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Reducing Emissions of Trace Greenhouse Gases as an Alternative to Reducing Emissions of Carbon Dioxide: Part I

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Abstract—The prospects for reducing emissions of trace greenhouse gases and pollutants in the power industry and other branches of the economy are considered. Their environmental control potential in the area of reducing the scale of global changes in the climate in the next century is appraised, as is the possibility of decreasing the ecological pressure on the branches of the economy that are responsible for emissions of carbon dioxide, first and foremost, on the power industry.

Lately, two assertions have been widely circulating that can exert a decisive influence on the lines along which many countries of the world, Russia included, will develop.

The first assertion is that humanity, in the course of its economic activities, will certainly increase at an intensified rate the emissions of different substances into the atmosphere, which negatively effect the state of the environment and, first of all, the climate. As a result of this, irreversible changes will take place in nature which can threaten the existence of the biosphere of our planet. This is just the point of view that helped form the anthropocentric approach to studying global changes in the climate that is still dominant in such investigations.

The second assertion is associated with the role of the power industry in these processes. It is conjectured that thermal power stations are the main source of the pollutants that pass into the atmosphere. Thus, thermal engineering is one of the main culprits behind changes in the climate that have been observed and forecasted, whose integral impact on the conditions of life have always been appraised as being negative or even catastrophic.

In Kyoto in 1997, the countries that participated in the Framework Convention of the United Nations on Changes in the Climate signed a Protocol on reducing emissions of greenhouse gases, in which several countries took upon themselves obligations to stabilize, and even to reduce, the amount of carbon dioxide emissions. Russia, in particular, committed itself not to exceed until 2010 the level of CO_2 emissions that was reached in 1990. Evidently, in view of the present decline in production in our country (from 1990 until 1999, consumption of fossil fuel in Russia fell by about 30%, and the production of electricity at thermal power stations decreased by about as much), this objective will be achieved without any difficulty. However, as it was proved in [1] by one of us, even in the rather favorable year 1990, in Russia, the per capita level of energy consumption (8.2 tce/person) was clearly insufficient for sustaining a standard of living that is comparable with that in the developed countries. In [2], the optimal level of per capita energy consumption was calculated; it is determined by the geographical and climatic conditions of our country and is equal to 18.9 tce/person, that is, 2.3 times higher than in the base level (for the Kyoto Protocol) of 1990. Most of the other countries of the world, for which the growth of energy consumption (and accordingly growth of carbon dioxide emissions) is a necessary condition for development, find themselves in a similar situation. Undoubtedly, the industrially developed countries, which have reached saturation of their demands for energy, can reduce the amount of fossil fuel burned without too many difficulties, because of the further increase in the efficiency of their economy and energy conservation technologies. However, in a great many countries, the objective of reducing (and frequently stabilizing) carbon dioxide emissions contradicts their national interests.

Nevertheless, the past ten years revealed many facts indicating that the above assertions are mistakes. First, systems for monitoring the state of the atmosphere since the early 1990s recorded a decrease in the rate of growth of concentrations of almost all the greenhouse components in the atmosphere (here, in addition to carbon dioxide, we have methane, steam, and the trace greenhouse components: nitrous oxide, tropospheric ozone, and the chlorofluorohydrocarbons (CFH)). In Table 1, we find the annual average growth rates of the average global atmospheric concentrations of five greenhouse gases calculated from the data of the Program for the Global Experimental Study of Atmospheric Gases ALE/GAGE/AGAGE [3] and the network of stations of the Laboratory for Monitoring and

Diagnosing the Climate of the National Agency of the United States on the Ocean and the Atmosphere NOAA/CMDL [4] during the last two ten-year periods. Moreover, the concentrations of several substances (methane, CFC-11, CFC-12) became practically stabilized in recent years and, for an entire series of other CFH of the CFC class, they even greatly decreased. Evidently, in the system human being–nature, certain negative feedbacks exist, which, like in the biosphere, retain acceptable conditions for sustaining life.

The objective of our study is to disclose the mechanisms of these feedbacks, to show just how the processes in different branches of human activity enhance the reduction of the anthropogenic load on the environment and what role energy plays in them. Moreover, a problem is raised to determine ways for reducing the scale of future changes in the climate of anthropogenic origin which can also solve other problems that humanity faces (improvement of the cleanliness of the atmospheric air, protection of the biosphere, and others) without changing for the worse the standard of life of a large part of the population of our planet.

SULFUR OXIDES

We many times addressed the problem of evolution of global emissions of sulfur oxides that fall into the atmosphere from several anthropogenic sources; specifically, when burning sulfur-containing fuel (coal and petroleum products) and also in processes in metallurgy, chemical engineering, and the paper-and-pulp industry. In particular, in [5], an appraisal was made for the first time of global anthropogenic emissions of sulfur during the entire industrial period starting from 1800, and a forecast of them was made for the next century. In a later study [6], more exact calculations of sulfur emissions were made for the last ten-year periods, with account taken of progress in nature control technologies in the economically developed regions of our planet, namely, Western Europe, the United States, and Japan, and also the countries of Eastern Europe. In this study, the main trends that appeared in the power industry concerning the control and reduction of SO_x emissions were analyzed.

For these purposes, in the Laboratory of Global Problems of the Power Industry (LGPPI) of the Moscow Power Institute (MEI), databases were created on energy consumption and the emissions of greenhouse gases and pollutants (CO_2, N_2O, NO_x, SO_x, CFH) in different sectors of the economy of 110 countries of the world. To correctly account for the specifics of economic development of different countries, we formed five groups. The main criteria for selection were the demographic and energy indices that characterize the level of development of the countries [1]; specifically, the annual growth of the population and the total per capita energy consumption referred to the optimal one for specified geographical and climatic conditions.

Table 1. Average annual growth rates of atmospheric concentrations of greenhouse gases, % (from the data of ALE/GAGE/AGAGE [3] and NOAA/CMDL [4])

Period, years	CO_2	CH_4	N_2O	CFC-11	CFC-12
1980–1989	0.5	0.9	0.3	4.7	4.8
1990–1998	0.4	0.4	0.2	0.5	1.6

In the database LGPPI that was created for industrial emissions of sulfur, we find countries from all five groups: for the developed countries, this database includes about 85% of the energy consumption of that group; for the new industrial countries, 50%; for countries with a transient economy, more than 95%; for the developing countries, 75%; and for the oil-producing countries, about 60%. Thus, the available information enables us to create a complete picture of the evolution of sulfur emissions from industrial sources for the entire world.

The absolute volumes of annual emissions of sulfur oxides (recalculated for SO_2) when burning fossil fuel in different countries were referred to the amounts of sulfur-containing fuels consumed by them, coal and petroleum, measured in tce. The series of the specific emissions that were obtained allow us to compare the dynamics of environmental losses inflicted by the industry of countries belonging to the different economic groups.

Every group has its own specifics. In the developed countries that consume a large share of the energy and that, accordingly, emit into the atmosphere the main part of the pollutants, a gradual reduction in the specific emissions of sulfur began in the early 1970s. The change for the worse of nature in the industrial areas made it necessary to control and to limit emissions by means of legislation; this was done at first in the United States and then in Japan and several countries of Western Europe. In addition to administrative measures, different economic instruments were resorted to in several countries. In particular, in the countries of Scandinavia, France, and Italy, taxes were levied on emissions of sulfur in thermal engineering and in transport [7]. As a result of introducing different methods of sulfur cleaning of the stack gases in these countries for the last 30 years, the specific emissions of sulfur in burning fuel decreased considerably. The power industry of France was especially successful in this area, which in 1975 had one of the largest coefficients of emissions—35 kg/tce. During the last ten years, this index decreased by almost five times, which ranked France alongside countries having traditionally active environmental control movements such as Finland and Norway. An important role in this matter was the high tax on emissions, which amounted to 30 USD/t of SO_2 (for comparison, in Scandinavia, similar payments are 1.5–4 USD/t of SO_2) [7]. For the region as a whole, an almost linear reduction in the specific emissions of sulfur when burning fuel was noted. It amounted to 18 kg/tce in 1975 and dropped to 10 kg/tce in 1995, while, in the enterprises of thermal engineering, even better results were obtained; the specific emissions during this period decreased by two to three times and, in 1995, amounted to about 5 g/kWh, on average.

For the countries with transient economies, more or less valid information is available for the period since 1980. In the former socialist countries, measures for reducing the sulfur content in the flue gases of power installations were first introduced in the second half of the 1980s. A reduction of the part of the high-sulfur fuels in the energy balance and the introduction of technological methods of sulfur cleaning led to a decrease in the specific emissions in the region under consideration from 23 kg/tce in 1985 to 18 kg/tce in 1990. Unfortunately, the social and economic shocks that the countries with a transient economy experienced in the early 1990s stopped this positive process. The power equipment that had become obsolete together with the shortage of funds for taking measures for cleaning led to a situation in which, today, the mean index for specific emissions of sulfur in the given region (19 kg/tce) exceeds by almost two times a similar value for the developed countries; moreover, we discovered a trend for its increase in the course of the past ten years.

However, in the past few years, the intensification of environmental control activities was observed in several countries of Eastern Europe. For example, in Poland, the Czech Republic, and Estonia, since 1997, ecological taxation of sulfur oxide emissions exists, which has become quite tangible (up to 940 USD/t of SO_2 for emissions above the norm in Poland) [7]. Note that, in spite of favorable changes in the fuel balance of Russia (in the last ten years there has been a changeover to coals having a smaller sulfur content), the lack of technologies for sulfur cleaning of the flue gases in the power industry of the country has led to a situation in which the level of sulfur emissions (about 17 kg/tce), although remaining lower than the average index for the group (about 21 kg/tce), is, nevertheless, unfortunately higher than the world average (16.6 kg/tce) and also the indices of several of the new industrial countries (South Korea) and even the developing countries (India, Turkey).

A group of new industrial countries is now experiencing a stage of intensive growth in the consumption of fossil fuel (at a rate of 5–7% annually) and, accordingly, of progressing pollution of the environment. In the 1980s, changes in the fuel balance of several of these countries (Malaysia, North Korea) led to a certain decrease in the specific emissions of sulfur oxides from energy sources. Other countries of this group (Thailand, South Korea, and others) at the start of the current ten-year period were faced with the necessity of taking urgent measures in the power industry so as not to find themselves in an ecological crisis. For example, in 1995, South Korea adopted a long-term program for environmental control calling for, in particular, reduction of emissions in the power industry. In the past 15 years, for the region as a whole, there was a decrease in specific sulfur emissions when burning fuel: the average coefficient fell from 22 kg/tce in 1980 to 17 kg/tce in 1987, and this trend still exists.

Large specific emissions of sulfur are characteristic for the group of petroleum-exporting countries due to recovery of the sulfur-containing components in extracting and refining the petroleum. Insufficient data and the low specific weight of these countries in world fuel consumption allow us to assign an average coefficient of 25 kg/tce to this group, which corresponds to its value for Saudi Arabia.

High levels of specific emissions of sulfur and their moderate change is typical for the developing countries. For example, in China, the main consumer of fossil fuel in this group of countries, they changed from 26 kg/tce in 1980 to 22 kg/tce in 1990. At present, China, which is experiencing serious problems concerning pollution of the air by industrial emissions, has signed contracts with leading Japanese firms for introducing environmental control technologies in the power industry. This should bring about a substantial reduction in specific emissions of sulfur in the coming ten-year period. At the same time, the fast growth of energy consumption, coal primarily, which is the main energy resource of the developing countries, and the lack of proper environmental control measures in this group, have put this country today in first place in the world as concerns specific emissions of sulfur.

For appraising sulfur emissions from other industrial sources (chemical plants, oil refineries, metallurgical works, and others), we used per capita emission indices for these branches of industry in different countries. In analyzing data for the last ten years, we saw that the average per capita index for annual SO_x emissions for the countries of the first group varies in a rather wide range: from 1 kg/person in Germany to 5 kg/person in the United States and Norway. Today, the former socialist countries have about the same coefficient of about 5 kg/person. Data for the time varying changes of this index have enabled us to make a linear estimate for the decrease in the average per capita emissions in these two groups from 20 kg/person in 1970 to 4 kg/person in 1995. Individual values of these indices for the new industrial and developing countries (considering that no environmental control technologies exist in this region today) allow us to conjecture that sulfur oxide emissions in industrial processes have risen linearly from 0.3 kg/person in 1950 to 1.0 kg/person in 1995.

For the world as a whole, the share of energy sources in the emissions of sulfur is increasing. In 1950, we estimated the share of industrial processes not due to burning of fossil fuel to be 12%; by 1995, it

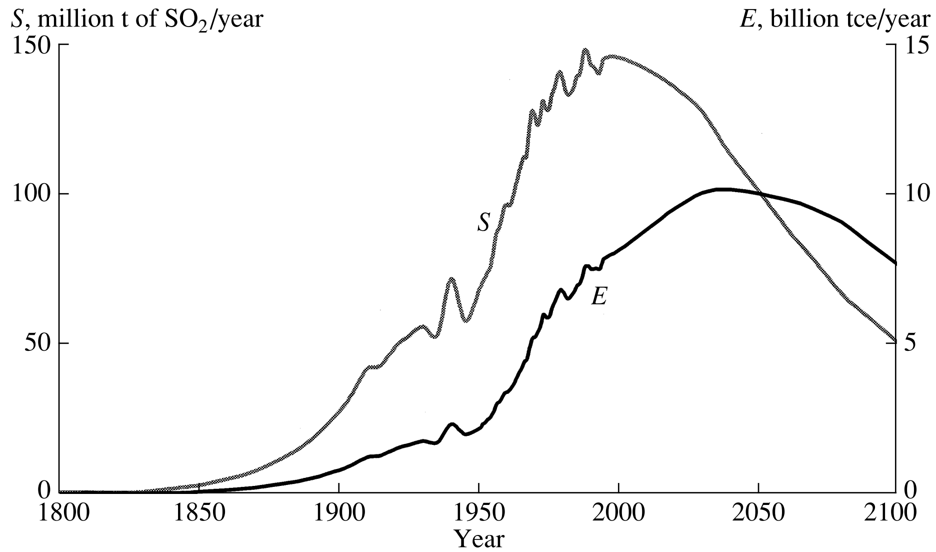

Fig. 1. Consumption of sulfur-containing fuel *E* and emissions of sulfur oxides *S* in the world in 1800–2100.

decreased to 8%. Thus, today, more than 90% of the anthropogenic SO_2 is emitted into the atmosphere when burning fossil fuel, of which 60% comes from thermal power stations. This makes it necessary for the power industry of the world to strictly control and limit emissions of sulfur. Besides, in the current stage of development of world civilization, we see a gradual transition of the main environmental load from the industrially developed countries to the developing ones. In view of the economic difficulties that the latter faces, these countries of the third world will not be able to reduce emissions of sulfur, or other harmful substances, on a global scale without the technical and financial aid of the West. Moreover, there are absolutely no grounds to conjecture that sulfur emissions in the coming decades may greatly grow, as is assumed, in particular, in the scenarios of the Intergovernmental Commission on Changes in the Climate (IPCC) [8, 9], which, as previously, are widely employed as the scientific basis in constructing forecasts for future changes of the climate.

Our basic forecast for changes in the specific emissions of sulfur oxides when burning coal and fuel oil in different regions assumes that a trend for their decrease will continue to exist. We can expect rather high rates of reduction of specific emissions in the coming decades as a result of introducing cleaning technologies; by the middle of the 21st century their total effect will fall as a result of the greater role of coal in the fuel balance of the world. These processes will apparently be typical for all of the groups of countries considered. Estimates of the specific emissions of sulfur oxides for different kinds of economic activity in the 21st century were used in constructing the forecast for global anthropogenic emissions of SO_x into the atmosphere in the period until 2100. The results obtained are presented in Fig. 1 together with the base forecast [10] on the amount of sulfur-containing fuel (coal, oil) that is burned.

As we see from the figure, right up to the 1970s, sulfur emissions grew at the same rate as coal and oil consumption in the world. In the last 30 years, the introduction of environmental control technologies substantially reduced this growth and presently has stopped it. The current period of stabilization of emissions will not last for a long time; in the forthcoming years, it will be replaced by their global decrease, and this process will take place on the background of a growth in the amount of coal and oil that is burned (until 2040) and of the continuing growth of the population. Until 2030, this decrease will be determined mainly by the actions of the economically developed countries; starting from the second half of the 21st century, the results of environmental policy in the developing countries and the global decrease in fossil fuel consumption (as the expected depletion of oil resources will take place) will begin to tell. In accordance with this forecast, we should expect by the end of the 21st century an almost threefold reduction in world emissions of SO_x (to 50 million tons of SO_2 annually in contrast to 144 million tons of SO_2 in 1995). These estimates are close to the base scenario of the World Energy Council (WEC) and are several times less than a similar scenario of the IPCC, which completely ignores the use of sulfur-cleaning technologies in the world (see Table 2).

NITROGEN OXIDES

Estimates of global emissions of nitrogen oxides during the entire industrial period (starting from 1800) and a forecast for these emissions in the 21st century were worked out at the LGPPI of MEI and are presented in [12]. Here, a description is given of the database (DB) on NO_x emissions that are created when burning fuel, in other production processes, in agriculture and in forestry, and when recovering wastes; this database used numerous statistical sources for more than 50 countries that cover a period from 1965 until the present time. Going over to specific emissions of NO_x when burning fossil fuel enabled us to determine the influence of changes in the fuel balance and the introduction of environmental control technologies in the power industry and other branches of the economy on reducing the negative impact of these emissions on the environment. In our study, we briefly noted the main trends in the development of the main source that forms nitrogen oxides, specifically, processes of burning fuel; also, an estimate is given of world emissions of another nitrogen compound that plays an important role in changes in the environment, namely, nitrous oxide N_2O.

After 1970, when the Amendments to the Clean Air Act were adopted in the United States, the first code of laws that put the state of the atmosphere under governmental jurisdiction, all the economically developed countries time and time again revised their environmental control legislation to make it stricter. On average, during the past 15–20 years, the maximal norms on nitrogen oxide emissions from stationary sources were reduced by more than 1.5 times. In addition, in several countries of Western Europe (France, Italy, Spain, Sweden) and Eastern Europe (the Czech Republic, Poland, Estonia), ecological taxes and payments for these emissions were introduced. These administrative and economic measures led to a situation in which, in 1994, the average specific emissions from burning fossil fuel fell with respect to those in 1980 as follows: in France by 50%; in Germany by 30%; in the United States and the Netherlands by 20%; and in Russia by 5%. It was established that environmental control technologies made a substantial contribution to reducing specific emissions (by more than 10% in the period 1970–1995) in the group of industrially developed countries alone. Here, the greatest effect was achieved in thermal engineering, in which, for example, NO_x emissions at thermal power stations decreased by 1.5 to 2.0 times with respect to electricity generation in this period. In the group of countries with a transient economy to which Russia belongs, the 5% reduction in specific emissions was mainly due to an increase in the share of gas in the fuel balance, whereas the introduction of air control technologies in the early 1990s was held back due to the economic crisis that the countries of the region suffered.

Table 2. Different forecasts of global anthropogenic emissions of sulfur oxides, million t

Author, source	Year			
	2000	2025	2050	2100
IPCC 1982 [8], scenario IS92a	178	240	308	296
WEC 1993 [11], scenario B	–	132*	–	–
N.Yu. Kudryavtsev *et al.* 1995 [5]	170	164	136	30
Our data	145	135	100	50

* Data for 2020 (without account of nonenergy sources comprising about 11% of all the emissions).

In the other groups, the changes in the specific indices were very small and were determined only by the type and quality of the fuel that was used; here, the first experiments on equipping enterprises of the power industry with technologies for suppressing the formation of NO_x were made in the last few years. Based on the concept of overtaking development (in which all countries pass in succession through the same stages of technological development), we succeeded in extrapolating trends that will come about in the 21st century. In accordance with our base forecast, the specific emissions of nitrogen oxides (here and henceforth recalculated for NO_2) from burning fossil fuels in the course of this period will decrease globally from 8.5 to 7.0 kg NO_2/tce, on average, mainly as a result of the progressive introduction of air control technologies. Here, starting from about the middle of the century, the rates of this decrease will become somewhat less due to the greater share of coal (having the highest coefficient of nitrogen emissions) in the world fuel balance. Using the data of the forecast for the development of global energy [10], we obtained the volume of gross world emissions of NO_x as a result of burning fossil fuel; they are presented in Fig. 2 together with estimates of NO_x emissions from other kinds of anthropogenic activities.

A comparative analysis of data on N_2O and NO_x emissions for the countries of Western Europe and the United States was made in order to estimate the emissions of nitrous oxide N_2O coming from energy sources. The ratio of emissions of these substances was found to be 0.014 (that is, for every 1000 t of NO_x there are 14 t of N_2O), which agrees well with the results of foreign field investigations of the composition of the stack gases at power installations. The amounts of nitrous oxide emissions in burning fossil fuel, which were calculated using this coefficient through NO_x emissions, are presented in Fig. 3.

The method of A. Bouwman *et al.* [13] was employed for calculating emissions of nitrogen compounds as a result of changes in land use (deforestation, plowing of farm lands, burning of plant waste). This method relates the emissions of CO_2, NO_x, and N_2O from these sources. In accordance with this method, there are about four tons of nitrous oxide and eight tons of nitrogen oxides for every thousand tons of carbon dioxide that pass into the atmosphere as a result of deforestation. Similar figures for farm lands are one and four tons. For the period 1800–1960, we used the data of R.Houghton *et al.* [14] on biotic emissions of carbon. An estimate of future emissions is supported by the base forecast of V.V.Klimenko *et al.* [10] on

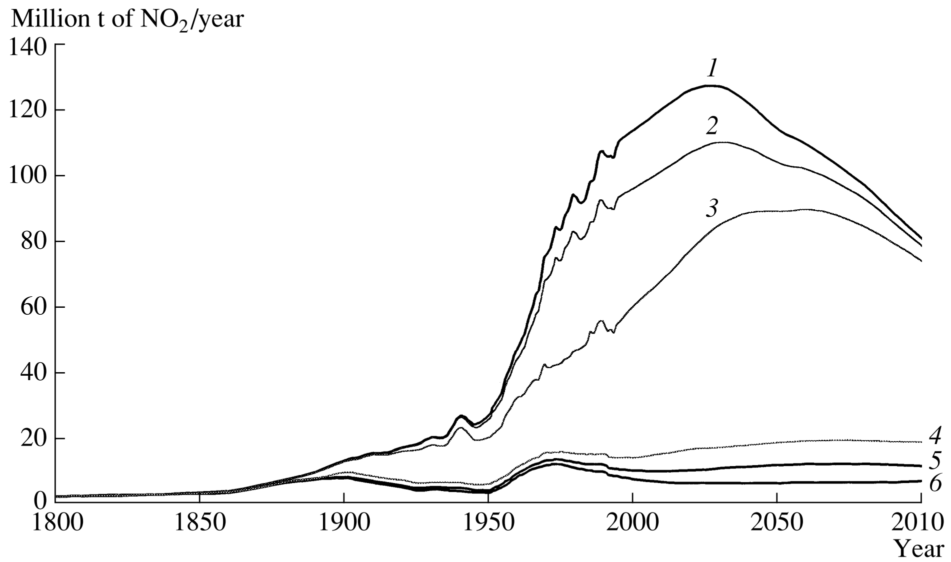

Fig. 2. Global emissions of nitrogen oxides NO_x (recalculated for NO_2) in the period from 1800 to 2100. When burning: (*1*) gas; (*2*) fuel oil; (*3*) coal; (*4*) biomass; fuel from other sources: (*5*) industry; (*6*) agriculture and forestry.

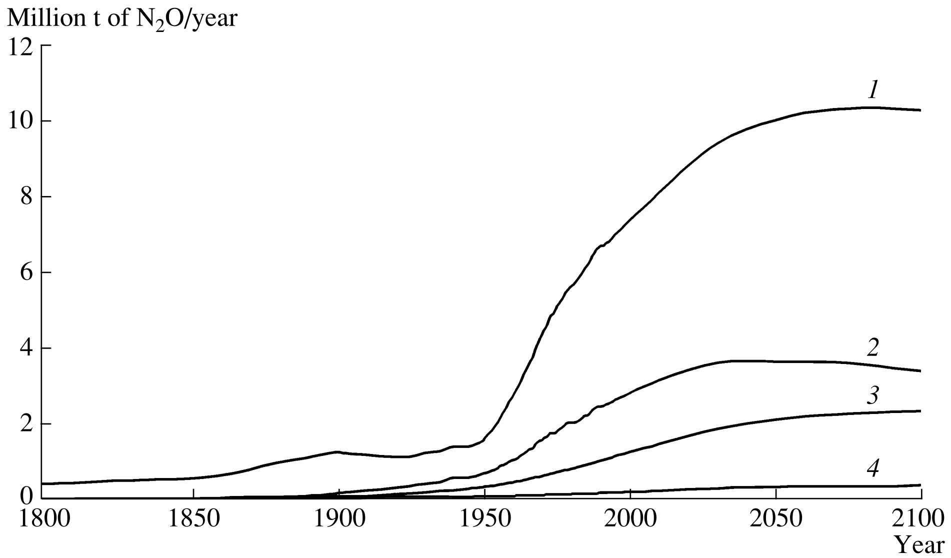

Fig. 3. Global emissions of nitrous oxide N_2O into the atmosphere for different kinds of human activity. (*1*) Agriculture and forestry; (*2*) burning fuel; (*3*) other production processes; (*4*) recovery of waste.

changes in land use and considers as being realities the stabilization that has appeared of areas of cultivated lands in the world and also the trend to recover the area of moderately felled tropical forests and to reduce the rates of their felling. The calculated volumes of wastes from these sources are also presented in Fig. 3.

A large part of the total emissions of N_2O comes from agriculture, in using mineral nitrogen fertilizer and in caring for the livestock. An analysis of world data was made by the Food and Agricultural Organization of the United Nations [15] in estimating and forecasting emissions of nitrous oxides from these sources on the basis of the per capita amount of fertilizer that is used and the livestock population. This analysis showed that the first index, after intensive growth in the period 1960–1980, has become nearly stabilized in recent years, and its course in time is well described by the logistics curve. At the same time, the increase in the livestock population noticeably lagged behind the growth in the population of the world, while the rise in the specific per capita consumption of the products of livestock remained constant. Evidently, further development of agricultural technologies will lead to gradual stabilization of this index, as well, at a level that ensures

Table 3. Different forecasts for global anthropogenic emissions of nitrogen oxides, million t

Author, sources	Year			
	2000	2025	2050	2100
IPCC 1992 [8], scenario IS92a	122	174	210	273
WEC 1993 [11], scenario B	–	89*	–	–
Our data	114	126	114	87

* Data for 2020 (without account of non-energy sources comprising about 10% of all the emissions).

Table 4. Different forecasts for global anthropogenic emissions of nitrous oxides N_2O, million t

Author, source	Year			
	2000	2025	2050	2100
IPCC 1992 [8], scenario IS92a	8.6	11.8	13.0	13.7
Results of our study	7.5	9.3	10.3	10.6

the main needs of the population for foodstuffs, which has already been reached today in quite a few countries. The emissions of nitrous oxides from this source were calculated using the results of Bouwman *et al.* [13], which showed that the following are emitted into the atmosphere in the form of N_2O: about 2% of the nitrogen contained in the mineral fertilizers and 0.5% of that in the wastes from caring for the livestock. The amounts of emissions calculated on the basis of these coefficients are also shown in Fig. 3.

The values of the specific emissions from the above-mentioned database were used in estimating the amount of emissions of nitrogen compounds in industrial processes that do not involve the burning of fuel. In the chemical- and petroleum-refining industries, about twice as much NO_x is formed than nitrous oxide N_2O, in contrast with the power industry, where this ratio is 1.0 : 0.014 = 70.

In Fig. 2, we find the results of calculations of total volumes of NO_x emissions for the world. For these substances, small changes in their emissions in the 19th century and intensive growth of these emissions during the greater part of the 20th century are typical. In the last few decades, the growth rate of emissions was seen to decrease; this is due to stabilization of the consumption of material resources and introduction of environmental control technologies in the power industry and also in several other branches of industry. Our calculations give us grounds to expect a reduction in NO_x emissions that will begin in 2020–2030, when they will attain their maximal value of 130 million tons of NO_2 annually, to about 90 million tons by the end of the 21th century. All of the decrease in emissions in the second half of the 21st century will be in the energy sector. The share of other sources, in which nitrogen oxides are formed, will remain at a level of 10%. The forecast that is presented gives a much more moderate value than does the scenario of IPCC IS92a "business as usual" [8], which frequently, without due substantiation, is used for estimating future ecological situations (174 and 273 million tons of NO_2 for 2025 and 2100, respectively; see Table 3). This scenario, in essence, ignores the existence and use of efficient technologies for suppressing the formation of nitrogen oxides and also their reduction in the stack gases of power installations and in transport and also the use of such technologies in the developing countries, which will grow gradually.

As we see from Fig. 3, in the course of one and a half centuries (1800–1950), there was a small growth in N_2O emissions determined in the 19th century in the main by greater activity in agriculture, and from the beginning of the next century, by the development of industry. By 1900, the volume of total emissions of nitrous oxides had reached 1.3 times the level of 0.5 t/year at the beginning of the 19th century; afterwards, throughout the next 50 years, this level remained practically unchanged.

During the last 50 years, the anthropogenic emissions of nitrous oxides increased by more than four times, from 1.7 million tons in 1950 to 7.4 million tons at present. These values fit in well in the interval of estimates in [9, 13]. In accordance with our estimates for the coming 20–30 years, the emissions of this greenhouse gas will increase by almost another 1.5 times and will exceed the value of 11 million t/year at the end of the first half of the 21th century. In the second half of this century, a decrease in emissions in the power industry will begin, due to the reduction in the share of fossil fuel in the world energy balance and also to the wider introduction of environmental control technologies. By the end of this century, anthropogenic emissions of nitrous oxides into the atmosphere will amount to about 10 million t/year, which is 40% higher than the current level. The main scenario of IPCC IS92a [9] envisages a much higher level of these emissions in 2100; they will be practically two times higher than the current volume, rising to 13.7 million t/year (Table 4). This is mainly due to the supposition of substantially greater emissions in agriculture (about 10.7 million t/year against our level of 7 million t/year), including the results of deforestation which, apparently, will stop at the beginning of the 21 century.

CONCLUSION

(1) The current stage in the development of civilization, which may be characterized as the final phase of global industrialization, is accompanied by a substantial decrease in the growth rates of consumption of the main material resources (energy, ferrous and nonferrous metals, fertilizers, the products of forestry and agriculture, and others). This is due to two main factors: saturation of the demand in the economically devel-

oped countries and growth of the efficiency of the world economy.

(2) The introduction of environmental control technologies, the higher efficiency of production, and the stiffer legislation on environmental control have already led to a substantial decrease in the specific volume of emissions of greenhouse gases and pollutants per unit of production and consumption of material resources (in particular, per unit of electricity produced at thermal power stations) and also per capita.

(3) About 90% of the total amount of SO_x and NO_x passes into the atmosphere as a result of burning fossil fuel; here, the share of thermal power stations amounts to 60% and 30% of these emissions, respectively. Today, the share of energy sources in anthropogenic emissions of N_2O amounts to only 20%.

(4) On the basis of the historical-extrapolational approach to studying the development of different branches of the world economy and an analysis of the above trends, forecasts of world emissions of sulfur and nitrogen oxides were made for the period until 2100. In accordance with our base forecast, if present-day trends in the global power industry and in other branches of the economy will continue, already at the outstart of the 21 century, global emissions of sulfur oxides from industrial sources will begin to decrease; by the middle of the century, this will be the case with nitrogen oxides; and by the end of the century, with nitrous oxides.

(5) A comparison of the results obtained with the data in the studies of IPCC showed that the forecasts of this scientific group for anthropogenic emissions of all the components of the atmosphere investigated in this study are clearly overestimated and do not account for the trends that have arisen in the last decades concerning the dynamics of global energy consumption and the introduction of environmental control technologies.

In the final part of our work, which will be published in the forthcoming issues of *Teploenergetika*, we will present our estimates of emissions of the chlorofluorohydrocarbons and also calculations of changes in the chemical content and the thermal radiation balance of the atmosphere that are associated with anthropogenic emissions of the compounds under study and their influence on the global climate.

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