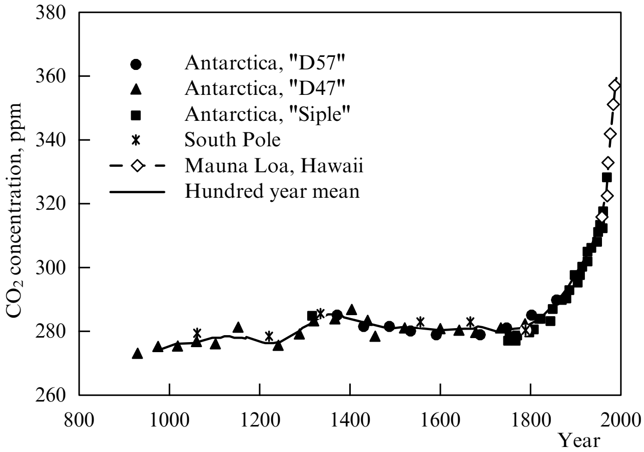

Figure 5. CO_2 concentration over the past 1000 years from ice records in Antarctica and from Mauna Loa, Hawaii [1]: ● — measurements from bubbles in the ice in Antarctica; ◇ — direct measurements over the Hawaiian Islands, made from 1958. 1 ppm = 10^{-6} of total volume.

Measurements also show that over the last 200 years the concentration of CO_2 has increased by 30% from its pre-industrial level.

We can conclude that the oceans and biota can absorb only 40% of the anthropogenic source of carbon dioxide, the rest, i.e., 60%, accumulating in the atmosphere.

Now we can estimate increase of CO_2 in the atmosphere by 2050 assuming that fossils fuels will remain the major energy source and assuming that in 2050 the power production will be twice the present level. In this case, the global energy system will emit about 400 Gt C and, hence, will increase the mass of CO_2 in the atmosphere from the present 750 to about 1000 Gt C by year 2050. This simple estimate is close to the results of much more elaborate models [1], which also predict an almost doubling of carbon dioxide from the pre-industrial level by the year 2050 in the case of 'business as usual' [1, 12]. If the net flux of 2 Gt C/y absorbed by the oceans is a response of the biosphere 'feedback system' to a 30% increase in atmospheric carbon dioxide, then one can estimate the maximum exchange rate of CO_2 with the oceans as 6 – 7 Gt C per year. This is comparable with the present anthropogenic source and smaller than the expected future pollution. Therefore, one should not expect that the natural feedbacks will somehow solve the problem and stabilize the CO_2 concentration. In 1957, R Revelle and H Suess — the pioneers in the study of the carbon cycle — wrote: "Human beings are now carrying out a large scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future. Within a few centuries we are returning to the atmosphere and oceans the concentrated organic carbon stored in sedimentary rocks over hundred of millions years" [12].

What could be the potential consequences of this global geophysical 'experiment' to the man – pig – crop community?

5. Effect of CO_2 pollution on the climate and biosphere

The consequences of CO_2 emission have been discussed and intensively studied over the last few decades. One of the major concerns is change in the greenhouse effect due to the variation in the concentration of CO_2 and other gases escaped into the atmosphere by thermal power stations.

The greenhouse effect is an essential part of the global power balance on Earth: without it the average temperature would be below the water freezing point. Carbon dioxide, water vapor, and some other gases in the atmosphere absorb the infrared radiation, emitted by the Earth surface heated by sunlight, and maintain the average surface temperature at about 10 °C. The larger the amount of greenhouse gases, the larger the effect which can be characterized by radiative forcing, i.e. additional power per m^2 trapped by the greenhouse gas.

Estimates of radiative forcing due to the present 30% increase in the concentration of CO_2 and other gases since pre-industrial times gives 2.45 W/m^2 [1]. This is about 0.7% of the average solar power reaching the Earth's surface and is about 70 times larger than the direct heating of the Earth surface by burning fossils. The climate models predict that the radiative forcing will increase from 2.45 to 5 – 6 W/m^2 by the year 2050 in the case of 'business as usual' [1]. At this level the anthropogenic effect will reach 1.5% of the solar power and will be comparable with the natural long-term variations of solar power. This gives serious concern about consequences for the global climate.

For the last 5 million years, the Earth's climate has been characterized by increasing variability. This is illustrated in Fig. 6 showing time traces of the average temperature on different time scales. The gradual cooling of the Earth over last 60 million years changed about 5 million years ago to a regime with large and periodical temperature variation with a major period of about 120 thousand years. The amplitude of the sawtoothlike perturbations is about 5 – 10 °C. Each of the 120 thousand years cycles usually starts with a fast increase of the temperature followed by a warm period lasting 10 – 20 thousand years. During next 100 thousand years the temperature gradually decreases to the lowest level before the next sharp rise.

The long-term periodical decrease of the temperature was accompanied by oscillations with a period of about 20 thousand years and a somewhat smaller amplitude. These periodical coolings were accompanied by the growth of land glaciers in the northern hemisphere and are called ice ages. The last and coldest one happened about 20 – 30 thousand years ago. At this time the glacier reached Europe to the latitude of northern France.

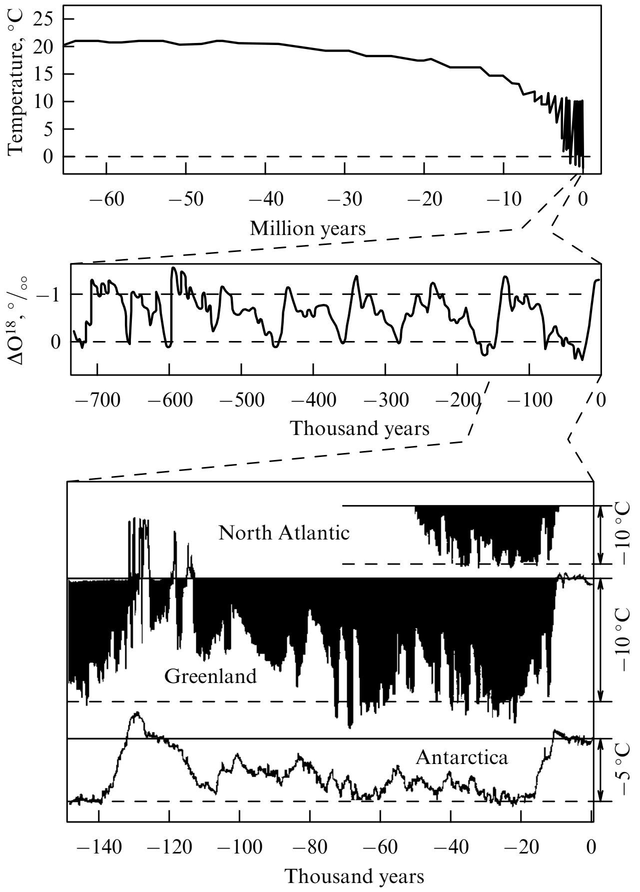

Figure 6. Paleoclimatic data for the Earth's surface temperature back in time. Top: estimates of the globally averaged surface temperature of Earth over a time scale of 60 million years (from Ref. [3]). Middle: composite ΔO^{18} curve (from Ref. [13]). Difference between the O^{18}/O^{16} ratio of calcium carbonate ($CaCO_3$) of sediments and that in sea water is a function of temperature and hence the ΔO^{18} curve indicates the variation of water temperature. Bottom: temperature changes estimated from the isotope composition of ice in Greenland and Antarctica and from faunal counts in the North Atlantic (Fig. 3.22 from Ref. [1]).

What is the cause of the long-term oscillations in the temperature? It is not clear. There are several hypotheses to explain the periodical ice ages: variability of solar luminosity, the passing of the Solar system through periodic intergalactic dust clouds, collisions with asteroids, and oscillations in the Earth orbital and axial characteristics. The latter, called the Milankovich mechanism, is considered to be the most likely. The orbit changes, which occur due to perturbations caused by the other planets of the Solar system, have similar periods to the ice ages (about 100, 40 and 20 thousand years) [9, 10].

The major concern of *homo industrial* should be the high-frequency oscillations with relatively large amplitude in the northern hemisphere and a period of 1 – 2 thousand years. A remarkable feature of these oscillations, which can be seen on the fine-time scale in Fig. 6, are the sharp fronts reminiscent of phase transitions. There are examples in the temperature records in Fig. 6 when the average temperature drops by 10 °C over only a few decades and then stays at this level for 2000 years and returns. There are indications that the last rapid warming which occurred 11 – 12 thousand years ago was also very fast [1]. The central Greenland temperature increased by 7 °C in a few decades. This change was accompanied by an even more rapid change in the precipitation pattern and a rapid reorganization of atmospheric circulation [1]. Conceivably that this event might be remembered as the great flood and was later described in the Bible.

What happened to the CO_2 concentration during these periodical oscillations in the climate history? It was found that the concentration of carbon dioxide followed temperature and glacier area variations. 20 thousand years ago, during the peak of the last ice age, the concentration of CO_2 was half the modern pre-industrial level and then increased following the rapid temperature rise [14]. It is known that the low CO_2 concentration had a significant effect on the productivity of the green plants even in the tropics where the temperature drop was not so significant as at high latitudes [15]. There is point of view that the increase of carbon dioxide concentration after the last warming led to an increase of the productivity of the green plants and made possible agriculture [15] and the present development of civilization.

Therefore, fast climate changes have occurred in recent climate history. These kind of changes happened on the time scale of a human life or even less and hence might be considered as global disasters of a kind that could affect the present infrastructures and the whole human race. Comparing the last 120 thousand years with the previous cycles, we can conclude that we are somewhere near the end of the warm period and the temperature should start gradually to decrease. Will the natural cycle repeat this time again or is the anthopogenic effect too large and are we facing fast global warming accompanied by melting of the polar ice caps [14]? Even if the effect of CO_2 pollution is less severe than expected from theoretical modelling, the increase of the carbon dioxide concentration by factor of two should cause serious changes in the biosphere. How long should we wait until CO_2 accumulation in the atmosphere causes change in the atmospheric and ocean circulations and triggers a fast transition to a different climate state? We do not know but sooner or later it will happen.

6. Nonfossil energy sources

The responsible inhabitants of the Earth, being used to high energy consumption and wishing to extend their well-being, have to think how to replace the present energy system based on burning fossils with an alternative one on a time scale of 40 – 50 years. In this section we discuss the available alternative energy sources and their potential role in the future global energy system.

There are not very many ready-for-use nonfossil energy sources. The candidates are: hydroelectricity, solar energy, biomass production and combustion, nuclear fission and fusion. The rest such as energy of wind, oceanic floods, geothermal sources and others should be promoted as much as possible but are clearly too small to make a significant contribution to the global energy system. As we saw in the previous sections, the present structure of the energy system of *homo industrial* requires about 50% of the baseline energy source which produces steady-state power used in industry, residential and commercial applications (heating, cooling, etc.) and a part of the transport. The rest of the power supply could be pulsed with the maximum consumption during the day time and a small consumption at night.

6.1 Hydroelectric power already contributes 7% to the world energy system [2]. It was actively developed from the beginning of this century and now most of the resources available for commercial exploitation have been used. It is likely that the present level of 0.88×10^{12} W will remain the same or rise only slightly in the future. Hydroelectric power is a contributor to the baseline energy system.

6.2 Solar energy is one of the most attractive candidates. The total solar power source is enormous in comparison with the energy demands and utilization of the required fraction of 10^{-4} could hardly affect the global environment. Present technologies for the direct utilization of solar energy are based on either photovoltaic cells (PVC) or on concentration of solar energy by mirrors (heliostats). Direct solar light can produce only a low temperature heat† and hence concentration is needed to increase the efficiency of energy production. In the case when high-temperature heat is not needed, for example, for household water heating, solar power is already widely used especially in southern regions.

The principle problem with the solar energy is that it is available only during the day. Hence, the average solar power density is more then three times lower than the peak one. Therefore, a baseline solar power plant of 1 GW of average electrical power should be designed for 3 GW of peak electrical power and in addition should be accompanied by a 1 GW electrical nonsolar power plant to produce energy during the dark time. It is also necessary to have an energy storage with a minimum of 5.8×10^4 GJ to feed the nonsolar power plant. To estimate the scale of the enterprise one can assume that the energy is stored by pumping water to an elevated reservoir (one of the most efficient energy storages). In this case the energy storage needs two lakes with a surface of 30 km^2 and a dam with 20 m in height between them. Hence, a solar power station capable of providing 1 GW electrical power shall require a minimum installed power of 4 GW and huge energy storage.

This example shows that solar power is not very attractive as a candidate for baseline power production. At the same time, solar energy can probably replace fossil sources in a large part of residential and commercial applications, communications, and a part of industry. With the present structure of energy consumption, solar power can probably satisfy up to 20% of the future energy demands [2].

6.3 Biomass fuels can be an important component of the nonfossil energy system. This energy source (wood) was the main energy source for the pre-industrial world ever since man started to use fire. Progress is expected from bioengineering which should develop highly productive crops and devise effective means of transformation of green mass to an efficient fuel capable of replacing petroleum.

This would be a fully renewable source and not affect the carbon balance in the atmosphere — the crops or wood absorb CO_2 from the atmosphere during growth and release it later when the biomass is burned. Besides the carbon cycle, the green plants are involved in the nitrogen and phosphorus cycles and a massive amount of biomass could shift the present equilibrium. Having in mind that all the green plants on the Earth produce 100 Gt C/y we can assume that the maximum harvest for energy crops should be limited to 10 Gt C/y gross in order not to seriously affect the biota (10% or less is a typical ratio between primary and secondary levels in the healthy ecological community). Now if we assume that 1 kg of efficient fuel can be produced out of 6 kg of green mass [2], we can estimate the upper limit for the energy which can be generated from biomass as 15 – 20% of the future energy demands.

Therefore, this energy source cannot replace fossil fuels in the baseline energy system. At the same time, fuels from biomass can in principle substitute a large part of the fossil petroleum used presently in the transport and, hence, can reduce atmospheric pollution. To achieve this goal, it is necessary to find energy-effective ways to grow and process biomass. As was shown above, the present agriculture spends 300 W to produce 100 W of food (see Section 3).

6.4 Nuclear fission power is one of the most mature candidates for the baseline energy system [16]. The technology is fully developed and a new generation of safe nuclear power plants will soon be available. The nuclear power plants produce at present 6% of the world energy. In some countries, such as France, the nuclear power plants generate more than 70% of the electrical energy. On the contrary to public opinion, nuclear energy has very good safety records and its environmental impact is the smallest among the other energy systems. The main and justified concerns are [16]:

(1) the potential spread of nuclear-weapons-relevant technology and materials, and

(2) the accumulation of radioactive waste.

If 50% of the total power is produced in 2050 by nuclear power stations, then the total waste production rate will be about 50000 t per year [16]. The total amount is not very large (notice that the all thermal power stations emit 50000 t of C in one minute) but the waste will remain active for the next 10 – 100 thousand years, which means that cost of handling and processing will grow in proportion to the integral of the produced energy.

Therefore, in the long term, nuclear power, although a much smaller polluter than the fossils, has the same disadvantage — it gives a temporary solution which will

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† Direct solar rays can heat the surface to a temperature $< 100\,^\circ\text{C}$.

extend the time available for developing a truly renewable energy source. There is a strong psychological barrier to the further development of nuclear energy — the populations of the mostly industrial countries are generally against expansion of the nuclear sector in the energy system — and, as a result, nuclear energy is overburdened by legislation and other restrictions on their safety, which limit its ability to compete with the fossil energy system. The present generation was frightened by atomic bomb during the cold war and since that time it has been scared of nuclear power. At the same time, nobody is afraid of a fireplace which has been in use for a hundred thousand years in spite of the fact that many thousands of people die from fire accidents each year and a huge amount of carbon dioxide is emitted by the industrial 'fireplaces'.

Therefore, we have no presently available candidates (except the nuclear fission as a temporary solution) capable of replacing fossil fuels in the global energy system. The direct transformation of solar power, biomass, and other renewables all together can provide for 50% of the energy demands at most. If fast and serious measures to reduce the emission of greenhouse gases are needed, the nuclear fission reactor is the only candidate to replace fossil fuels.

There is a further potential candidate for the baseline energy system — controlled nuclear fusion — but it requires many years of research and development before it will be available.

7. Controlled nuclear fusion

Controlled nuclear fusion uses the nuclear energy that can be produced by fusion of light nuclei such as hydrogen or its isotopes — deuterium and tritium. Nuclear fusion reactions are very common in nature. It is believed that these reactions supply the energy for stars. The Sun is a natural nuclear fusion reactor which supplies energy on Earth for many billion years. Nuclear fusion energy has already been harnessed in the Earth's conditions but only for nuclear weapons — an H-bomb. Starting from the early fifties, Russia and many other countries have been carrying out research to develop a controlled nuclear fusion energy reactor. Very soon it became clear that this area of scientific research has no military applications. The nuclear fusion programs in Russia, US, and other countries were declassified and since that time a wide international cooperation has been established. At the very beginning of this research it seemed that the goal was very close and the first fusion experimental machines (designed late in fifties) would demonstrate controlled nuclear fusion. However, it took more than 40 years to develop a prototype of the reactor and to create conditions where the fusion-produced energy exceeds the energy spent for heating the reacting mixture. In 1997, the largest experimental device — the European tokamak JET — demonstrated 16 MW of fusion power and operation close to this breakeven.

What was the reason for the 40 year delay in achieving the fusion goal? It was found that to reach the goal physicists and engineers had to solve many difficult problems which were not foreseen at the beginning. Physicists developed a new branch of physics science — plasma physics — which was required to describe the complicated processes in the reacting mixtures. Engineers also had to solve many complicated problems so as to find ways to create deep vacuum in a large volume, develop big superconducting magnets, create powerful lasers and X-ray sources, develop injectors of neutral-beam ions, provide powerful sources for high-frequency plasma heating, and many others.

The first generation of nuclear power reactors, which are under development, will use the fusion of deuterium and tritium, viz.

$$\mathrm{D} + \mathrm{T} = \mathrm{He} + \mathrm{n}\,, \tag{3}$$

resulting in the transformation of these hydrogen isotopes into a He nucleus and a neutron. A necessary condition for any nuclear fusion reaction is a very high temperature of the reacting mixture (a hundred million degrees). Only at such a high temperature can the reacting ions overcome the repelling Coulomb forces and approach close enough to each other to fuse. Beside the high temperature, it is necessary to have a high ion density n and long particle and energy confinement times τ in the reactor to satisfy the condition: $n\tau > 5 \times 10^{14}$ s cm^{-3}. Only in this case will the energy production exceed the energy loss from the reacting mixture. The last condition is called the Lawson criterion. The major physics problem encountered by researchers was plasma instabilities which led to plasma turbulence and a low plasma confinement time, which did not allow the Lawson criterion to be reached in the first experimental devices. The following forty years of the fusion research has been spent for developing fusion devices capable of confining turbulent plasmas.

There are two principally different approaches to nuclear fusion and at present it is not clear which will eventually win and result in an economical fusion reactor.

In so-called inertial fusion, a few milligrams of reacting fuel is compressed to a very high density by a shell ablated by a very powerful laser or X-ray radiation (driver) and accelerated by a rocket force produced by ablated material of the shell. Energy is produced in the form of a microexplosion of the fuel. The lifetime of this mixture is defined by a free inertial expansion of the reacting mixture and, hence, the Lawson criterion is usually expressed in terms of the product ρr, where ρ is the density of the compressed fuel, and r is its radius. To achieve a sufficient burn out of the mixture, one should achieve $\rho r \geqslant 3$ g cm^{-2}. It can be seen that the critical mass of the fuel will be smaller if one can reach a high compression, $M \sim \rho r^3 \sim 1/\rho^2$, and thus can decrease the energy released in a single explosion. The limitations on the compression arise from the nonuniformity of the radiation and the initial nonuniformity of the target, which can increase during compression due to the Rayleigh – Taylor instability. As a result, there is a critical mass and hence a critical energy of a single explosion at which one can achieve breakeven conditions. The present theoretical estimates predict that a target containing 5 mg of the DT fuel, with an initial radius of 1 – 2 mm, requires deposition of about 2 MJ of driver energy in a very short time $(5-10) \times 10^{-9}$ s [17]. The energy released from the microexplosion will be only about 5×10^8 J (equivalent to about 100 kg of chemical explosions) and hence can be easily confined by a specially designed vessel. It is expected that a future energy reactor will work in a regime of frequent explosions (several explosions per second) and the produced fusion energy will be removed by a coolant and will then be used to generate electricity.

Significant progress in understanding the physical processes that control compression of the target has been achieved during recent years of intensive research. Moreover, prototypes of the targets have already been checked in experiments with underground nuclear explosions, which are able to provide the required radiation power [17]. An ignition and high-fusion energy gain have been achieved in these experiments and, therefore, there is no doubt that this approach can be successful in principle. The main technical problem in this area of nuclear fusion research is the development of an effective (other than nuclear fission) driver for acceleration of the target shell. The required power densities can be produced by lasers (this is done in the present experimental devices [17]), but the efficiencies of lasers are too low to achieve breakeven. Other drivers, such as electron and ion beams, and *Z*-pinches are under development. The gradual progress in this area of nuclear fusion technology is encouraging [18], but a driver with the required characteristics does not yet exist. A large experimental device, NIF, targeted to achieve ignition with the help of a laser driver, is under construction in the US. Figure 7 shows a cross section of the vessel where the targets will be compressed.

The other direction in nuclear fusion research is magnetic confinement of the reacting fuel. A magnetic field is used to isolate a hot plasma from contact with the walls in these reactors. On the contrary to inertial reactors, the magnetic reactors are steady-state devices with a low-power density and relatively large volume. During forty years of fusion research many different types of magnetic fusion devices have been suggested and tested experimentally. Among them the tokamak is a leading system. The other successful magnetic device is a stellarator. Large experimental stellarators are under construction in Germany and Japan.

In a tokamak, the hot plasma has a donut shape and is confined by a combination of an external magnetic field and a magnetic field produced by electrical current running in the plasma. The typical plasma density in tokamak is 10^{20} m^{-3} and the typical plasma temperature is $T = 10-20$ keV (1 eV $\approx$ 12000 °C) and the plasma pressure is about 2–3 atm. To confine this pressure, one should have magnetic field of about $B = 1$ T. However, plasma instabilities limit the plasma pressure to a few percent of the magnetic pressure and, hence, tokamaks have to have a magnetic field about ten times higher than that required for plasma confinement. To avoid excessive energy expense in maintaining such a high field, it may created by superconducting coils. This technology is already available — one of the largest experimental tokamaks, the Russian tokamak T-15, has superconducting magnetic coils.

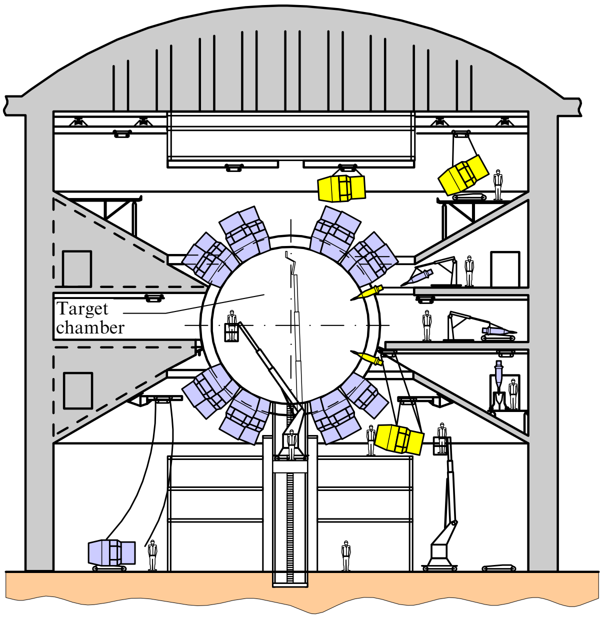

Figure 7. Chamber of the installation NIF being built in the USA, in which compression and ignition of the target using laser radiation will be carried out [17].

The tokamak reactor will work in a regime with self-sustaining plasma heating when the high plasma temperature is sustained with plasma heating by energetic alpha-particles, i.e. the He ions produced in DT reactions described by Eqn (3). To achieve ignition, a tokamak must have an energy confinement time of about 5 s. The long energy confinement time is achieved in a tokamak by its large size and hence there is a critical size of a tokamak reactor. Estimates show that a self-sustaining DT reaction is possible in a tokamak with a major radius of 7–9 m. Such a reactor will produce a thermal power of 1–3 GW. It is interesting to note that this power is similar to that of an inertial nuclear fusion reactor.

Impressive progress has been achieved during the last few years in understanding the physical phenomena responsible for plasma confinement and plasma stability in tokamaks. New effective means for plasma heating and plasma diagnostics have allowed study of the prototypes of the tokamak reactor scenarios and operating regimes. The present generation of large tokamaks: JET (Europe), JT-60U (Japan), TFTR (US), T-15 (Russia), TORU SUPRA (France) were built in the 80's to study plasmas with parameters close to those in a nuclear fusion reactor and with the aim of reaching breakeven conditions. Two tokamaks operating with a DT mixture demonstrated 10 MW (in TFTR) and 16 MW (in JET) of fusion power. The tokamak JET achieved, in a DT mixture, a ratio of fusion to plasma heating power $Q = 0.9$. Tokamak JT-60U reached $Q = 1.06$ on a model DD mixture. Therefore, this generation of experimental machines have achieved their goals and provided the scientific information needed for the next step — tokamaks aimed at studying ignition and high ($Q \geqslant 5$) operation and having all the elements of the future tokamak reactor.

The next step tokamak — the first International Thermonuclear Experimental Reactor, ITER — is being designed by an international team from Europe, Japan, Russia, and the US. The layout of the tokamak is shown in Fig. 8. The device will be constructed by 2010.

Nuclear fusion has huge energy resources. Deuterium is a widely spread isotope which can be extracted from sea water. Tritium will be produced in a reactor from lithium. The available resources of deuterium and lithium are very large and could supply energy for several thousand years. The fuel as well as the final product of the fusion reactions, helium, are not radioactive. However, radioactivity is produced in the nuclear fusion reactor by neutrons in the constructional material of the first wall. There are candidates for lowly active materials for the first wall which cool down in 30–50 years to a hand-on-level. One can imagine that the nuclear power reactor with the first wall built from these materials will be closed for 30–50 years on the site after 30 years of operation and then the materials will be recycled in a new power reactor. Besides the DT reaction which can occur at a low temperature and is hence less difficult to harness, one can use other reactions [21]. For example, the fusion of deuterium with ^{3}He or protons with boron do not produce neutrons and hence do not activate the first wall materials. However, the

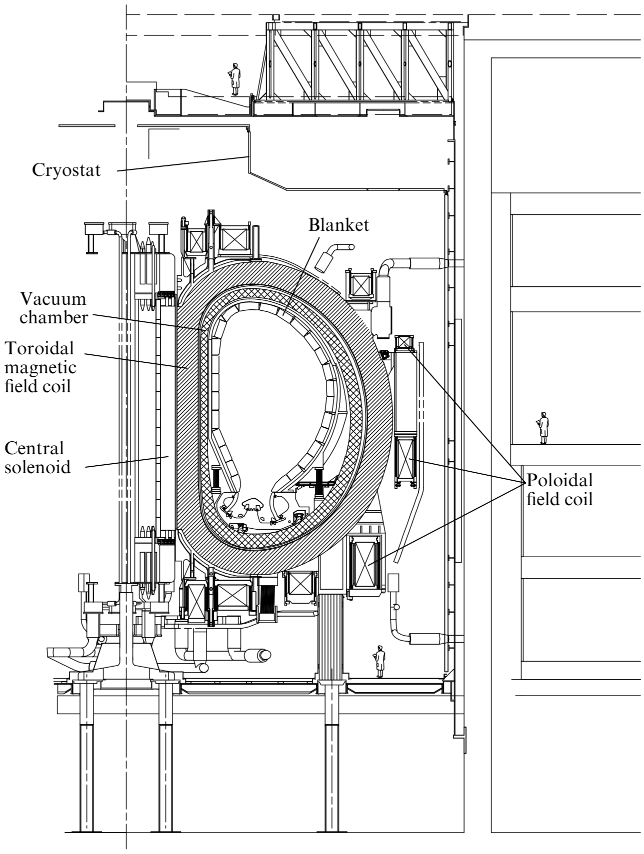

Figure 8. General view of the projected tokamak-reactor ITER.

Lawson criterion for these reactions is more stringent and hence the present fusion program is aimed at the DT reaction.

In spite of steady success in nuclear fusion research it will take a long time before the first commercial nuclear fusion reactor can be constructed. The development of fusion energy requires large and long-term funding of the development of new technologies and materials and of physics research. At the present level of financing, fusion energy will not be available before 2020 – 2050.

8. Conclusions

The present well-being of *homo industrial* is based on a large consumption of relatively cheap energy. It is expected that the energy consumption will grow faster than the world population and will at least double by the year 2050. At present, more than 86% of the total energy is produced by burning fossils — oil, natural gas, and coal — which results in the emission of 5.5 Gt of carbon per year in the form of CO_2 into the atmosphere. In the case of 'business as usual', the emission of CO_2 and other greenhouse gases will reach about 11 Gt C/y or more by the year 2050.

Even the present level of emission exceeds what the natural feedbacks of the biosphere can accommodate. Each year 3.3 Gt C out of 5.5 Gt C emitted into the atmosphere by industry accumulates and will stay there for many hundreds of years. During the last 300 years, the anthropogenic sources have increased the CO_2 concentration in the atmosphere by 30%. In the case of 'business as usual', the concentration of CO_2 will double by the year 2050.

Accumulation of CO_2 and other greenhouse gases in the atmosphere leads to effective heating of the atmosphere due to trapping of thermal radiation from the Earth surface. The present greenhouse effect from increase of CO_2 concentration is equivalent to an effective surface heating on the level of 2.45 W/m^2. By 2050, the radiative forcing will rise to 5 – 6 W/m^2 and will become comparable with the magnitude of the natural variations of solar power, which in the geological past led to significant changes in the global climate. Paleoclimatic data shows that the climate can change very quickly, even faster than the lifetime of a single generation. The seriousness of the situation is becoming more and more apparent to the general public and today the first steps are being made to reduce CO_2 emission†.

What has to be done — is a radical change of the present energy system. We have about 50 years to replace the present energy system, based on burning of fossil fuels, by a system using other ecologically clean energy sources. It is likely that the future energy system will use a combination of different energy sources: solar energy, biomass production, nuclear fission and nuclear fusion reactors. Only the combined efforts of people working in different areas can solve this global problem in a relatively short time.

At the same time, it is clear that the only candidate for the baseline energy source is nuclear power. Nuclear fission reactors are ready to start replacing thermal power stations based on fossil fuels. While the nuclear fission power is also a temporary solution, it can give the time needed to develop nuclear fusion reactors. Many years of fusion research have proven that the fusion has real potential to become a safe, environmentally clean and recyclable energy source with vast resources available for many thousands of years. This is a real candidate to replace eventually the fossil fuels as the baseline source in the global energy system. It is time now to start a long-term energy program based on a wide international cooperation to arrive in 40 – 50 years at the fusion energy system needed for the future prosperity of the human race.

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† At the last International meeting in Kyoto, Japan [22] it was possible to come to an agreement to reduce CO_2 emission into the atmosphere by 5% by the years 2008 – 2012.

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