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Climate and Energy*

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Abstract

The paper is devoted to the analysis of climate change issues and the transition to renewable energy sources. The features of the current climate situation are associated with a general increase in the average global temperature as a result of an extremely high concentration of carbon dioxide (CO_2) in the atmosphere, the amount of which is increasing and posing a threat to the stability of the global ecological system as a whole. Taking into consideration the fact that the main share of CO_2 emissions is accounted for by energy consumption (which experienced over the entire timeline of history transitions from one type of energy resources to another – from biomass to coal, from coal to oil and from oil to natural gas), the authors analyze the possibilities of transitioning to renewable energy sources (RES) forecasted to take place by the second half of the 21st century. They carry out mathematical modeling of this transition with various scenarios for the future of the fuel and energy balance in the 21st century. For this, the authors have developed a specialized mathematical model that takes into account current trends in energy consumption based on the data from the largest energy companies and international organizations in the energy sector, such as BP, Equinor, Shell, International Energy Agency (IEA), International Renewable Energy Agency (IRENA), and others. Three scenarios

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for the increase in the average global temperature of the surface atmosphere in the 21st century are proposed: the conservative scenario, the ambitious scenario, and the Net Zero scenario. The conservative scenario assumes that government policies, technologies and social preferences continue to evolve in the same way as in the recent past. The ambitious scenario envisages the introduction of measures leading to a significant reduction in carbon emissions from energy use, which in turn makes it possible to limit the increase in global temperature in the 21st century. The Net Zero scenario, which the authors consider the optimal one, assumes that the measures proposed in the ambitious scenario are complemented and reinforced by significant changes in the behavior and preferences of society. The paper details modern energy-efficient technologies and methods of using renewable energy sources, the implementation of which is envisaged in the framework of the optimal Net Zero scenario.

Keywords: *climate, energy, climate change, energy transition, energy resources, renewable energy, ecological system, future scenarios, conservative scenario, ambitious scenario, Net Zero scenario.*

1. Current Situation

Since 1850, the concentration of carbon dioxide in the atmosphere has increased significantly, from typical for the pre-industrial period 280 ppm and observed for hundreds of years, to 421 ppm at present, *i.e.* more than 50 %, which significantly contributed to the climate warming (NOAA 2022). Two-thirds of global warming have been caused by the increase in the concentration of CO_2 in the Earth's atmosphere in the 19th and 20th centuries. These figures are substantiated by physical measurements over the past 150 years of both the average world temperature of the surface atmosphere and the growth of CO_2 concentration in the Earth's atmosphere (IPCC 2014, 2021). Carbon dioxide is constantly accumulating in the Earth's atmosphere, and its emissions are currently at their peak (British Petroleum 2021; IEA 2020a, 2020b, 2021a, 2021b, 2021c). According to the World Meteorological Organization, the average global temperature in 2021 was 1.2 °C higher than the pre-industrial level of +14 °C, which is a direct consequence of anthropogenic activity (WMO 2021). Climate change has become one of the most pressing issues for the mankind. The effects of climate change are universally observed.[1] Global ocean temperatures are rising, glaciers are melting, sea levels are rising (NOAA 2020), and extreme weather is becoming more and more severe and destructive. Droughts,

[1] This issue has been in the focus of attention of many recent reports to The Club of Rome (see, *e.g.,* Randers 2012; Maxton *et al.* 2016; Wijkman and Skånberg 2017; Randers *et al.* 2018; von Weizsäcker and Wijkman 2018; Berg 2019).

wildfires, floods, hurricanes have become more frequent. During 2020 alone, more than 415 natural disasters occurred in the world (Statista 2022). Natural disasters kill an average of 60,000 people a year worldwide (Our World in Data 2021). The rate of degradation of arable land is 30–35 times higher than historical rates (UN 2021; Kovaleva 2023) more territories are desertified, and crop yields are decreasing (World Bank 2014; IPCC 2019; UN 2016; Ortiz-Bobea *et al.* 2021) due to the depletion of water reserves among other things. According to Welthungerhilfe, 811 million people were affected by hunger in 2020 (Welt-hungerhilfe 2021), which could intensify regional tensions and exacerbate existing conflicts. Climatologists have shown that if CO_2 emissions are not reduced by two or three times by the middle of the century, then warming cannot be kept at the level of 2 °C, and by the end of the 21st century it will exceed 3–4 °C, which will lead to catastrophic consequences (IPCC 2021), so urgent action is needed.

In 2015, the Paris Agreement was adopted, the goal of which was to keep the warming at 1.5–2 °C (United Nations 2016). To achieve this goal, according to estimations of the International Panel on Climate Change, it is necessary to reduce energy emissions of greenhouse gases into the atmosphere by three times compared to 2019 emissions (33.3 Gt) by about 2050 (1.5 °C) or by 2070 (2 °C) (Allen *et al.* 2018).

Carbon dioxide emissions can be natural or anthropogenic. Natural emissions come from the oceans, during volcanic activity, natural fires and in the process of decay of organic materials. Previously, such emissions were absorbed through natural processes, and balance was maintained. As a result of anthropogenic activities (burning of fossil fuels, deforestation, agriculture, *etc.*), the balance has been disrupted (*Ibid*.)

Currently, about 15–20 % of CO_2 emissions are generated by the 'agriculture, forestry and land use sector' (Our World in Data 2020; World Resources Institute 2021). Soils developed by humans became sources of carbon dioxide. An increase in global temperature causes more intense release of carbon dioxide from soils. Every year, about 60 petagrams of CO_2 enter the atmosphere from soils due to 'breathing' (*Ibid.*).

Of course, global levels of industrial CO_2 emissions into the atmosphere are significantly affected by energy consumption (which has already reached 14 billion tons of oil equivalent per year [British Petroleum 2021]), as well as the structure of the global fuel and energy balance. The contribution of energy consumption to global CO_2 emissions today exceeds 73 % (Our World in Data 2020). Throughout the historical period, the structure of energy consumption has been constantly changing, there have been so-called 'energy transitions' to new models, from the predominant use of one resource to another (Smil 2012).

Three types of such transitions are known in history – from biomass to coal, from coal to oil, and from oil to natural gas (ERI RAS 2019). At the moment, the shares of energy sources in world energy consumption are distributed as follows: oil – 31.2 %, natural gas – 24.7 %, coal – 27.2 %, nuclear energy – 4.3 %, hydropower – 6.9 %, renewable energy sources – 5.7 % (British Petroleum 2021). In the 21st century, the fourth energy transition to renewable energy sources is forecasted.

The great energy transition from the use of currently dominant fossil hydrocarbons to predominantly using renewable energy sources (RES), when the share of RES in the total energy balance exceeds 40 %, may take place in the 2060s.

2. Possible Scenarios for Further Development of the Situation

In order to forecast the upcoming energy transition and to choose an optimal scenario for the development of the fuel and energy balance in the 21st century, a specialized mathematical model has been developed (see Malkov *et al.* 2023). To develop and verify the model, the current trends in energy consumption were studied, and statistical data on energy consumption and the fuel and energy balance provided by the following organizations were analyzed: BP (British Petroleum 2021; BP 2020), International Energy Agency (IEA 2020b, 2021c), International Renewable Energy Agency (IRENA 2020, 2021), Intergovernmental Panel on Climate Change (IPCC 2014, 2018, 2021), World Nuclear Association (WNA 2020), World Energy Council (WEC 2019), Organization of the Petroleum Exporting Countries (OPEC 2021), Equinor (2020, 2021), Greenpeace (2015), DNV GL (2020, 2021), Shell (2013, 2018), Skolkovo (ERI RAS 2019), REN 21 (REN21 2019, 2021), ExxonMobil (l 2019, 2021) and others.

The proposed mathematical model allows forecasting changes in the average global temperature of the surface atmosphere in the 21st century (Akaev and Davydova 2020, 2021a, 2021b) in accordance with the following calculation mechanism:

– calculation of various population growth scenarios (see Korotayev, Malkov *et al.* 2023, as well as, *e.g.,* Akaev and Sadovnichy 2010; Akaev *et al.* 2012; Kapitza 2006);

– calculation of scenarios for energy demand dynamics (Akaev 2012, 2014a, 2014b);

– forecast of the energy consumption structure by types of energy sources (coal, oil, gas, renewable energy sources, nuclear energy, hydropower) (Akaev and Davydova 2021a, 2021b);

– calculation of the dynamics of CO_2 emissions into the atmosphere during the combustion of hydrocarbon fuels, taking into account structural changes in the consumption of organic fossil fuels (coal, oil, gas), as well as the use of carbon capture and storage technologies;

– calculation of the dynamics of CO_2 accumulation in the atmosphere, taking into account non-productive CO_2 emissions (due to deforestation and soil erosion) and the absorption of part of the emissions by oceans and terrestrial ecosystems;

– calculation of the change in the average global temperature of the surface atmosphere based on the Tarko technique, which relates the dynamics of the deviation of the average global temperature to an increase in the dynamics of carbon (carbon dioxide) accumulation in the Earth's atmosphere.

Taking into account the statistical data from 1960–2021 and the trends observed in recent years in the field of energy consumption, as well as the implemented energy-efficient technologies, three scenarios of the increase in the average global temperature of the surface atmosphere in the 21st century have been specified and calculated, including the conservative scenario, the ambitious scenario, and the Net Zero scenario. The conservative scenario assumes that government policies, technologies and social preferences continue to evolve in the same way as in the recent past. The ambitious scenario envisages the introduction of measures that would lead to a significant reduction in carbon emissions from energy use, which in turn makes it possible to limit the increase in global temperature in the 21st century.[2] The Net Zero scenario assumes that the measures proposed in the ambitious scenario are complemented and reinforced by significant changes in the behavior and preferences of society. The dynamics of changes in the structure of the global fuel and energy balance for the 21st century under the conservative scenario, the ambitious scenario, and the Net Zero scenario is shown in Figs 1–3:

[2] On the global development scenarios in economic, social, and political dimensions that are relevant for the issue of preventing catastrophic climatic changes see Grinin, Grinin, and Malkov 2023a; Grinin, Grinin, and Malkov 2023b; Grinin, Malkov, and Korotayev 2023; Grinin, Grinin, and Korotayev 2023; Grinin and Korotayev 2023; Korotayev, Shulgin *et al.* 2023.

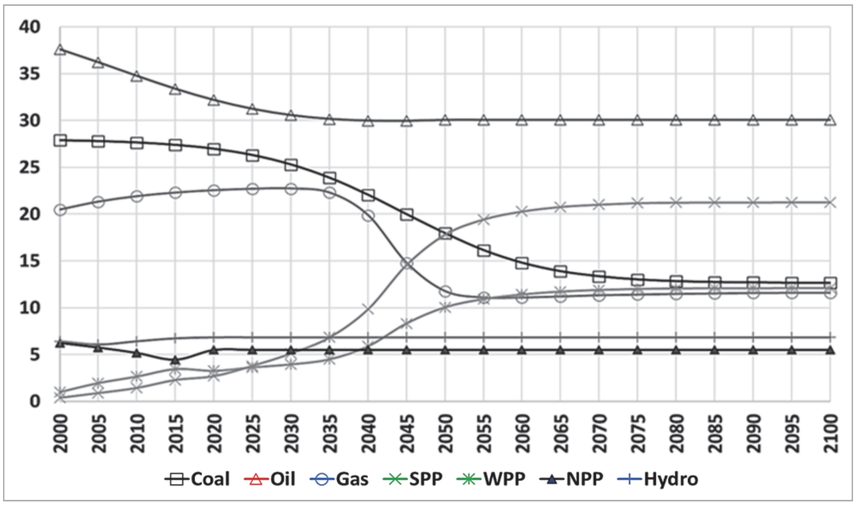

Fig. 1. Dynamics of changes in the structure of the global fuel and energy balance for the 21st century (for Coal, Oil, Gas, Solar Power Plants (SPP), Wind Power Plants (WPP), Nuclear Power Plants (NPP), and Hydro energy) under the conservative scenario

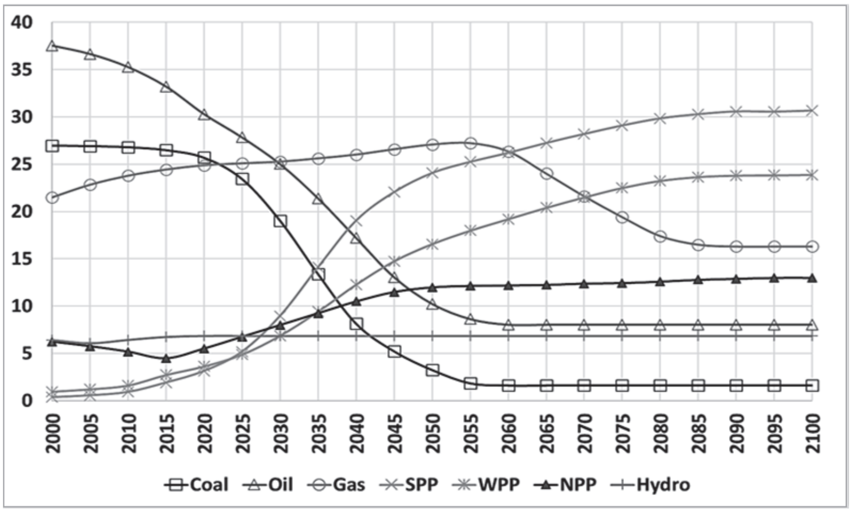

Fig. 2. Dynamics of changes in the structure of the global fuel and energy balance for the 21st century under the ambitious scenario

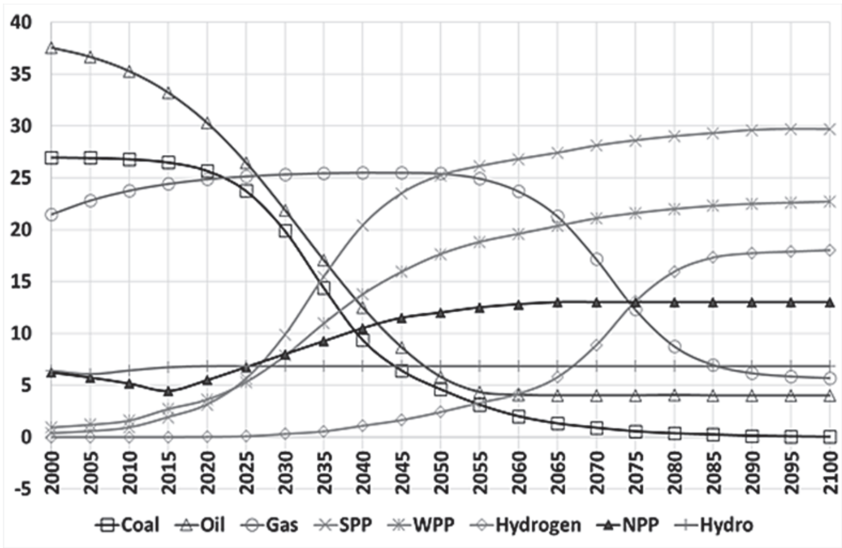

Fig. 3. Dynamics of changes in the structure of the global fuel and energy balance for the 21st century under the Net Zero scenario

With the help of the developed model, the optimal scenario (the Net Zero scenario) has been found, the implementation of which will meet the requirements of the Paris Climate Agreement to keep global warming at the level of 1.5–2 °C compared to the pre-industrial level. The Net Zero scenario assumes (Akaev and Davydova 2021a, 2021b):

– the use of energy efficient technologies (Randers *et al.* 2018);

– wide use of hydrogen as an energy carrier;

– further development of renewable energy sources;

– widespread use of chemical technology for the capture, sequestration, and storage of carbon dioxide.

There are many energy-efficient technologies available that can help to reduce carbon emissions (see Grinin and Grinin 2023). An example of significant savings in energy consumption is the widespread use of intelligent digital technologies for energy management. The data collected by 'smart sensors' is key for the energy consumption system, the operation of which is optimized by intelligent digital devices through adjusting supply and demand in real time.

'Smart grids' based on data from producers and consumers make it possible to synchronize supply and demand in real time in an optimal way (ERI RAS 2019). They can regulate the flow of electricity from one region to another, taking into account prevailing weather conditions.

Currently, 'smart energy consuming devices' are also being developed (*Ibid.*). The consumer installs equipment to optimize the modes of acquisition of electric energy based on the needs and load of the system. Thus, it becomes possible for the consumer not only to receive energy, but also to give it to the network, making profit.

Currently, 26 % of global CO_2 emissions are generated by the transport sector (IEA 2019). Vehicles driven by electric motors can solve the problem of such emissions. Hybrid electric vehicles have already achieved 65 % greater fuel efficiency than gasoline-powered vehicles (Vorrath 2015). Gasoline-powered vehicles consume four times more energy than fully electric vehicles (Vorrath 2015; Energy Efficiency Day 2020; Virta 2021). In 2019, more than two million new electric vehicles were sold worldwide (IEA 2021a), but this number needs to be increased significantly.

The use of various energy-efficient technologies for the home should also be expanded. For example, thanks to solar panels, annual greenhouse gas emissions can be reduced by more than 1,350 kg within a single household. Using clean, renewable solar energy to power a million homes can reduce carbon dioxide emissions by 4.3 million tons per year (NCAT 2021). Wind generators can be used to generate direct or alternating current with its further conversion into heat by means of heat pumps in order to heat buildings and water. 'Cold Roofs' help reduce air conditioning costs in summer by 15 %. Due to the high efficiency of LEDs and low power consumption, LED lighting can save up to 80 % of energy (Janeway 2015). Considering that about 20 % of heat loss from a home occurs through poorly insulated windows, installing energy-efficient double or triple glazed windows has the effect of reducing heating costs during cold seasons and air conditioning in hot seasons. According to the Lawrence Berkeley Laboratory, between 5 and 10 % of all household energy consumption is spent on standby appliances, which ultimately contributes up to 1 % of global carbon dioxide emissions (Meier 2021). Smart extension cords can turn off unused appliances, thus reducing energy consumption. Programmable room thermostats allow saving up to 30 % of energy, since the heating of the premises is not carried out continuously, but at programmable time intervals. ENERGY STAR certified appliances will use 10–50 % less energy each year than inefficient equivalents (HomeAdvisor 2021).

Thus, one of the important keys to success is the development of a wide variety of energy-saving and energy-efficient technologies and traps for CO_2 and other pollutants, and not just attempting to replace carbon energy technologies with green ones (see Grinin and Grinin 2023).

Although hydrogen is widely used today, it is far from reaching its full potential as an energy source. A lot of research is required to provide cheap and sustainable clean hydrogen energy derived only from renewable energy sources (hydropower, solar panels, or wind farms) without emissions or at least using carbon capture and storage (CCS) systems, which help avoid carbon emissions into the atmosphere. Green hydrogen is produced by electrolysis, where electricity is generated only from sources with zero carbon content. This technology can significantly reduce CO_2 emissions, but it is currently too expensive (IRENA 2019). In 2015, the production cost of 1 kg of green hydrogen was US$ 6 (Casey 2021). Over the past five years, the cost of producing green hydrogen has dropped to US$ 3 per kilogram (S&P Global 2021). For comparison, one kilogram of gray hydrogen produced from carbon sources costs US$ 1.80, blue hydrogen (using CCS technology) costs US$ 2.40. The US Department of Energy expects that in 2025 the cost of producing green hydrogen will drop to US$ 2 per kilogram and in this case green hydrogen can become competitive with other non-renewable sources (EIA US 2021). The European Union, Japan, South Korea, Australia, the Netherlands, Norway, Chile and Canada have already developed their hydrogen strategies. The European Union has set itself the goal of increasing the capacity of electrolyzers to 6 GW by 2024 and to 40 GW by 2030 (Patel 2021).

Today, the share of green hydrogen is less than 1 % of the total hydrogen produced. Exponential growth (up to 60 % per year) in green hydrogen production is expected in the coming decades (Holbrook 2021). In general, most reports assume that hydrogen produced from renewable energy sources only will account for 10–25 % of energy consumption in the 21st century (Buli 2021; Flowers 2020; Scott 2020). Calculations based on the developed model show that green hydrogen will reach 18 % of energy consumption in the 21st century (see Fig. 4).

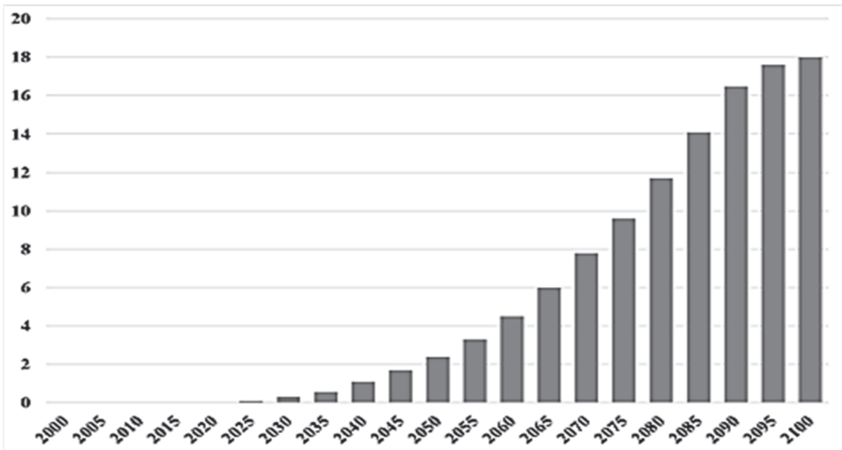

Fig. 4. The share of green hydrogen in the structure of the global fuel and energy balance for the 21st century under the Net Zero scenario (calculated by authors)

Also, widespread use of chemical technology is required to capture, sequestrate, and store carbon dioxide, both in the process of burning hydrocarbons in power plants and directly from the atmosphere, which is reflected in the calculations by the model. However, this path is hindered by the high cost of technology.

Evidently, significant investments are required to successfully implement the Net Zero scenario. Unfortunately, investment flows are currently directed toward those areas that bring maximum profit, rather than those that benefit society in the long term (Randers 2012; Maxton *et al.* 2016). Only when there is compelling evidence of damage is the money spent on reducing the negative effects of climate change that could have been prevented.

The results of forecast calculations of the dynamics of the reduction of anthropogenic carbon dioxide emissions into the atmosphere in the 21st century under the conservative, ambitious, and the Net Zero scenarios are presented in Figs 5–7:

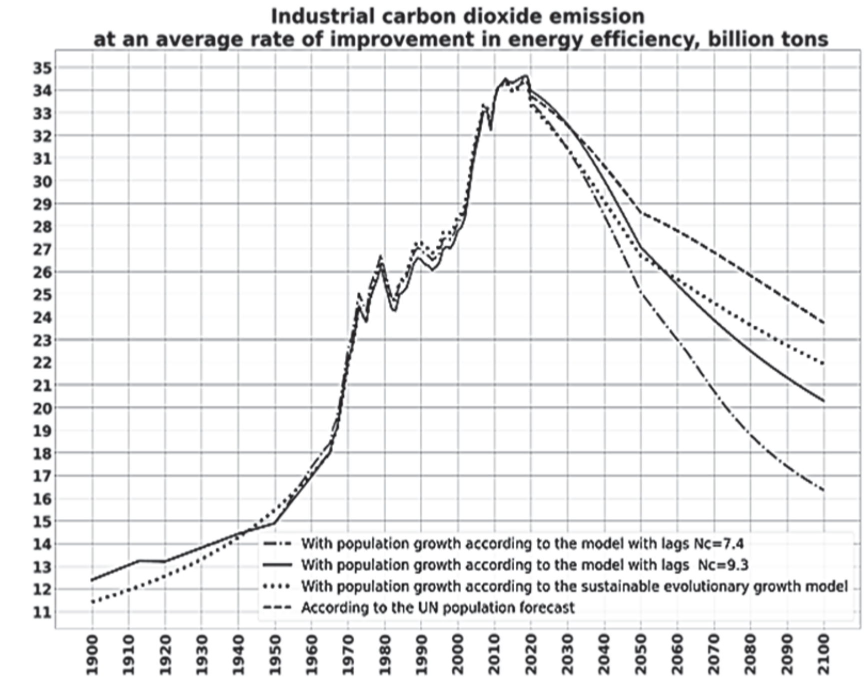

Fig. 5. The dynamics of the reduction of anthropogenic carbon dioxide (CO_2) emissions into the atmosphere in the 21st century under the conservative scenario of energy transition

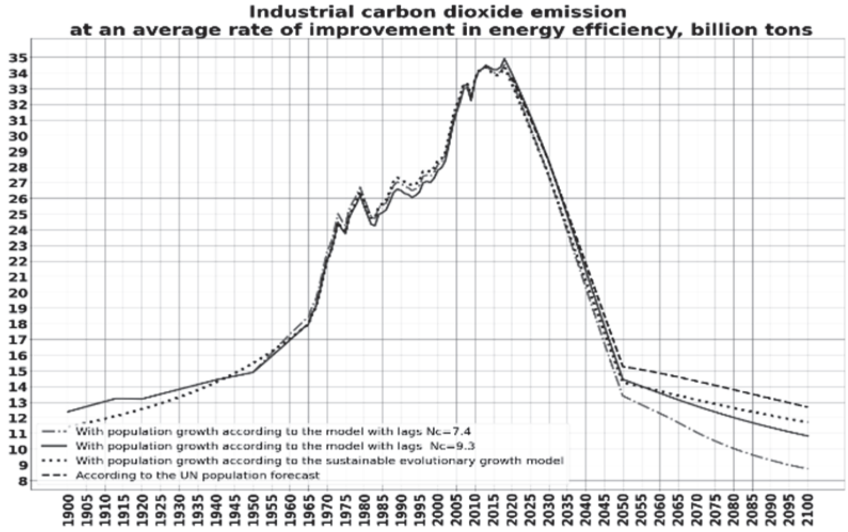

Fig. 6. The dynamics of the reduction of anthropogenic carbon dioxide (CO_2) emissions into the atmosphere in the 21st century under the ambitious scenario of energy transition

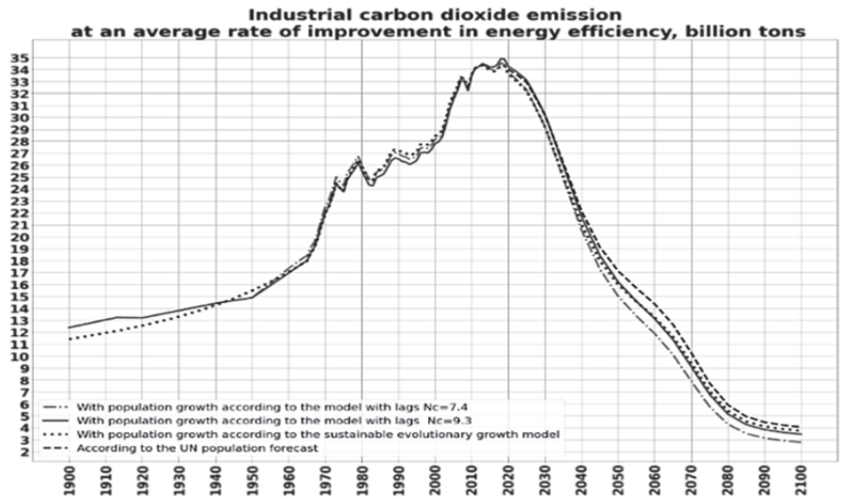

Fig. 7. The dynamics of the reduction of anthropogenic carbon dioxide (CO_2) emissions into the atmosphere in the 21st century under the Net Zero scenario of energy transition with the use of hydrogen and CCS technology for capture and storage of some part of CO_2

The results of projection of the deviation of the average global temperature of the surface atmosphere dynamics in the 21st century under the conservative, ambitious, and the Net Zero scenarios are presented in Figs 8–10:

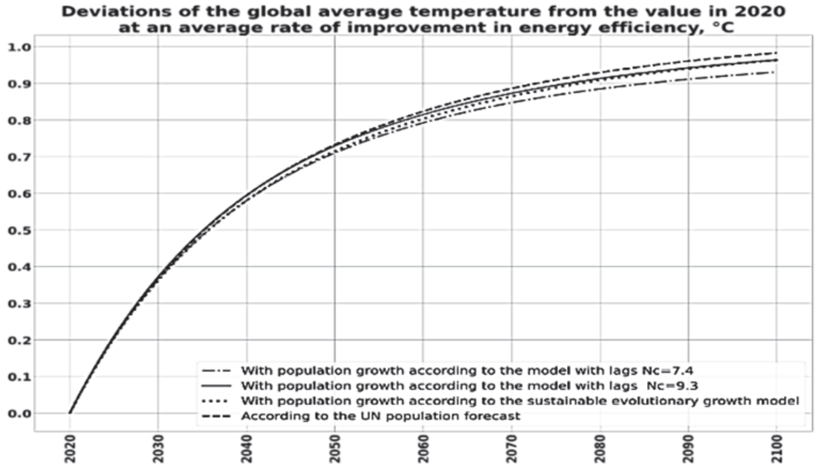

Fig. 8. The dynamics of the deviation of the average global temperature of the surface atmosphere in the 21st century under the conservative scenario of energy transition with the use of CCS technology in coal energy

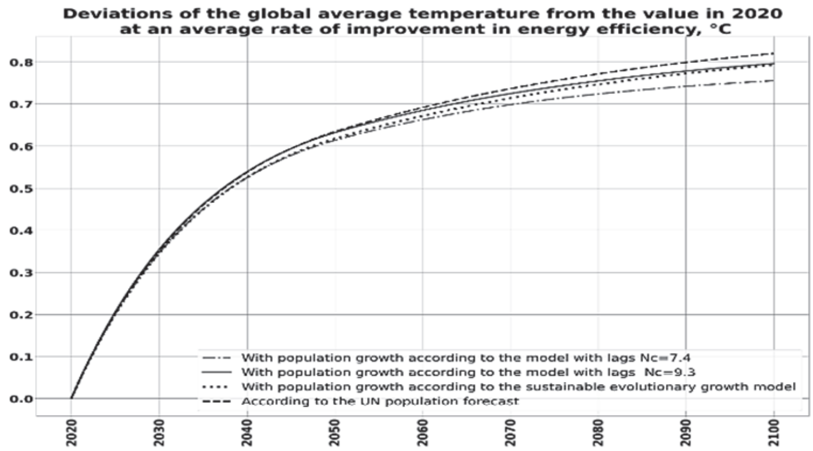

Fig. 9. The dynamics of the deviation of the average global temperature of the surface atmosphere in the 21st century under the ambitious scenario of the 'Great Energy Transition' with the use of CCS technology in coal energy

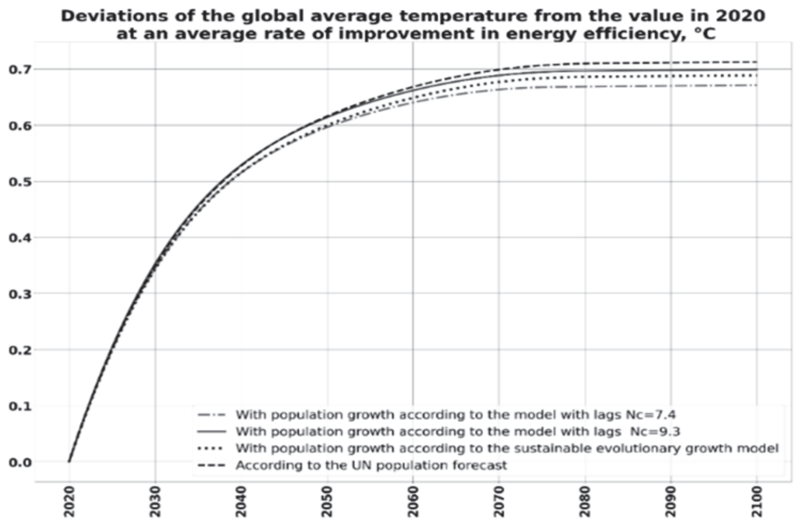

Fig. 10. The dynamics of the deviation of the average global temperature of the surface atmosphere in the 21st century under the Net Zero scenario of energy transition with the use of CCS technology in coal energy and the use of hydrogen

Calculations show that if the conservative scenario is implemented, global warming will reach 2 °C, while if the ambitious scenario is implemented, it will be 1.8 °C. The Net Zero scenario will keep global warming at 1.7 °C (Akaev and Davydova 2021a, 2021b).

Since the conservative scenario assumes that by 2050 the share of fossil energy sources will remain at about 60–65 %, this will lead to an unacceptable level of CO_2 emissions. This is far from the current ambitious goals of reducing emissions by 50–80 % by 2050. Under the conservative scenario, more frequent extreme weather events will be observed in the coming decades. In many places, floods that previously occurred once a century will occur much more frequently by 2050, possibly annually. When sea levels rise by several meters, about 30 % of the land, which is a densely populated territory, will be flooded (Mir 24 2021). According to a study conducted by scientists from the Potsdam Institute for the Study of Climate Change, by 2100, due to melting of continental ice, the level of the World Ocean may rise by 0.75–1.5 meters (PIK 2013). As a result, in 100 years Venice will go under water, followed in another 50 years by Amsterdam, Hamburg, Los Angeles, St. Petersburg, and other cities.

The climate crisis can be avoided if the world acts decisively and collectively and takes measures necessary to reduce carbon emissions. In particular, global community needs to redirect investment flows from the most profitable solutions to those that will benefit society in the long term. Annual global investment in climate averaged US$ 632 billion per year during 2019 and 2020

(Burg 2021). For comparison, global GDP in 2020 amounted to US$ 85 trillion, meaning that, at the moment, global investment in climate is less than 1 % of the global GDP. Calculations show that successful implementation of the Net Zero scenario requires significant investment in the development of renewable energy sources. The Net Zero scenario assumes an increase in the share of renewable energy sources in the fuel and energy balance to 50–60 % by 2050 from the current 6 %. Thus, it is necessary to expand the use of solar and wind energy more significantly. Investments are also needed to increase the use of energy-efficient technologies, including smart digital technologies and energy-efficient technologies for homes. The study and improvement of chemical technology for the capture, sequestration, and storage of carbon dioxide also requires funding. In addition, investments should be directed to the development of hydrogen, nuclear and thermonuclear energy. Part of the investment can be obtained through increased taxes on CO_2 emissions, which in turn will contribute to solving the problem of global warming. Calculations show that the implementation of the above measures will meet the requirements of the Paris Climate Agreement to keep global warming at 1.5–2 °C compared to pre-industrial levels.

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