RESEARCH PAPER

HISTORY VERSUS ASPIRATIONS: CARBON NEUTRALITY POSTPONED BY SEVERAL DECADES

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ABSTRACT. Here, we use modeling and literature assessments to quantify the prospects for achieving carbon neutrality by nine major developing economies (China, India, Indonesia, Brazil, Iran, Saudi Arabia, Turkey, Mexico, and South Africa). We examine the structure of energy consumption, electricity generation, and land use in these countries. Scenario estimates of the dynamics of carbon indicators of the world's leading economies at global and subglobal scales based on a historical approach have been developed.

It is shown that the current rate of decarbonization and the development of the carbon capture and storage industry in the studied countries is not sufficient for these countries to fulfill their obligations to achieve carbon neutrality in 2050-2070 – this goal cannot be attained before the end of the century. The key challenge in achieving the carbon neutrality is the rapid, large-scale deployment of the carbon capture and storage technologies in all possible forms. Of the countries studied, however, only China and Brazil have their capabilities to store carbon for more than a century.

Although climate change occupies practically a leading place in the global agenda, the actual results of efforts in this area are far from the declared ones, and the climate warming can no longer be kept within 1.5°C. The core problem is to minimize the residence time for the global climate system in the dangerous zone (with a temperature overshoot above 1.5°C), which will require the emergence of the world economy with negative greenhouse gas emissions.

KEYWORDS: developing countries, energy, greenhouse gases emissions and absorption, carbon neutrality, scenarios

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INTRODUCTION

The year 2023 became the hottest year in the history of instrumental observations and finished with an outstanding record for the GMT, exceeding (according to CRU data[1]) the pre-industrial (1850-1900) level by 1.46°C. At the same time, the previous record of 2016 was exceeded by 0.17 OC at once, a huge margin at the planetary level, which is a unique event in the entire era of instrumental observations and causes serious concerns among the global scientific community (Schmidt 2024). In the year 2024, the record-breaking succession continued, and a unique 13-month (from June 2023 to June 2024) series of monthly temperature maximums was recorded. Finally, contrary to the expectations, the year 2024 was even hotter than the year 2023, having the annual mean temperature 1.55°C higher than the pre-industrial level, thereby overcoming the first critical threshold set by the Paris Agreement. And although this is only the temperature of one year, this fact is an alarm signal and a warning message to the world community that dangerous levels of warming are very close. Is spite of the fact that the strong El Niño[2], which was largely responsible for the temperature surges in 2023 and 2024, ended in May 2024, the temperature remains at the same level close to the record marks in the first nine months of 2025. The climatically significant average global temperature anomaly over the decade (2015-2024) attained 1.26°C, and thus the world was about to reach the 1.5°C threshold, which is clearly considered by the world community as an extremely undesirable event (King et al. 2023). Should a warming rate of about 0.2°C per decade achieved over the last 30 years be maintained, the critical threshold may be crossed as early as the mid-2030s. In the current situation, the best and still feasible scenario is the temporary overshoot of the 1.5°C threshold, attainment of the warming peak followed by the temperature decrease as a result of the effective implementation

[1]CRU Global temperature dataset HadCRUT (https://crudata.uea.ac.uk/cru/data/temperature/)
[2]El Niño is an irregular phenomenon occurring every 3-7 years, which increases water temperature in the tropical Pacific and is the main cause of interannual fluctuations in the global average temperature

of the initiatives of the Glasgow (2021) and Dubai (2023) summits (Klimenko et al. 2022a) or the implementation of low demographic scenarios (Klimenko et al. 2022b). This overshoot represents a serious threat to the stability of the global climate system, and the world community already poses the problem to minimize the residence time in this potentially devastating elevated temperature zone.

Over the past thirty years, the world community has made considerable efforts to control the hazardous global warming, and the core of these efforts is the measures to slash GHG emissions, the purpose of which is to achieve so-called carbon neutrality (the term "*carbon neutrality*" used in the paper refers only to anthropogenic activities and means the balance of emissions and sinks into natural or anthropogenic reservoirs of man-made greenhouse gases and other climate active matters - aerosols etc., – recalculated to carbon dioxide through global warming potential) (Fragkos et al. 2021, Das et al. 2023).

In our recent works (Klimenko at al 2023a, Klimenko at al 2024a, Klimenko at al 2024b), we examined the capabilities of the world's leading economies and Russia, which can be employed to solve the critical climate protection problem – achieving carbon neutrality by national economies by 2050–2060. We have demonstrated that, despite the great potential for reducing greenhouse gas emissions in various sectors of the economy, both Russia and OECD countries face serious difficulties in solving the problems in question.

In this paper, we examine whether the developing countries, which will become the backbone of the world economy in the immediate future, will be able to achieve their goals within their own timeframes. According to the WRI[3], the selected nine countries (Table 1) are currently responsible for almost half of global greenhouse gas emissions, and their development pathways are critical to the feasibility of implementing the Paris Agreement on limiting the global warming to "well below 2°C and preferably within 1.5°C".

It follows from Table 1 that all these countries, except Iran and Mexico[4], have put forward the ambitious targets of attaining carbon neutrality in 2050-2070 with a peak of GHG emissions occurring before 2030.

The aim of this paper is to find out how great the chances are of these countries implementing such impressive plans.

HISTORY AND CURRENT STATUS

All selected countries are characterized by a considerable increase in GHG emissions in recent decades (Fig. 1), but in the last 8–10 years, almost half of them (Iran, Saudi Arabia, Mexico, and South Africa) demonstrate its stabilization. The growth rate of specific (per capita) emissions is much lower, and stabilization of this indicator is already seen in all countries, while in Brazil, Saudi Arabia, and South Africa, it even decreases.

Table 1. Voluntary commitments to reduce net greenhouse gas emissions by UNFCCC parties[5]

UNFCCC party	Reference year	Emissions in % to the reference year		Attainment of	
		in 2030	in 2050	peak emission	carbon neutrality
Brazil	2005	47		2008	2050
India	2005	100	62	NA	2070
Indonesia	2010	95	50	2030-2035	2060
Iran	2010				
China	2005	175	55	before 2030	2060
Mexico	2000	65	50		NA
Saudi Arabia	2020	61		2016	2060
Turkey	2012	216			2053
South Africa	2010	70-80			2050

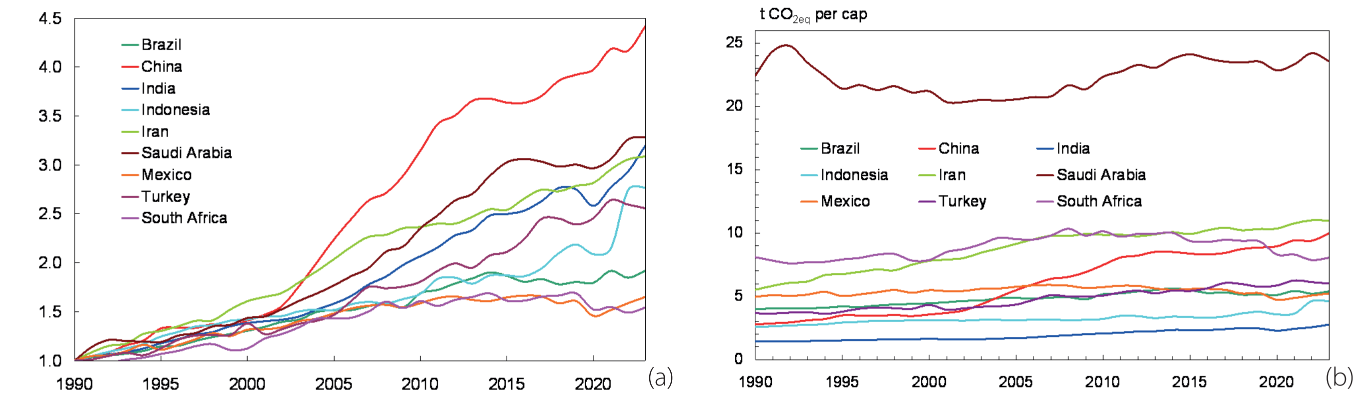


Fig. 1. GHG emissions (excluding LULUCF) - gross relative to 1990 levels (a) and per capita (b) (according to WRI[3] and UN[6] data)

[3]WRI Greenhouse gas emissions database (https://www.wri.org/data/climate-watch-cait-country-greenhouse-gas-emissions-data)[2]El

[4]Iran makes targets to limit GHG emissions and achieve climate neutrality depending on lifting of economic sanctions. Mexico has no net-zero or any other long-term climate neutrality targets.

[5]UNFCCC Nationally Determined Contributions (https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs)

[6]World Population Prospects 2024. New York: United Nations, Department of Economic and Social Affairs, Population Division.

Terrestrial biota (LULUCF, Fig. 2) can be either a net sink (such as in China and India, where increased reforestation exceeds forest loss due to logging and fires) or a net source of GHGs (Brazil and Indonesia, where ongoing large-scale tropical deforestation is not compensated for by reforestation, including planting and natural tropical regrowth). Carbon dioxide emissions from the LULUCF sector have accounted for almost 50% in Indonesia over the past 20 years and about 30% of the total national emissions in Brazil.

The emission rate of the main greenhouse gas – carbon dioxide – is controlled essentially by the total energy consumption (in all sectors of economy - power generation, industry, transportation etc.) and the structure of the energy mix (Fig. 3). The cement production (referred only to chemical process and do not include the fuel combustion to produce heat for this process) in the above-listed countries accounts for a maximum of 5% of the total CO_2 emissions.

As with all rapidly developing national economies, the studied countries demonstrate a high growth rate of energy consumption (Fig. 4a). Thus, over the 1990-2023 period, the gross consumption of primary energy increased by about 5.5 times in China, by about 4-4.5 times in India, Indonesia, and Iran, and by 2.5-3.5 times in Brazil, Turkey, Mexico, and Saudi Arabia.

The dynamics of specific energy consumption indicators (Fig. 4b) look less pronounced. Stabilization and even some decrease of this characteristic have been observed in China, Brazil, Saudi Arabia, Mexico, and South Africa in recent years, while its growth rate declined considerably in India, Indonesia, Turkey, and Iran.

Considerable differences are seen in the structure of the fuel mix (Fig. 5a).

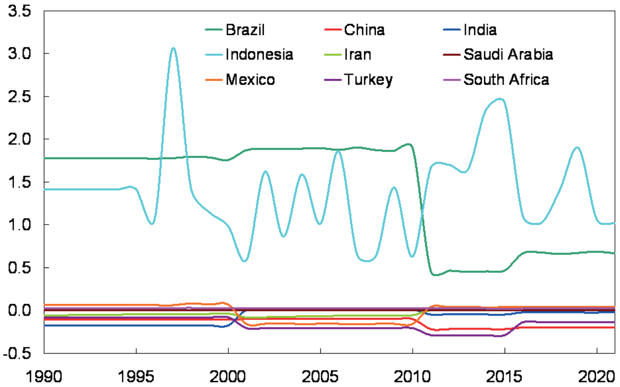


Fig. 2. Ratio of GHG emission/sink from LULUCF to industrial emissions in 1990–2021 (according to WRI data[3])

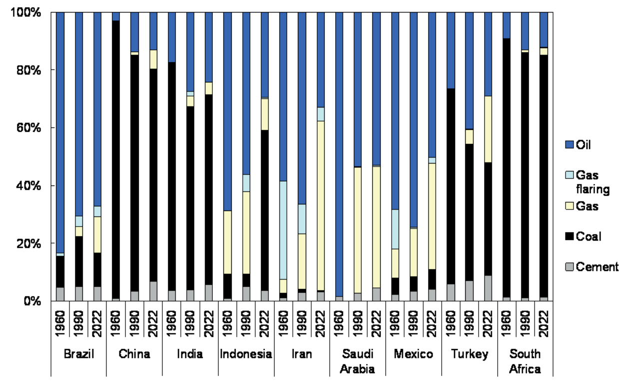


Fig. 3. Structure of CO_2 emissions from combustion of various fuel types and cement production (according to WRI data3)

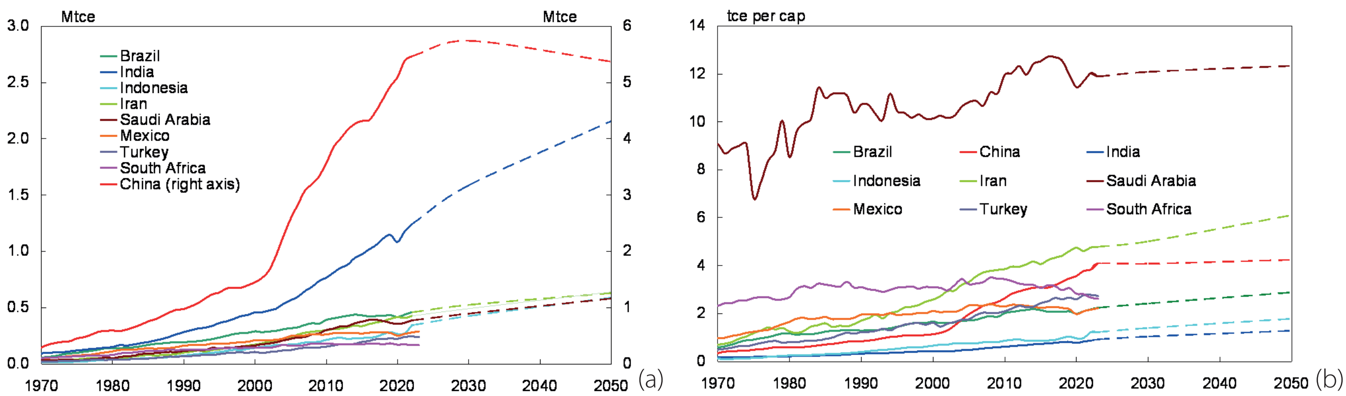


Fig. 4. Primary energy consumption (fossil fuels, hydro- and nuclear energy, and renewables combined) – gross (a) and per capita (b) tce values (according to the historical data[7], UN data[6] and IEA STEPS scenario[8]

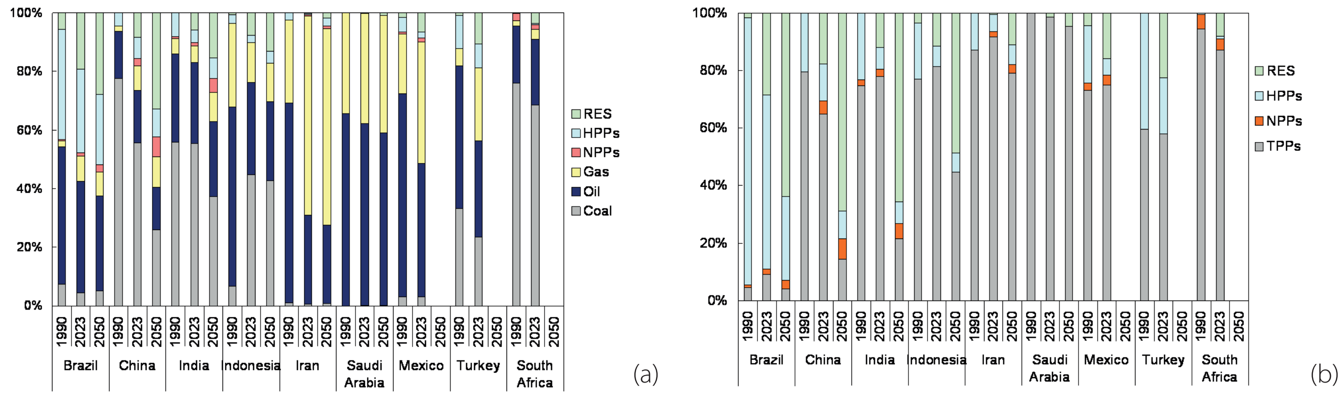


Fig. 5. Structure of energy consumption (a) and power generation (b) (according to the historical data[7] and STEPS scenario[8])

[7]Statistical Review of World Energy 2024. London: Energy Institute, 2024.

[8]The latest forecast from the IEA World Energy Outlook 2024 (Paris: International Energy Adency, 2024) examines two scenarios – STEPS, which is based on the applicable decarbonization programs of national economies, and APS, which assumes that national targets under the Paris Agreement are achieved as scheduled and in full.

The power industry in China, India, Indonesia, and South Africa is predominantly based on coal. At the same time, over the past 60 years, the share of this fossil fuel in the national energy balance of China and India steadily decreased to about 55% in 2022, while in Indonesia, on the contrary, it has grown to 45%. Carbon-free energy sources (such as HPPs, NPPs, and RES) account for 5-15% of the total energy consumption in these three countries, and their share of the energy balance grows continuously. This trend will receive a powerful boost in the coming decades – thus, China, being the absolute world leader in the deployment of carbon-free energy sources, intends to produce 50% of electricity using renewable energy sources (including HPPs) already by 2028.

The main source of energy in oil- and gas-producing Iran and Saudi Arabia is hydrocarbons, and a marked trend of transition from oil towards gas, whose percentage was almost 40% in Saudi Arabia and 70% in Iran by 2022, has been observed over the past 60 years. Currently, carbon-free energy sources in these countries contribute very little to their overall energy balance.

Brazil has the most balanced low-carbon energy complex, with almost half of its energy consumption currently covered by hydropower, the share of oil having decreased to 40%, the share of gas having increased to 10%, while coal accounts for a maximum of 5% of the total energy demand.

In the electric power industry (Fig. 5b) the situation is even more unusual. In Iran and Saudi Arabia, almost all electric power is generated at TPPs fired with natural gas and fuel oil. In India and Indonesia, about 20% of electricity generation comes from carbon-free sources (HPPs, NPPs, and RESs), and the rest is covered by coal-fired TPPs. In China, more than a third of power plant output is generated without burning fossil fuels; thermal power generation predominantly uses coal as fuel. In Turkey, HPPs and RESs provide 20% of the total electricity generation, while Brazil receives almost 90% of its electricity from HPPs, RESs, and NPPs, making it one of the world's leaders in carbon-free electricity generation.

The volume and structure of energy consumption determine the level of carbon dioxide emissions in the power industry (Fig. 6). Gross CO_2 emissions in the examined countries (Fig. 6a) are growing at a lower rate than the energy consumption does (Fig. 4a), which is explained by an increase in the percentage of power generation using low-carbon (natural gas) and carbon-free (HPPs, NPPs, and RESs) energy sources in the energy balances.

As a result, the specific emission of carbon dioxide (per unit of consumed primary energy, Fig. 6b), called carbon intensity or carbon intensity of energy consumption, decreases in all studied countries.

For instance, in Brazil, this process occurred intensively as early as the 1970s due to the construction of large HPPs, as a result of which the energy intensity of its power industry has been at a very low level of 1.1 t CO_2/tce for over 40 years, which is much lower than in developed economies of the EU or the USA. Iran and Saudi Arabia have been continuously reducing the carbon intensity of their energy consumption during the last decades by replacing oil with natural gas in their energy balance, thereby reducing the specific emissions from 1.9 t CO_2/tce in 1980 to 1.55 t CO_2/tce in 2023, which is much lower than the current global average value of 1.75 t CO^2/tce.

China also systematically reduced specific emissions in its national power industry, mainly by commissioning large HPPs and NPPs in the period before 2005 and at an even higher pace due to the large-scale construction of solar and wind power plants in the last two decades. This reconstruction of the power industry reduced the specific emissions from 2.6t CO_2/tce in 1970 to 2.35t CO_2/tce in 2005 and 1.9t CO_2/tce in 2023.

No visible progress in cutting down specific emissions is typical for the power industry in India, Indonesia, and South Africa, where the share of coal is still great, and the rate of introduction of carbon-free energy sources falls far short of the global average value.

Fig. 6b demonstrates that the power industry is a very inertial sector of the economy, and decades are always required to make substantial progress here.

The land use sector is even more inert than the power industry and is just as crucial for covering the basic needs of the population. FAO[9] data collected since 1961 (Fig. 7a) have demonstrated a slower growth of agricultural land areas, including arable land, in all studied countries, and in tropical countries (Brazil and Indonesia) this is caused by deforestation. Forested areas increase in India, Iran and especially in China, including due to large-scale forest plantations (Fig. 7b). Reforestation activities in Brazil and Indonesia are still in an embryonic state and cannot yet compensate for deforestation, often illegal.

As a result, forest areas are increasing only in Turkey, India, China, and Iran (by 14%, 15%, 20% and 40% compared to 1990, respectively) and continue to decrease in South Africa, Mexico, Brazil, and Indonesia (by 6%, 7%, 15% and 22% compared to 1990, respectively) (Fig. 8a).

Another essential trend is the decrease in the specific arable area per capita (Fig. 8b). The development of agricultural technologies means that today, providing food requires a smaller area of cultivated land, specifically 0.1-0.2 hectares per person, which is 2-3 times smaller than the area needed 60 years ago.

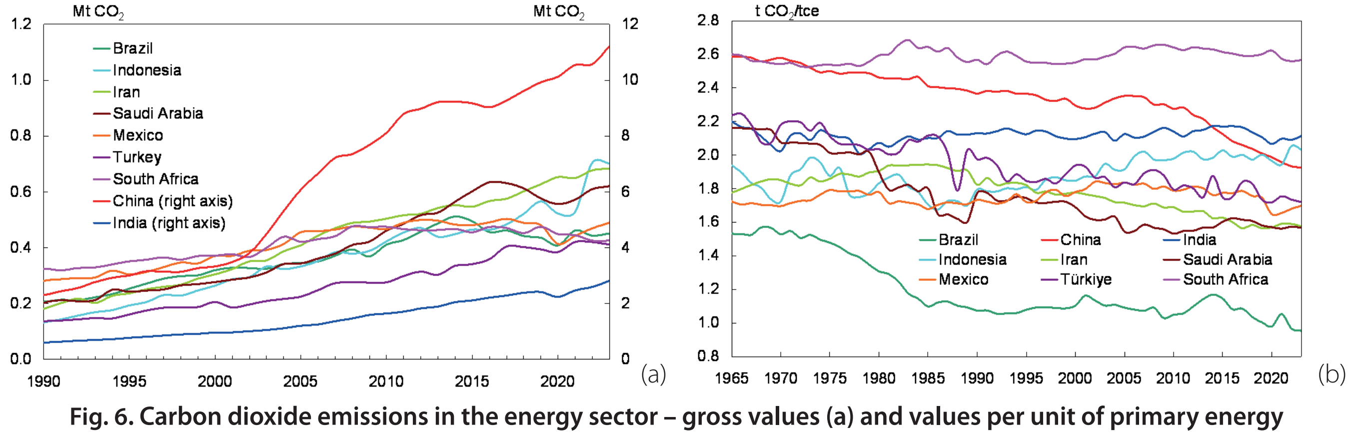


Fig. 6. Carbon dioxide emissions in the energy sector – gross values (a) and values per unit of primary energy consumption (b) according to historical data[7]

[9]FAO Food and agriculture database FAOSTAT (http://www.fao.org/faostat/en/#data)

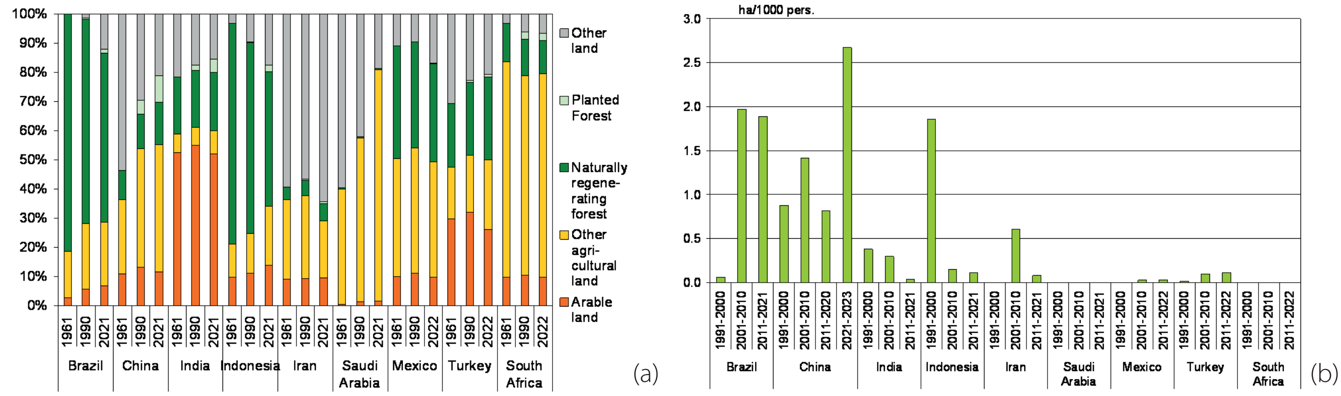


Fig. 7. Structure of land use (a) and forest plantations area per capita (b) (according to FAO data[9])

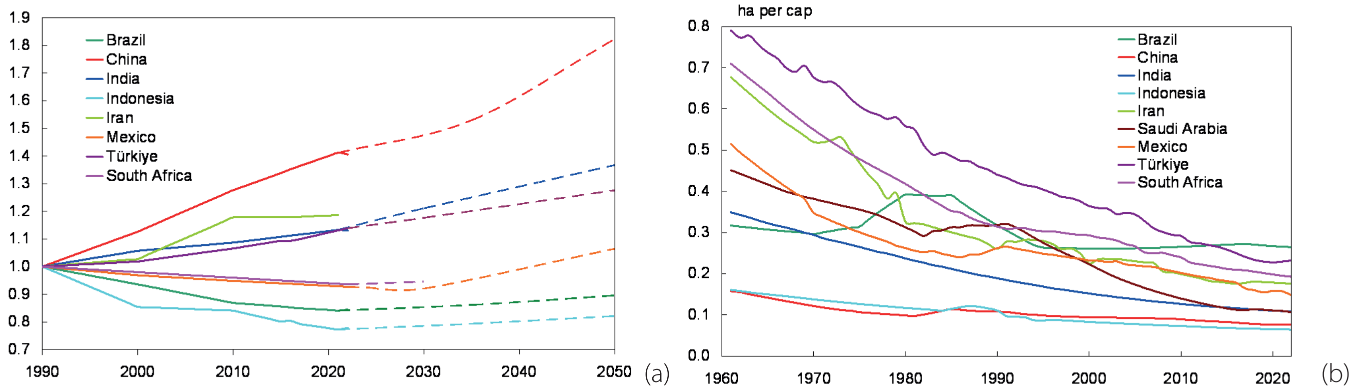


Fig. 8. Forest area relative to 1990 levels (a) and arable land area per capita (b) according to historical FAO data9 and national plans[10,11,12,13,14] (Gonzalez-Abraham et al. 2024)

Thus, the current state of the power industry and land use in the studied countries as sources of greenhouse gases has the following main features:

– continued growth in gross energy consumption against the background of stabilization (and even a decline in certain countries) of its specific indicators (per capita);

– lower carbon intensity of energy consumption due to the transition to low-carbon (natural gas) energy sources and rapid development of carbon-free (HPPs, NPPs, RESs) energy sources;

– larger area of agricultural land (including arable land) with its smaller area per capita due to the enhancement of agricultural technologies;

– formation of a trend towards enhanced reforestation, which in some countries (China, India) already exceeds the scale of deforestation, thereby increasing the area of forests – the main absorber of carbon dioxide.

SCENARIOS

To assess the prospects for decarbonization of the economies of developing countries, the relationship between the rate of change in specific GHG emissions per capita and GDP per capita was analyzed (Fig. 9). The initial data used were GHG emission indicators from WRI (excluding LULUCF) and IMF economic data. For this study, 130 countries with national GHG emissions above 10 million tons of CO_{2eq}/year each were selected; countries with unstable political situations (Sudan, Syria, Somalia, Yemen) were excluded.

As expected, low GDP per capita values do not promote lower carbon intensity of the economy – countries with the specific GDP below approximately USD 10,000 per person are essentially characterized by greater specific GHG emissions per capita. Here, the top priority problem for the government of these countries is to fight poverty, while environmental issues and, in particular, emission control problems inevitably take second place. At the same time, on an increase of the nominal GDP above a threshold of USD 14 thousand per person (this value coincides with the conditional boundary between rich and poor countries according to the IMF terms), the rate of specific GHG emission reduction depends nearly linearly on the specific GDP – a linear dependence of the reduction rate of specific GHG emissions on the specific GDP is observed – rich countries can already afford implementation of such activities and readily finance the energy transition and decarbonization of the economy.

To assess the potential for decarbonization in the studied countries in the coming decades, the medium UN population scenario (UN 2024) and the long-term economic forecast of the Goldman Sachs group (Daly et al 2022) were employed within the scope of the proposed approach. According to the IMF (Fig. 9a), at present only Saudi Arabia has a specific GDP above US$14 thousand per person. The long-term projections (Daly et al 2022) suggest

[10]China sets ambitious forestry development goals for 2050 (https://bioenergyinternational.com/china-sets-ambitious-forestry-development-goals-2050/)

[11]India's long-term low-carbon development strategy. Submission to the United Nations Framework Convention on Climate Change. (2022) New Dehli: Ministry of Environment, Forest and Climate Change. Government of India.

[12]Indonesia Long-Term Strategy for Low Carbon and Climate Resilience 2050. 2021. 156 pp. https://unfccc.int/sites/default/files/resource/Indonesia_LTS-LCCR_2021.pdf

[13]Saudi Green Initiatives. (https://www.greeninitiatives.gov.sa/about-sgi/sgi-targets/reduce-carbon-emissions/)

[14]2030-2050 Vision. The future of forests and agriculture in Brazil / General edition: F. Macedo, M. Campanili. Brazilian Coalition on Climate, Forests and Agriculture, 2018

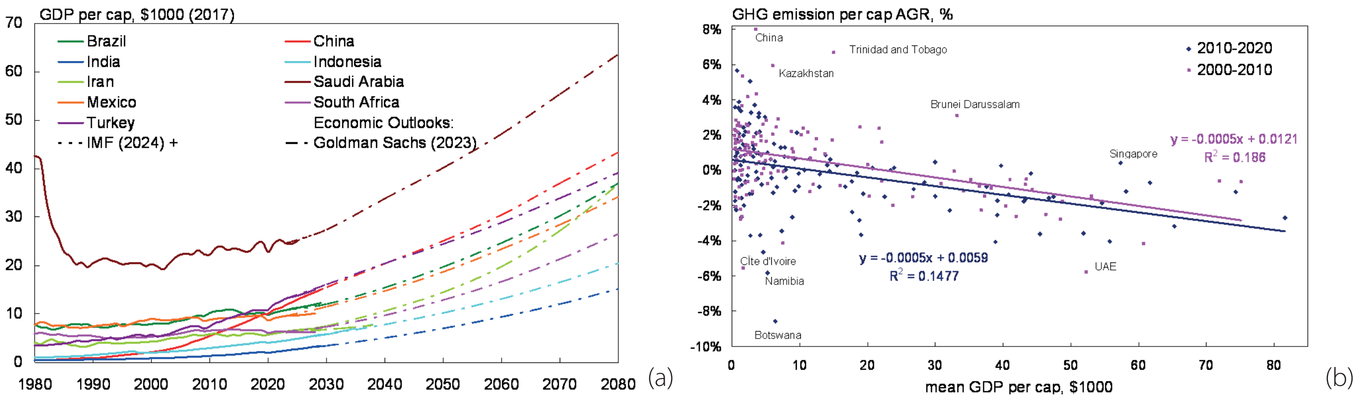


Fig. 9. Constant price GDP per capita (IMF data[15], Daly et al 2022) (a) and its relationship with the rate of change of GHG specific emission per capita (according to IMF[15] and WRI[3] data) (b)

that China and Turkey will cross this threshold by 2030, Brazil and Mexico by 2040, Iran in 2050, and Indonesia and South Africa only after 2060. India will reach this level only by the end of this century due to still uncontrolled population growth. The obtained estimates of the dynamics of specific emissions per capita are shown in Fig. 10, and the gross emissions are presented in Fig. 11.

The results of the calculations demonstrate that, with the current trends in the field of climate protection, only China and Brazil would be able to achieve carbon neutrality by the end of the century, but with a long delay of 20-40 years relative to the declared deadline. To achieve this, China will have to maintain the record high level of energy decarbonization achieved over the past 15 years, and Brazil will have to completely abandon further severe deforestation of its forests and gradually harmonize its forestry practices with those applicable in other South American countries (FAO 2020; Harris et al. 2021; Houghton and Castanho 2023). Today Brazil seems to remain the only major country that can achieve carbon neutrality solely through the full activation of its biological potential without using CCS technologies. All other countries cannot attain carbon neutrality even by 2100, not to mention earlier dates, since GHG emissions in the economy are not compensated for by the growth in the absorption capacity of forest areas. Current efforts are clearly insufficient – this will become completely obvious in just five years, when it becomes clear that at the turn of 2030, China, Brazil, and Saudi Arabia will most likely locate themselves on a plateau of emissions, without having even begun to really reduce them, and India, Indonesia, and Iran will increase their emissions by another 15-20%. The consistent failures of many countries to implement climate protection plans generally arise from the fact that the expected rates of transformation of highly resistant areas of human activities, particularly the power industry, seem to exceed the capabilities of these countries shaped by their historical experience.

Nevertheless, the potential for reducing GHG emissions in some of the examined economies is quite high: by 2080, GHG emissions will decrease by 60% compared to 1990 levels in China, by 50% in Saudi Arabia, and by 30% in Brazil and Iran. India and Indonesia, due to continued population growth and lagging economic development, will continue to increase their GHG emissions until the second half of the century, remaining their main emitters.

The capabilities of increasing carbon absorption by forests are also very limited. Despite ambitious plans of China10 (Yu et al. 2024), India[11], Indonesia[12], Saudi Arabia[13], and Brazil[14], Mexico (Gonzalez-Abraham et al. 2024) (see Fig. 7) to increase forest areas in the coming decades, they will clearly be insufficient to offset large residual emissions everywhere except Brazil. Moreover, all countries with large forest areas, with the sole exception of China, face stubborn resistance from business and widespread violations of forest conservation laws.

Thus, the only solution to the problem of carbon neutrality for these countries is a development of CCS technologies (Filippov et al. 2022, Kök 2015, Vourliotakis et al. 2024, Kearns et al. 2017, Collaborating 2024). However,

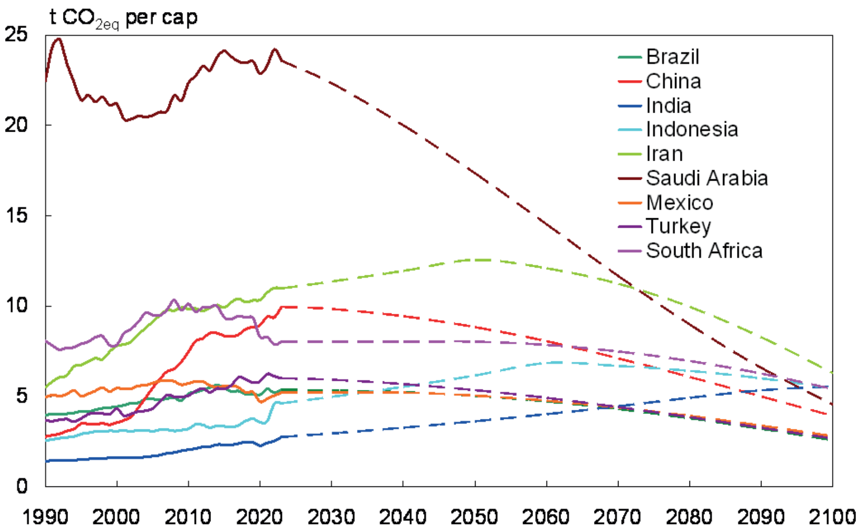


Fig. 10. GHG specific emission per capita in developing countries – history based on WRI data[3] and projections of this study

[15]IMF Economic Outlook database (https://www.imf.org/en/Publications/WEO/)

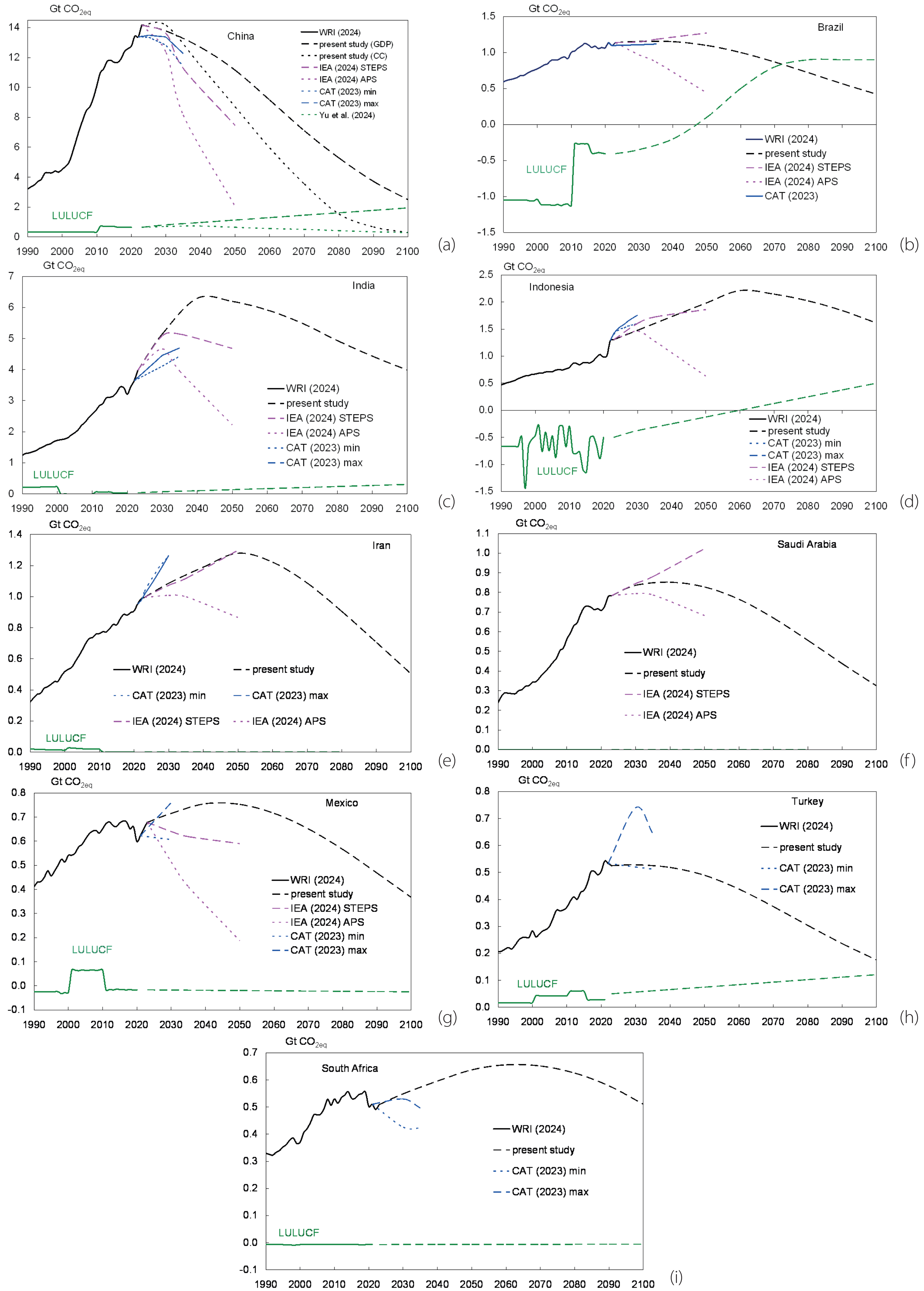


Fig. 11. ynamics of gross GHG emissions (excluding LULUCF) and LULUCF net sinks based on WRI data[3] and results of the calculations in this study, as well as IEA[8] and CAT[16] scenarios in China (a), Brazil (b), India (c), Indonesia (d), Iran (e), Saudi Arabia (f), Mexico (g), Turkey (h) and South Africa (i)

[16]https://climateactiontracker.org/

current estimates of geological rock resources for CO_2 storage (Table 2) indicate that only Brazil has sufficient capacity, as it is the only country capable of storing its emissions at their current level for hundreds of years. This indicates that within the horizon of the next few decades, when, in fact, it is planned to achieve carbon neutrality, only China has promising plans for implementing CCS projects of sufficient capacity (Table 3).

The obtained calculation results demonstrate that none of the studied countries, except Brazil, can achieve carbon neutrality within the anticipated timeframe without widespread use of CCS technologies, since lower GHG emissions in the economy are not compensated for by a higher absorption capacity of forest plantations. At the same time, we should bear in mind that the intensity of the global biotic sink has a natural maximum of 6-9 Gt CO_2/year and may begin to decline as early as the middle of this century (Klimenko et al. 2020, Gidden et al. 2019).

The implementation of the decarbonization policy in the economies of the studied countries will reduce the GHG emissions by 2080, compared to the 2020 level, by 90% in China, 50% in Saudi Arabia, and 30% in Brazil and Iran. Continued high population growth rates and low levels of economic development in India and Indonesia will continue to increase GHG emissions, which will exceed the current levels by 1.2 and 1.7 times, respectively, by 2080.

Carbon capture by terrestrial ecosystems also has its limits. Although impressive plans of China, India, Indonesia, and Brazil to increase forest areas in the coming decades will play an important role in reducing anthropogenic GHG emissions, they will not be able to completely offset increasing emissions (see Table 4).

The only solution to the carbon neutrality problem for all these countries is CCS technologies[19] (Debarre et al. 2021, Cai et al. 2021, Rao et al. 2023). Although current estimates of geological rock resources for CO2 storage (see Table 2) indicate that theoretically such storage can be found in all studied countries, the revision of operational, in-construction, and prospective CCS projects for the coming decades (see Table 3) leaves only China on this list.

Table 2. Carbon dioxide geologic storage resource capacity estimates for studied countries, Gt CO_2 (Filippov et al. 2022, Kök 2015, Vourliotakis et al. 2024, Kearns et al. 2017)

Country	Lower estimate			Upper estimate		
	Onshore	Offshore	Total	Onshore	Offshore	Total
Brazil	224	73	297	1572	515	2087
India	75	24	99	525	172	697
Indonesia	96	67	163	672	472	1144
Iran*	68	22	90	477	156	633
China	325	78	403	2286	544	2830
Mexico	79	59	138	556	411	967
Saudi Arabia*	89	29	119	629	206	835
Turkey*	34	11	45	238	88	326
South Africa	34		34	34	150	184

* This work estimates.

Table 3. Total capacity *Q* (Gt CO_2) and annual capacity *G* (Mt CO_2/year) of operational, in construction and under development CCS projects (according to OGCI[17] and GCCSI[18]

Country	Operational and in construction		Advanced development		Early development	Total
	Q	G	Q	G	Q	Q
Brazil	0,08	10.6	2.47	0,4	n/a	13
India	–	–	0.84	0,54	63.3	64
Indonesia	–	–	2.46	4,4	13.4	16
Iran	–	–	n/a		n/a	n/a
China	n/a	11.3	9.5	4	3067	3078
Mexico	n/a	–	–		138	138
Saudi Arabia	–	9.8	44		n/a	44
Turkey	–	–	–		0.1	0.1
South Africa	–	–	–		34	34

[17]OGCI CO_2 Storage Resource Catalogue (https://www.ogci.com/ccus/)
[18]Global Status of CCS Report 2024.Collaborating for a Net-Zero Future. Melbourne, Australia: GCCSI, 2024.
[19]China Carbon Dioxide Capture Utilization and Storage Annual Report. Chinese Academy of Environmental Planning / China's Ministry of Ecology and Environment, 2021.

Table 4. Estimates of GHG emissions (E), LULUCF removals (S), and CCS annual capacity (G) required to achieve carbon neutrality within the expected timeframe, as well as required storage capacity by 2100 (Q_{2100}) and available geological reservoirs (Q)

Country	Year	*E*, Gt CO_{2eq}/year	*S*, Gt CO_{2eq}/year	*G*, Gt CO_{2eq}/year	Q_{2100}, Gt	*Q*, Gt
Brazil	2050	1.1	0.1	1.0	13	224
India	2070	5.5	0.2	5.3	239	75
Indonesia	2060	2.2	0.0	2.2	102	96
Iran	2080	0.9	0.0	0.9	37	68
China	2060	6.0	0.6	5.4	153	325
Mexico	2080	0.6	0.0	0.6	25	79
Saudi Arabia	2060	0.0	0.0	0.0	34	89
Turkey	2053	0.5	0.1	0.4	16	34
South Africa	2050	0.6	0.0	0.6	38	34

The lower estimates of the capacity of onshore storages from Table 2 are used as the potential volumes of geological CO_2 storages in Table 4. Simple calculations yield that after commissioning of all these huge reservoirs; Brazil alone will have nearly unlimited capacity to store the amount of GHG needed to achieve and ensure in the future its carbon neutrality. The geological reservoirs in China, Iran, Saudi Arabia, Turkey, and Mexico can store the required amounts of GHGs, but the available CCS resources in Indonesia and South Africa are clearly insufficient to meet their climate pledges, and, finally, India, with its high GHG emissions and low CCS resources, even theoretically does not have storage capacities to meet its climate targets. In a few decades, it will be India that will take the place of China as the leading emitter of GHGs (Fig. 11) and gradually become the main obstacle to the implementation of the Paris Agreement.

To assess the scale of problems arising in the development of CCS technologies, it is worth comparing the obtained estimates of the required capacities from Table 4 with the performance indicators of modern facilities from Table 3, which differ by two orders of magnitude. This means that a new, huge industry comparable in scale to the current gas industry must be created without any delay within the next two to three decades. This new industry, which includes storage facilities, pipelines, and compressor stations19 (Cai et al. 2021, Rao et al. 2023), should have a storage capacity above 15 Gt CO_{2eq}/year by 2075. Given the current very high rates of development of the CCS industry, which average 11% per year from 2010 to 2023 (Global Status.. 2024), it is projected that a global GHG storage capacity of 10.5 Gt CO_{2eq}/year can be achieved by 2075; however, only about one-third of this capacity will likely be located in the studied countries, which is clearly y insufficient to address the identified problems (Table 5). It should therefore be assumed that the achievement of carbon neutrality by developing countries on the whole is postponed to the end of the century, 30-40 years later than the leading OECD countries, which by that time will have to create a developed economy with negative GHG emissions to keep the global warming below 2^{o}C.

ESTIMATION OF GLOBAL GHG EMISSIONS

To assess the global climate effect of the decarbonization measures of developing countries' economies examined in this paper, we used the results of calculations presented in our recent works for Russia (Klimenko et al. 2023a, Klimenko et al. 2024a) and economically developed countries (Klimenko et al. 2024b).

The prospects for reducing the carbon intensity of the Russian economy and the possibility of achieving carbon neutrality of the national economy by 2060 were studied in Klimenko et al. (2023a) and Klimenko et al. (2024a). Based on the historical-extrapolation approach to the study of the development of various socio-engineering systems and by comparison with the dynamics of carbon indicators of the economies of the world's leading countries, it has been demonstrated that at present the anthropogenic emissions of GHG can be compensated for by absorption by the biosphere (primarily forests) only theoretically. The condition for such an achievement is to perform extremely ambitious large-scale programs for the transformation of all sectors of the Russian economy - from the power industry to forestry management. Thus, according to the optimistic scenario, the rate of reduction of GHG emission per capita should be 1% per year, which is consistent with the maximum value achieved in the world over the past 50 years, and the forest management should include full compensation for increasing deforestation and a 50% reduction of the forest losses caused by fires, which are currently the second (after the power industry) source of atmospheric GHG emissions. The most feasible is a scenario with 0.5%/year reduction of specific GHG emissions per capita and a moderate growth in the absorption capacity of forests mainly due to the implementation of forest climate projects and a reduction in fire emissions. Under this scenario, net GHG emissions can reach about 700 Mt CO_{2eq} by 2060, which will require the creation of a national carbon capture and storage industry that provides the large storage capacities required to achieve carbon neutrality.

The prospects for achieving carbon neutrality in economically developed countries (such as the USA, EU, Norway, Canada, Japan, and Australia) were studied elsewhere (Klimenko et al. 2024b). The structure of the power industry and land management in these countries was analyzed. Scenario estimates of the dynamics of carbon indicators of the economies of the world's leading countries have been developed. It has been demonstrated that the current rate of decarbonization and development of the CCS industry cannot ensure the achievement of carbon neutrality by 2050 even in the world's leading economies. The main challenge in achieving climate neutrality is rapid and large-scale deployment of CCS technologies capable of storing carbon for more than a century. To achieve carbon neutrality by 2050, leading OECD countries will have to store annually at least 6 billion tons of CO_2, which is almost 25 times greater than the available capacity of storage facilities (operational, in construction, and being developed).

Table 5 and Fig. 12 summarize estimates of emissions, capture by LULUCF, and CCS, as well as net GHG emissions in 2023-2100 in Russia, developed and developing countries, and the total world (Gt CO_{2eq}/year)

The pathways of CCS scale development adopted in this paper for the historical scenario correspond to the revolutionary APS[8] scenario estimates for the historical scenario and to the even more extreme Net Zero scenario from BP[20] for the intensive scenario.

The estimates of emissions in the studied countries, which were obtained in this work (Fig. 11) for the period up to 2050, are close to the STEPS scenario[8], which assume the implementation of the current energy decarbonization policy, thereby confirming the effectiveness of the historical approach employed. The dynamics of GHG emissions under the APS scenario[8] assume much higher rates of decarbonization of national economies, aimed at meeting the stated net zero emission targets, which are unique in history and, therefore, can hardly be attained at all.

It is also worth noting that the scenarios proposed in this paper for China, Brazil, and India are located in the range of estimates presented at the CAT portal16 (Fig. 11), which is an expert website for climate policy analysis. At the same time, attention is drawn to the CAT-provided rather high overestimates of future GHG emissions in Indonesia and Iran (Fig. 11), which are inconsistent with either current trends or expert vision[8].

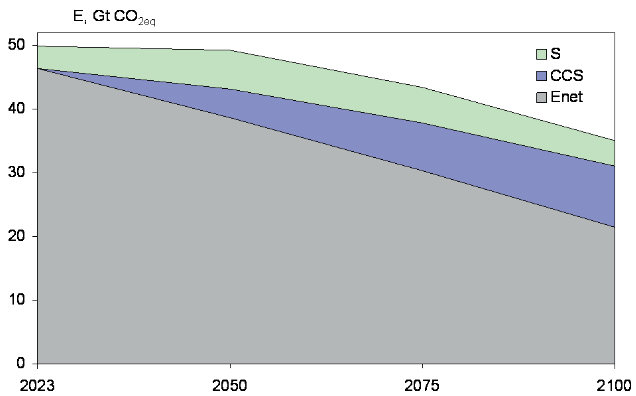
Thus, the global net GHG emissions projected by the scenarios proposed in this paper, considering the LULUCF absorption and CCS, will be 80% and 60% of the 2023 level for the historical and intensive options, respectively, by 2050, and 45% and 5% by 2100. These figures are between the "Paris" and "Glasgow" scenarios from our recent work (Klimenko et al. 2022a). The model projections (Klimenko et al. 2022a, Klimenko et al. 2022b) demonstrate that full implementation of the Glasgow scenario is able to keep the GMT within 1.5°C above the pre-industrial level, while according to the Paris scenario, it will exceed this level by

Table 5. Estimates of industrial emissions *E*, capture by LULUCF *S*, residual emissions E_{res}, *CCS*, and net GHG emissions (E_{net}) in 2023-2100 in Russia, developed and developing countries, and the total world (Gt CO_{2eq}/year)

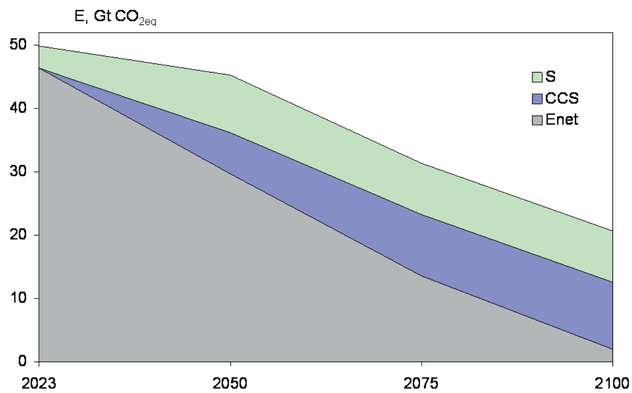
Country	Scenario	2023[7]	2050					2075					2100				
		E	E	S*	E_{res}	CCS	E_{net}	E	S*	E_{res}	CCS	E_{net}	E	S*	E_{res}	CCS	E_{net}
Russia (Klimenko et al, 2023a)		2.1	1.6	1.1	0.5	0.0	0.5	1.4	1.1	0.3	0.2	0.1	0.8	1.1	-0.3	0.1	-0.4
Six developed countries (Klimenko et al, 2024b)		12,1	6.5	2.0	4.5	3.0	1.5	3.5	2.0	1.5	3.5	-2.0	2.0	1.5	0.5	3.5	-3.0
Nine developing countries**	Historical	24.1	24.3	1.5	22.8	1.0	21.8	20.1	1.5	18.6	2.5	16.1	14.8	0.8	14.0	3.5	10.5
	Intensive	24.1	22.0	3.0	19.0	2.0	17.0	13.8	3.5	10.3	4.0	6.3	8.2	3.5	4.7	4.0	0.7
Other countries**	Historical	12.2	16.8	1.5	15.3	0.5	14.8	18.4	1.0	17.4	1.3	16.1	17.4	0.6	16.8	2.5	14.3
	Intensive	12.2	15.2	3.0	12.2	1.5	10.7	12.6	1.5	11.1	2.0	9.1	9.6	2.0	7.6	3.0	4.6
Total world**	Historical	49.9	49.2	6.1	43.1	4.5	38.6	43.4	5.6	37.8	7.5	30.3	35.0	4.0	31.0	9.6	21.4
	Intensive	49.9	45.3	9.1	36.2	6.5	29.7	31.3	8.1	23.2	9.7	13.5	20.6	8.1	12.5	10.6	1.9
	IEA STEPS8	49.9	37.9			0.4											
	IEA APS8	49.9	15.5			4.5											
	BP Current Trajectory 20	49.9	36.7			0.9											
	BP Net Zero20	49.9	2.4			6.8											

* FAOSTAT scenario and GEPL1997 scenario (Klimenko et al. 2020) for historical and intensive alternatives, respectively

** this study assessment



(a)



(b)

Fig. 12. Dynamics of global gross GHG emissions (excluding LULUCF) E, net sink S due to LULUCF, and carbon CCS amounts according to the calculations of this paper for the historical (a) and intensive (b) scenarios

2.4°C by the end of the current century. Within the scope of the rather optimistic "intensive" scenario proposed in this paper, the temperature increase will peak at around 1.8°C, which means that the period of the dangerous temperature overshoot will be very long and likely last at least a century (Klimenko et al. 2022b).

There is no doubt that the world community's current efforts to achieve carbon neutrality by mid-century are doomed to failure, but they are not in vain. Although the temperature increase cannot be kept below 1.5°C, we are still able to keep this parameter below the 2°C threshold and minimize residence time in the dangerous beyond-the-limit zone. According to our preliminary estimates, this beyond-the-limit period will be more than a century long, and the core problem for the global community during this period will be adaptation to previously unknown conditions and building of a global economy with negative GHG emissions. The foundations of this economy arise today.

MODEL ESTIMATES OF GLOBAL ATMOSPHERIC AND CLIMATE CHANGES

Based on the estimates of anthropogenic net GHG emissions developed in this paper, a combined climate model (Klimenko et al. 2017) along with a global carbon cycle model (Klimenko et al. 2020) were employed to simulate changes in the concentration of carbon dioxide in the atmosphere and changes in the average global temperature, and the obtained results were compared with other scenarios – "Paris" (Klimenko et al. 2016a, Klimenko et al. 2016b) and "Glasgow" (Klimenko et al. 2022a, Klimenko et al. 2022b), which assume the implementation of decisions of the relevant conferences of the UNFCCC's parties.

The combined climate model (Klimenko et al., 2017) consists of the global energy balance model calculating the temperature response to both anthropogenic and natural forcing and a statistical block connecting the latter to the observed data. The model simulation results obtained for the last 35 years (1990-2025) are fairly consistent with the instrumental data (Klimenko et al. 2015).

The carbon cycle model (Klimenko et al. 2020) is the global box-diffusion model with the advanced biotic block, whose projections have also shown a very good agreement with the observations of the last 25 years (Klimenko et al. 2015).

The calculations were performed using scenarios of anthropogenic industrial net emissions (emission minus storage) (indCO_2) and biotic fluxes (bioCO_2) of CO_2, as well as radiative forcing of other GHGs (nonCO_2) and TSA of anthropogenic origin (Table 6 and Figs. 13–15). In addition, the effect of the main natural factors, such as solar and volcanic activities, as well as quasi-periodic processes in the ocean – atmosphere system, was considered.

According to the simulation results, the limits set forth in the Paris Agreement do not prevent a further temperature increase of up to 2.4°C by the end of the 21st century and nearly 3°C by the end of the 22nd century and are completely insufficient. At the same time, as we have already pointed out earlier in (Klimenko et al. 2023b), even the sluggish Paris limitations are not fully implemented today. Regarding the limits outlined in the Glasgow Pact,

Table 6. Combinations of scenarios of emissions and anthropogenic forcings for selected scenarios

Scenarios	Emission		Forcings	
	ind.CO_2 with CCS	bioCO_2	nonCO_2	TSA
«Paris»	«Paris» (Klimenko et al. 2016a, Klimenko et al. 2016b)	FAOSTAT (Klimenko et al. 2020)	«Paris» (Klimenko et al. 2016a, Klimenko et al. 2016b)	«Paris» (Klimenko et al. 2016a, Klimenko et al. 2016b)
«Glasgow»	«Glasgow» (Klimenko et al. 2022a, Klimenko et al. 2022b)	GEPL'97 (Klimenko et al. 2020)	«Glasgow» (Klimenko et al. 2022a, Klimenko et al. 2022b)	«Glasgow» (Klimenko et al. 2022a, Klimenko et al. 2022b)
Net-Zero Intensive	This work	GEPL'97 (Klimenko et al. 2020)	This work	«Glasgow» (Klimenko et al. 2022a, Klimenko et al. 2022b)
Net-Zero Historical	This work	FAOSTAT (Klimenko et al. 2020)	This work	«Glasgow» (Klimenko et al. 2022a, Klimenko et al. 2022b)

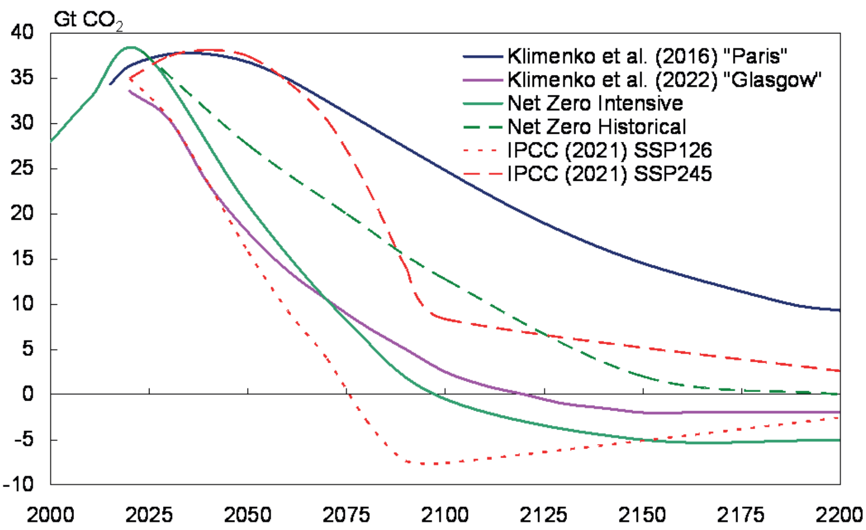


Fig. 13. Dynamics of industrial net-emissions of carbon dioxide (considering CCS) – history[7], scenarios SSP126 and SSP245 (Gidden et al. 2019, Meinshausen et al. 2019), and from this work (Table 6)

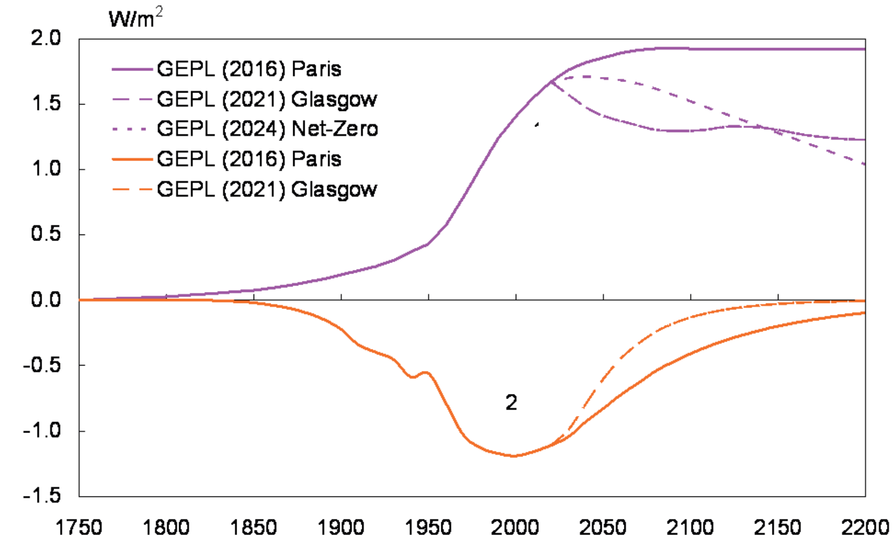


Fig. 14. Dynamics of radiative forcing of other GHGs (1) and tropospheric sulfate aerosol (2) – history (IPCC 2021) and scenarios from Table 6

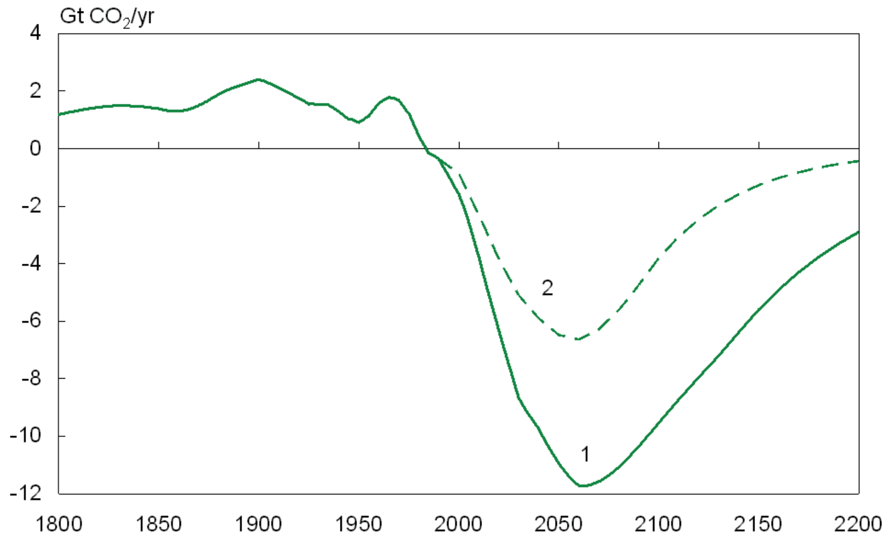


Fig. 15. Dynamics of biotic carbon fluxes (from LULUCF with bioproductivity change): history (IPCC 2021) and scenarios (Klimenko et al 2020) GEPL1997 (1) and FAOSTAT (2)

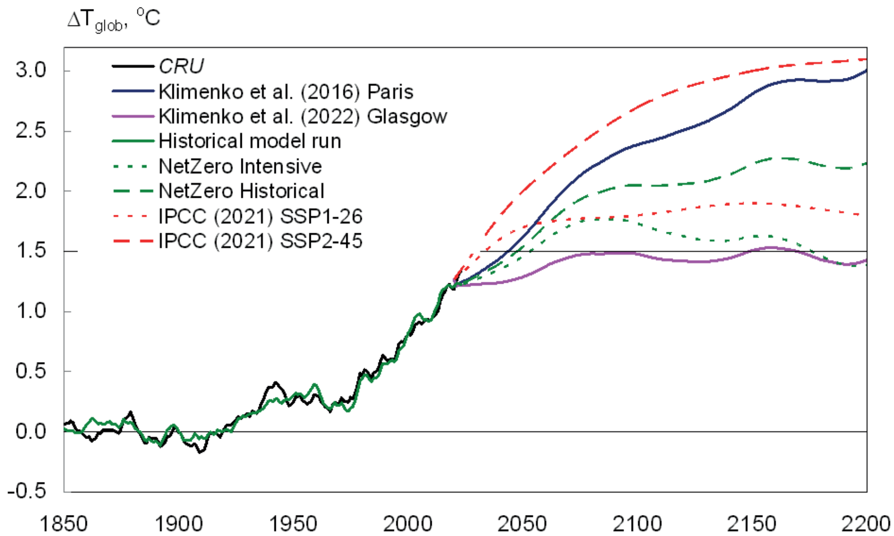


Fig. 16. Dynamics of the GMT (referenced to the average over 1850-1900) – history (CRU[1]), model simulations according to scenarios in Table 6 and (IPCC 2021; Klimenko et al. 2016; Klimenko et al. 2022b) studies

only their full and timely implementation will allow for keeping global warming below the targeted 1.5°C. However, an analysis of current trends shows that the Glasgow scenario rather demonstrates such a possibility, but in fact it cannot be implemented since the existing developing historical trends (Klimenko et al. 2023b, Klimenko et al. 2024c) cannot be overcome. At present, deployment of the most revolutionary scenario, NetZero Intensive, still seems feasible. It envisages that the temperature increase will reach its maximum of about 1.8°C at the end of this century and then gradually decline to the current values as a result of removing excess CO^2 from the atmosphere. However, even with this most revolutionary scenario, the period of the dangerous temperature overshoot above 1.5°C will likely last longer than a century.

RESULTS AND DISCUSSION

Figs. 11 and 13 compare the estimates of production and net emissions of greenhouse gases predicted in this work with the results of other studies carried out by leading global energy agencies (IEA[8], BP[19]), as well as academic institutions within the scope of the IPCC activities (Gidden et al. 2019, Meinshausen et al. 2019)[20].

Since the time horizon of energy forecasts of IEA8, BP19 is limited to 2050, for closer comparison, this time interval is shown in Fig. 17.

Despite the fundamental difference in the approaches to the simulation of the development of the power industry and other fields of human activities, the scenarios of application of the decisions of the UNFCCC parties conferences in Paris (2015) and Glasgow (2021), developed earlier by the authors of this paper, agree well with the low SSP245 and SSP126 scenarios (Gidden et al. 2019, Meinshausen et al. 2019), respectively.

As for the estimates of the present work, in the period up to 2050 they lie in a much narrower range, approximately halfway between the SSP245 and SSP126 trajectories. The "NetZero Historical" scenario is consistent with the inertial forecasts STEPS[8] and Current Trajectory20 of the energy agencies, which indicates a proper interpretation of the current trends in the global energy and the overall global economy within the scope of this work. Considerable differences are observed when comparing more radical scenarios. The accelerated decarbonization pathways of the APS8 and Net Zero20 scenarios assume exceptionally high rates of net GHG emissions decrease, reducing them by several times (by three times for APS scenario and by more than 10 times for Net Zero scenario) in just two and a half decades. In such an inertial system as the energy industry, such rates of radical change can hardly be attained at all.

Calculations of the cumulative (2020-2200) biotic carbon uptake according to the projections of the present study (160 Gt C for the historical scenario and 330 Gt C for the intensive one) are fairly consistent with its current potential estimates from Mo et al., 2023: 150-350 Gt C.

Over a longer time period (up to the end of the current century and further – see Fig. 9), the net GHG emissions scenarios proposed in this paper follow the trajectories of long-term SSP scenarios. The emission according to the NetZero Historical scenario by 2100 in its cumulative value roughly agrees with the SSP2-45 estimates, and according to the NetZero Intensive scenario, just like in the SSP1-26 option, it goes into the negative area, but only 20 years later.

The results of model simulations of changes in the GMT, performed using the authors' complex of models of the global climate system and presented in Fig. 12, are in good agreement with the IPCC estimates (IPCC 2021) obtained within the scope of the project of comparing the results of CMIP6 climate models for the corresponding scenarios. Thus, a growth in the GMT according to the "Paris" scenario agrees with the SSP2-45 model calculations, according to which the GMT will increase compared to the preindustrial level by 2°C by 2050 and by 2.7°C by 2100. The results of calculations for the NetZero Intensive scenario are close to the estimates of the SSP1-26 option, according to which the GMT peaks at 1.7-1.8°C above pre-industrial level in the second half of the current century.

Thus, employing here the historical-extrapolation approach to the projection of the development of the energy sector and other fields of business activities and their impact on the global climate system yields results that

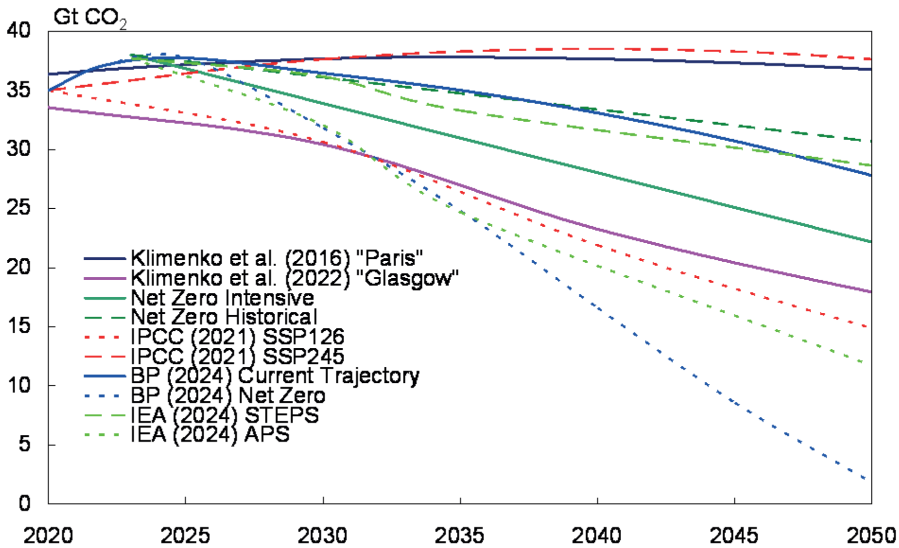


Fig. 17. Scenarios of industrial net emission of carbon dioxide (considering CCS): SSP126 and SSP245 (Gidden et al. 2019, Meinshausen et al. 2019), STEPS and APS of IEA[8], Current Trajectory and Net Zero of BP[20], and this work (Table 2)

[20]By the issue of the IPCC Sixth Assessment Report (IPCC 2021), a group of scenarios of anthropogenic impact on the atmosphere and climate, SSP ("Shared Socioeconomic Pathways"), was developed, offering various trajectories of greenhouse gas emission dynamics depending on the target level of impact by 2100 and the paths of global socio-economic development. This paper intentionally ignores the most severe of them – SSP3-7.0 and SSP5-8.5, which assume that anthropogenic emissions will not only retain their current level but even will grow at a higher rate, as well as the unjustifiably optimistic SSP1-1.9, aimed at achieving the climate neutrality by 2050.

are quite consistent with the outcome provided by other methods of simulation of socio-engineering systems. Our findings show that the historical approach can probably more accurately capture the boundaries of potential future changes, which makes it a valuable tool in constructing long-term adaptation scenarios.

CONCLUSIONS

1. All studied countries are considerably behind schedule in their emissions reduction activities, and none of them is on track to achieve carbon neutrality within the specified timeframe.

2. In various relevant areas of human activities characterized by considerable inertia (power industry, agriculture and forestry, other industries), certain historical patterns have profound effects that prevent the desired transformations from being carried out at arbitrary rates.

3. The climate protection targets set by the studied countries cannot be attained since the capacities available in these countries are not adequate to transform their economies even in the face of increasing climate risk.

4. The window of opportunity has closed finally. The threshold of conditionally safe warming of 1.5°C will inevitably be exceeded in the next ten years, and the period of the dangerous temperature overshoot will be longer than a century.

5. The focus of the global community's efforts should be gradually shifted from mitigation to adaptation to unique climate conditions based on proactive measures.

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