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GEOGRAPHY

Stabilization of the Planetary Climate in the Twenty-First Century by Transition to a New Paradigm of Energy Consumption

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In this article we assume the hypothesis that the current global warming is caused largely by anthropogenic increase in the CO_2 concentration in the Earth's atmosphere. For the past 150 years, resulting from industrial activity, the CO_2 concentration in the Earth's atmosphere has increased from the natural pre-industrial level of 280 ppm to the present-day value of 390 ppm (i.e., by 40%). This has led to growth in the average global temperature approximately by 0.6°C, or by 1°C with natural factors taken into account, relative to the pre-industrial level [1, 2]. What are the acceptable limits of global warming? At the recommendation of the leading world climatologists, in 1996 the European Council made the decision that the "average global temperature of the pre-industrial level should not be exceeded by more than 2°C; therefore, global efforts for restricting or reducing the emissions must be oriented at an atmospheric concentration of CO_2 of no more than 550 ppm" [2].

The warming limit of 2°C was confirmed by the United Nations in the Declaration adopted at the 2009 United Nations Conference on Climate Change (Copenhagen Summit); the specified value of CO_2 concentration in the atmosphere that should not be exceeded became 450–550 ppm, and this can be achieved if the annual increment of carbon emissions will be reduced to at least 3.3 Gt, or nearly twice relative to the level of 2000 (6.61 Gt). Since the anthropogenic emissions of great volume of carbon in the form of CO_2 occur from combustion of coal, petroleum, and natural gas for energy reasons, it is obvious that the scenarios of the low-carbon energy sector development (or ecological energy development) with small CO_2 emissions should be considered. The International Energy Agency (IEA) has considered many scenarios of energy development and has elaborated, in particular, the Blue Map scenario, which is aimed at 50% decrease (relative to the level of 2005) of CO_2 emission by as early as 2050 and implies common use of low-carbon technologies [3]. But is it possible to achieve this by 2050?

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To answer this question, from a number of energy development scenarios, one has been chosen that meets the new paradigm of energy consumption and implies stabilization of energy consumption per capita for the population of developed countries in the twenty-first century at a low but still comfortable level. It has been shown that such a level for the world as a whole is approximately 2.5 tons of reference fuel (TRF) per year [4, 5]. The transition to a new paradigm of energy consumption began in the 1970s, when energy collapse hit the world after the oil crisis. The developed countries abruptly enhanced the effectiveness of their energy consumption after the energy crisis by widespread use of energy saving technologies. In fact, the decrease in energy consumption per capita in the developed countries began as early as the 1990s. This decrease will continue for the entire twenty-first century. The recent world economic crisis and unprecedented growth of oil prices are additional factors for this. Thus, transition to a new paradigm of energy consumption is an autonomous process caused, first of all, by gradual exhaustion of organic fuel and continuing growth of its prices. It is expected that by the mid-twenty-first century energy consumption per capita in the developed countries will decrease by 40–45% and then stabilize at levels (Table 1) that are to become norms in the future. They correspond to the obligations taken by both developed and developing countries at the Copenhagen Summit. Additionally, experts think that a level of energy consumption of over 3.5 TRF per capita is very comfortable for the developed countries. In turn, the developing countries will increase their energy consumption to 2.25 TRF per capita to support industrialization of their economies (see Table 1). It was shown in [1] that a decrease in energy consumption per capita in the developed countries and an increase in the developing ones can be described with sufficient validity by descending and ascending logistic functions.

Our paper aims to show that a transition to a new paradigm of energy consumption with differentiated norms of energy consumption per capita for different countries, in accordance with their obligations and combined with a widespread application of partial CO_2 capturing and storing (CCS) technologies, will help to reduce the volume of industrial CO_2 emissions by two times and to stabilize the global climate within the conditions comfortable for humankind.

Before the oil crisis, energy consumption grew proportionately to the square of the world's population ($E \sim N^2$) [7]. Transition to the new paradigm of energy consumption should lead to growth in direct proportion ($E \sim N$) [5]:

$$E_w = 2.5N \text{ (TRF/year)}. \quad (1)$$

Note that N is expected to be stabilized at about a stationary value, as well. In the calculations below, the values of N are assumed at 5.2, 7.4, and 9.2 billion people; additionally, we will consider the extreme stationary value of $N_{max} = 11.36$ billion people, which can be achieved solely if the sustainable development conditions are satisfied. It is described by the simplest model by S.P. Kapitsa [8]. The new paradigm of energy consumption is aimed in fact at practical implementation of the Blue Map scenario by IEA [3], because it utilizes the comprehensive set of tools and measures, starting from energy saving technologies and those for increase in finite energy consumption, to widespread use of CCS systems and renewable energy sources (RESs). Thus, the key role in calculation of the total world energy consumption, as is given in Eq. (1), is played by the population of the world (N). This value can be calculated by the mathematical model implying "growth with reduction and stabilization at a stationary level," suggested in [9]. The calculation method is presented in detail in [6]. The prognostic calculations of the world population dynamics using this model for different stationary levels mentioned above are presented in Fig. 1. To compare, the prognosis of the United Nations until 2010 [10] is given in the same figure. The figure shows that the UN prognosis nearly coincides with the path of sustainable growth from the model by Kapitsa and is the most optimistic.

The dynamics of energy consumption for the avant-garde countries in the twenty-first century can also easily be calculated using the method from [6]. These results are presented in Fig. 2, where one can see that with a gradual and smooth decrease in energy consumption in the developed countries, rapid growth takes place in the avant-garde developing ones (China, India, etc.), which are in the phase of industrialization of their economies.

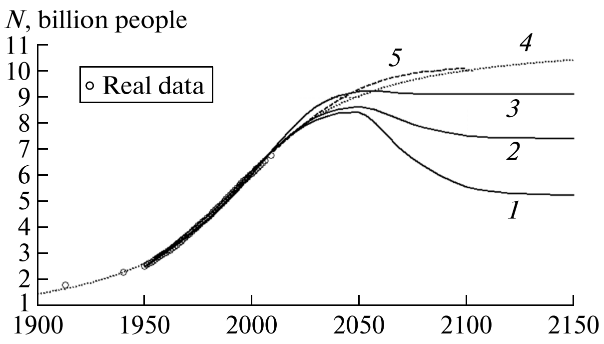

Fig. 1. Different scenarios of the world population dynamics in —the twentieth and twenty-first centuries. (*1*)–(*3*) Models with different delays: (*1*) $N_c = 5.2$, (*2*) $N_c = 7.4$, (*3*) $N_c = 9.1$; (*4*) model of stable evolutionary growth; (*5*) UN prognosis.

Table 1. The levels of energy consumption per capita in the leading countries in the twenty-first century

Countries	Energy consumption, TRF per capita	
	Present time	By the mid-twenty-first century
World in whole	2.4	2.5
Countries with energy consumption per capita more than average global value	6.9	4.0
United States	9.5	5.5
Russia	6.2	4.5
European Union, Japan	5	3.5
Countries with energy consumption per capita less than the average global value	1	2.25
China	1.2	2.25
India	0.8	2.25

Up to here, the total energy consumption has been discussed; this total value is provided owing to different energy sources, such as coal, oil, natural gas, hydraulic power (HP), nuclear power (NP), and RESs. We are mainly focused on coal, oil, and natural gas, because their combustion produces a great amount of carbon emissions into the atmosphere largely in the form of carbon dioxide. The dynamics of the global energy balance (GEB) for the last half-century (based on the IEA data [11]) and the IEA prognosis until 2030 [11] are presented in Table 2, in tons of oil equivalent (1 TOE = 1.4 TRF).

As is seen from Table 2, about 87% of primary energy is produced from fossil fuel resources (coal, oil, and natural gas) at present. In recent decades, great efforts have been made to replace hydrocarbon fuels with nuclear energy, RESs, and alternative energy sources such as hydrogen-based energy. Many experts have decided that as early as the mid-twenty-first cen-

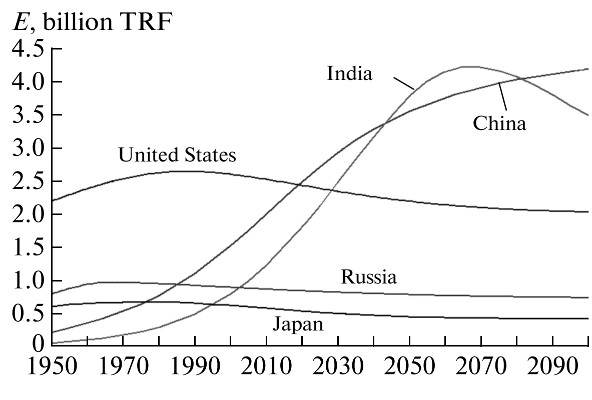

Fig. 2. Energy consumption in avant-garde countries.

Table 2. The global energy balance, after [11]

Years	1950	1960	1970	1980	1990	2000	2005	2010	2015	2020	2025	2030
World energy consumption, mil. TOE					8194	9277	10678	11863	13371	14600	15558	16518
Coal, %	51.8	35.3	23.4	16.5	27.4	24.3	27.0	29.5	30.2	29.5	28.2	27.1
Oil, %	31.8	41.5	50.3	50.8	38.9	38.8	36.5	32.9	30.7	29.2	28.2	26.0
Natural gas, %	10.2	15.8	18.3	19.3	21.8	23.5	23.6	24.1	24.5	25.2	25.7	26.2
HP, %	6.2	7.4	7.2	6.2	5.9	6.5	6.2	6.5	6.4	6.6	6.7	6.9
NP, %	–	–	0.8	7.2	5.6	6.3	5.8	5.2	5.4	5.6	6.0	6.6
RES, %	–	–	–	–	0.4	0.5	0.7	1.3	2.1	3.0	4.0	4.8
Biofuel, %	–	–	–	–	0.1	0.1	0.2	0.5	0.7	0.9	1.2	1.4
Organic fuel, %	93.8	92.6	92.0	86.6	88.1	86.6	87.1	86.5	85.4	83.9	82.1	79.3
Organic fuel, mil. TOE					7219	8034	9300	10102	11419	12249	12873	13098

tury (by 2050) the share of hydrogen-based energy will exceed 50% and become prevailing instead of hydrocarbon-based energy. It seems that such a value is greatly overestimated. In fact, the analysis and prognosis made in the framework of the present study indicate that hydrocarbon-based energy will be still the main source for the world energy sector, however, their share will be more that a one-third of the GEB.

Despite major progress, RESs are only planned to be commonly used and their present share in the GEB is a few percent (1.3% in 2010, according to Table 2). By 2025, its share jointly with biofuel will be 5%, and only then will it be able to be said that hydrocarbon fuels have started to be replaced with RESs and alternative energy sources.

It is well known that replacement of one technology with another occurs in terms of the logistic law [12]. Therefore, the dynamics of hydrocarbon-based energy share in the GEB of the twenty-first century can be described by a descending logistic function like

$$e_c = 0.881\left(1 - \frac{r\exp[k(T-T_0)]}{1 + r\{\exp[k(T-T_0)] - 1\}}\right), \quad (2)$$

where T is the time (in years AD); $T_0 = 1990$ is the time when the use of RESs and biofuel became significant in the GEB. Multiplier 0.881 is explained by the share of fossil fuels in the GEB in 1990 (see Table 2). In order to define parameters r and k, we based our thinking on the following. A thorough analysis of total confirmed resources of coal, oil, and natural gas (by the beginning of the twenty-first century, up to 2006) was made in [13]; additionally, the total energy requirement has been analyzed proceeding from the average energy consumption per capita of 5 TRF (the current standard for the European Union and Japan). It has been shown finally that the confirmed resources will be used up in 75–80 years. As the standard of energy consumption per capita in the twenty-first century is assumed at 2.5 TRF, this period will expand to 160 years. Thus, it can be assumed that fossil fuels will still be in use in 2160, while nearly exhausted (i.e., their share will be about 5%). The five-percent replacement is to come approximately in the early 2020s, when the share of fossil fuels will be about 83%.

In generalizing this information, the parameters of the logistic function can be defined proceeding from the level of 95% fossil fuels used corresponding to 2020 and that of 5% corresponding to 2160. They are $r = 0.05$ and $k = 0.042$. Calculations by formula (2) using these values indicate that the share of fossil fuels will be significant throughout the whole twenty-first century, decreasing to 35% only by its end. Thus, to calculate the total value of the fossil fuels (coal, oil, and natural gas) needed for the scenario to be implemented, the value of total GEB from formula (1) must be multiplied to the coefficient from formula (2):

$$E_c = e_c E_w. \quad (3)$$

As different types of fossil fuels produce different volumes of CO_2 in combustion, the structure of fossil fuel consumption (i.e., the relative shares of coal, oil, and natural gas) should be taken into account when calculating the dynamics of CO_2 emission. The Marland–Rotti method is the most convenient for this purpose; it gives the following value of the general coefficient of carbon intensity [4]

$$c_c = \frac{0.733E_s + 0.586E_l + 0.398E_g}{E_c}, \quad (4)$$

where E_c is the total quantity of hydrocarbon fuels intended for consumption at a set moment of time (in TRF); E_s, E_l, and E_g are consumption values for solid, liquid, and gaseous fuels, respectively (all in TRF).

Since the dynamics of the internal structure of fossil fuel consumption is unknown, the following approximation method can be used. Let us consider the behavior of the coefficient c_c from formula (4) in retrospective and extrapolate it into the future. It is known that in 1900, when coal was dominated fossil fuel, the c_c coefficient exceeded 0.7, which is typical for coal. Then it monotonically decreased down to 0.57 in 2000 (a typical value for oil, which was the main energy carrier in the second half of the twentieth century). Carefully viewing Table 2, one can see that the share of coal has been growing since 2000, while the summarized share of oil and natural gas has dropped; before 2000, the trend was the opposite. Proceeding from this, we suppose that around 2000 the c_c coefficient had its minimal value (about 0.57). It is natural to assume that the coefficient c_c will grow monotonically during the whole twenty-first century, because of the share of coal in the structure of fossil fuels. High growth rates for this coefficient are expected in the 2050s, when natural gas will start slowly decreasing after reaching its peak value. Further, the growth rates for the share of coal in the GEB will unavoidably decrease, as well.

Hence, the coefficient c_c can be approximated quite well by an ascending logistic function with the initial value $c_c^0 = 0.57$ in 2000 and the end point in 2160, when $c_c = 0.99 \cdot 0.733 \cong 0.726$ (one-percent deviation from the extreme value). By 2160, when oil and natural gas will nearly be exhausted and of all fossil fuels only coal remains in relative abundance, the coefficient c_c will naturally tend to the value typical for coal (i.e., 0.733 tons of carbon/TRF). With these data taken into consideration, we derive the following logistic function for describing the behavior of coefficient c_c throughout the twenty-first century:

$$c_c = c_{-\infty} + \frac{a}{1 + r\exp[-k(T - 2000)]}, \qquad (5)$$

where $c_c^0 = 0.57$ at $T_0 = 2000$; $c_{-\infty} = 0.564 = 0.99c_c^0$; $a = 0.169$; $r = 37$; and $k = 0.045$. Proceeding from this, the value c_c^* in 2100 will be 0.683.

Thus, the dynamics of total CO_2 emission into the atmosphere from fossil fuels combustion, with the approximate formula (5) of the total carbon intensity coefficient taken into consideration, can be calculated by the formula

$$C = c_c e_c E_w. \qquad (6)$$

The carbon mass derived by formula (6) can easily be recalculated into the carbon dioxide mass by multiplying by the constant coefficient 3.664.

Assume that a certain part of CO_2 released during fuel combustion is caught and bound using a special technology for further storing in order to reduce CO_2 emissions into the air. For example, if CCS technologies will be intensively introduced now and in accordance with the Blue Map scenario, then CO_2 emission into the atmosphere by 2050 is predicted to be reduced by 19% [3]. The dynamics of reduction in CO_2 emission using CCS technologies can be described by a logistic function, as well. Therefore, in order to take this effect into account, we must multiply the mass of carbon emitted into the atmosphere (see Eq. (6)) by the coefficient

$$k_{CCS} = \frac{2\exp[-\vartheta(T - T_0)]}{1 + \exp[-\vartheta(T - T_0)]}, \qquad (7)$$

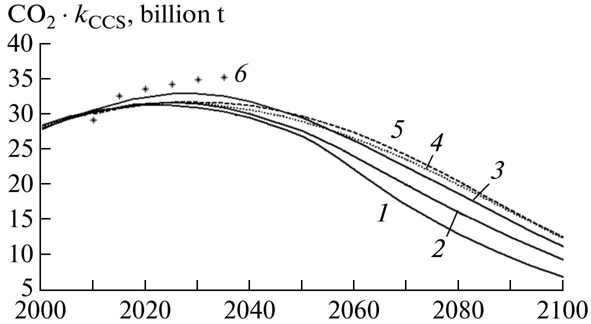

Fig. 3. Dynamics of industrial CO_2 emissions in the twenty-first century, if CCS technologies are used. Numerical designations (*1*)–(*5*) are given in Fig. 1. (*6*) IEA prognosis.

where $T_0 = 2015$, $\vartheta = 0.01$. It is clear that $k_{CCS} = 1$ at $T = T_0$, and $k_{CCS} = 0.81$ at $T = 2050$ (i.e., the decrease fits the mentioned value of 19%). Thus, we have

$$C_{CCS} = k_{CCS} \cdot C. \qquad (8)$$

Calculations show that if a CSS technology is used, the peak of industrial CO_2 emissions will be as early as 2020 (Fig. 3), but will decrease two times or more by the end of the century, fitting the condition of the global climate stabilization. In contrast to this, if a CSS technology is not used, CO_2 emissions will be reduced only 1.5 times, which is insufficient for stabilizing the global climate. The results of calculations indicate the same in the sense that CO_2 emissions cannot be reduced two times by the mid-twenty-first century, as is planned by the Blue Map scenario. Nevertheless, this scenario can be implemented, but the global climate will be stabilized only by the end of the twenty-first century.

Anthropogenic CO_2 emission into the atmosphere takes place not only resulting from industrial activity, but also as a consequence of forest cuts and soil erosion. The effect from forest cuts occurs as follows: the forest biomass decomposes and transports into the atmosphere in the form of CO_2 with a certain delay; the main part of such emissions is produced in tropical regions. Soil erosion is caused by inappropriate agricultural activity. We will assume that the mass of tropical forests is reduced by 0.6%, and the rate of erosion is 0.15% per year [1]. Simultaneously, a certain part of CO_2 is absorbed and stored in the World Ocean and land ecosystems. It is typical that approximately half of anthropogenic CO_2 emissions stably persisted in the atmosphere for a long period in the second half of the twentieth century [1]. Therefore, anthropogenic carbon continuously accumulates in the atmosphere and this process can be described by the formula following from the balance of CO_2 currents for 2000:

$$C_\Sigma = \int_{2000}^{T} C(t)dt - 3.1(T - 2000), \qquad (9)$$

where $2000 \le T \le 2100$. Industrial emissions of carbon $C(t)$ into the atmosphere can be used in this formula as

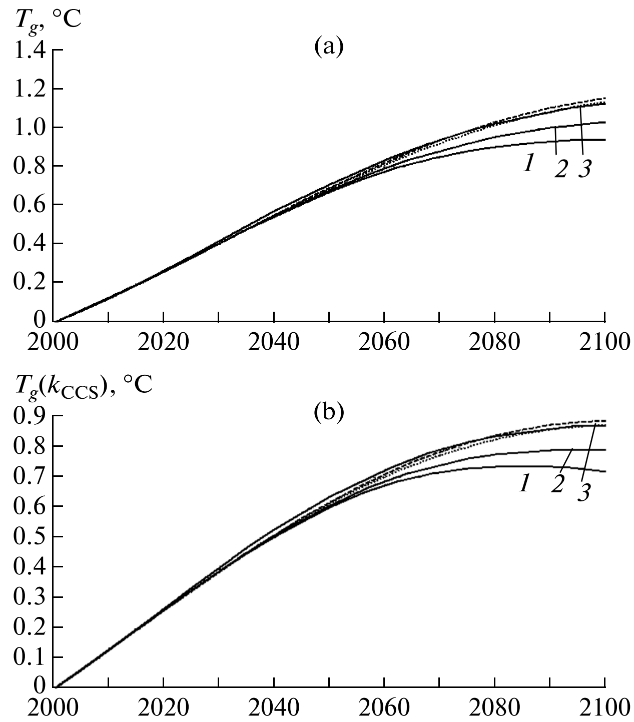

Fig. 4. Deviation of the average global temperature of the near-surface atmosphere in the twenty-first century from the value of 2000 (a) and that if CCS technologies are used (b). Numerical designations (*1*)–(*5*) are given in Fig. 1.

in either Eq. (6) or (8). The latter corresponds to capture and storing of a certain part of CO_2, thereby reducing CO_2 emissions into the atmosphere. Formula (9) is obtained under the assumption of continuous nonindustrial anthropogenic emissions and unchanging CO_2 absorption by oceans and land ecosystems during the whole twenty-first century. Naturally, this is an approximate assumption. In practice, a more convenient way is to take the value of carbon mass accumulated in the atmosphere (z) into account:

$$z = \frac{C_0 + C_\Sigma}{\tilde{C}_0} = 1 + \frac{C_\Sigma}{\tilde{C}_0}, \tag{10}$$

where $\tilde{C}_0$ is the total carbon mass in the atmosphere in 2000 ($\tilde{C}_0 \cong 767$ Gt), and $z = 1$ in 2000.

Finally, when the data on the dynamics of carbon accumulation in the atmosphere in the twenty-first century are available from Eq. (9), we can calculate the temperature change of the near-surface atmosphere. The type of temperature dependence on the CO_2 content in the atmosphere has been found by approximation of empirical data on the basis of different visualizations [14]. We utilize the approximation formula from [1]:

$$T_g = \begin{cases} 2.5\{1 - \exp[-0.82(z-1)]\}, & z \geq 1; \\ -5.25z^2 + 12.55z - 7.3, & z < 1. \end{cases} \tag{11}$$

Here, T_g is the deviation of the average global temperature of the near-surface atmosphere from the modern value (only that caused by greenhouse effect due to industrial CO_2 emissions into the atmosphere); z is the increase in the relative CO_2 (or carbon) content in the atmosphere by Eq. (10). Therefore, the real deviation of temperature of the near-surface atmosphere will be $\Delta T = T_g + T_e$, where T_e is the temperature change caused by environmental factors. The graphs illustrating deviation of the average global temperature of the near-surface atmosphere, T_g, during the whole twenty-first century are presented in Fig. 4.

CONCLUSIONS

The graphs in Fig. 4 show that transition to a new paradigm of energy consumption without using CCS technologies will lead to deviation of average global temperature exceeding the acceptable level of 1°C as early as 2080; in contrast to this, application of CCS technologies with an extending tendency will lead to an increase in the average global temperature by the end of the twenty-first century only by 0.7–0.9°C and to temperature stabilization at that level. If we take into consideration that the average global temperature increased approximately by 1°C compared to that in the pre-industrial epoch, then it is obvious that stabilization of energy consumption per capita in the whole world, along with widespread use of CCS technologies, will reliably help to stabilize temperature deviations.

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