THE DUAL ROLE OF GLOBAL INFRASTRUCTURE IN CLIMATE CHANGE: NEW RISKS AND CHALLENGES

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Abstract

The paper (opening keynote lecture of the 6-th Eurasia Risk 2024 Conference) examines, from the interdisciplinary positions of the infranetics umbrella science and MABICS convergent technologies, the problem of climate change as a generally recognized consequence of the heating of the Earth's atmosphere due to uncontrolled emissions of greenhouse gases (GHG) by the global infrastructure (GI) – the second, artificial, nature created by man. An overview is given of the state of the problem of reducing the carbon footprint (CF) of the global system of infrastructure systems, which, on the one hand, ensures the sustainable development of the mankind, and on the other hand, is the main cause of global warming, which, if not combated, poses an existential threat to humanity. It is shown that the problem of restoring and maintaining the homeostasis of planetary ecology consists in ensuring a balance between two opposite processes – sustainable socio-economic development of the world community and greenhouse gas (GHG) emissions, by achieving net zero emissions. The problem of quantitative accounting, assessing and minimizing the infrastructures CF at all stages of their life cycle (LC), including diagnostics, monitoring, maintenance, recovery from accidents and disasters, is considered. Significant information gaps and scatter in CF estimates are noted, which indicate insufficient accuracy of the currently used methods. It is shown that it is necessary to develop a working algorithm for solving the global carbon balance equation considering climate change, according to the top-down scheme, which shows the contribution to the global CF of each infrastructure over time, according to the criterion of achieving zero CO_2 emissions by 2060, in accordance with countries' obligations under the Paris Protocol of 2015.

Keywords: global warming, global carbon budget, greenhouse gas emissions, economic and digital footprints of infrastructure, decarbonization, carbon offsetting

I. Introduction

The heating of the Earth's atmosphere has led to an increase in the frequency, strength and duration of geometeorological phenomena (drought, wind speed, precipitation amount), the emergence of new climatic phenomena (reduction of the ice cover of the Arctic Ocean, thawing of the Arctic tundra, accelerated melting of the Antarctic and Greenland ice, rising sea levels, thermal domes/islands), which have led to the emergence of new existential threats and risks, and imperatively requires a revision of almost all ideas about how to design and operate the global cyber-physical infrastructure of the 21st century in order to ensure its reliability, resilience and security.

The paper presents a system classification and structuring of greenhouse gas (GHG) emissions and absorption on a global scale. It analyzes the global, country, sector and corporate (dis)balance of the CF in the context of each individual infrastructure's CF during its creation, operation and disposal. It considers a risk-oriented problem of Pareto optimization of an infrastructure system based on its CF indicator, with given country, sector and/or corporate time-based restrictions on GHG emissions. It presents data on existing methods of GHG extraction from the planet's atmosphere and its burial at the bottom of deep oceans or in fractured rocks of the Earth's mantle (Nobel Peace Prize 2007).

The problem of preserving the vitality and fertility of agricultural lands and soils, which arose due to global warming and directly affects the food security of mankind, is also considered.

The role of the human factor in the problem of mitigating the consequences of the climate change when managing the second nature is considered. It is shown that all decision-makers (DMs) at all levels of the global, national, regional and corporate hierarchy, every inhabitant of planet Earth must be involved in solving this existential problem. It is necessary to find (in addition to existing ones) new ways to support, stimulate and finance all scientific, technical and organizational efforts aimed at solving this global problem.

At all stages of the presentation, an interdisciplinary approach to solving the problem is traced based on the use of convergent MABICS-technologies of the infranetics umbrella science.

II. Status of the problem: a brief review

We are interested in the problem of anthropogenic climate change as a generally recognized consequence of the heating of Earth's atmosphere due to uncontrolled emissions of greenhouse gases (GHG) by the global infrastructure (GI) – the second, man created artificial nature. A greenhouse gas (GHG) is a gas of natural or anthropogenic origin that absorbs and emits radiant energy in the thermal infrared range, causing the greenhouse effect (GE).

The main GHG is carbon dioxide (CO_2). Although other GHGs are more effective per molecule in warming the planet than CO_2, the enormous amount of CO_2 emitted by human activity and the fact that some emissions remain in the atmosphere for hundreds or thousands of years make CO_2 the single biggest problem in the fight against climate change. Emissions of all other GHGs are converted to carbon dioxide using special formulas and expressed in terms of mass of CO_2-eq. Carbon footprint is the amount of CO_2-equivalent that enters the atmosphere through human activity. Of the total estimated GHGs emitted into the Earth's atmosphere, about 90 % is due to human activities.

Without GHGs, the average surface temperature of the Earth would be about -18 °C, rather than the current average of +15 °C. The main GHGs in the Earth's atmosphere are water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3).

For a long time, the atmosphere contained a safe amount of GHGs, emitted by evaporation of the oceans, volcanic activity and forest fires. Human activity since the beginning of the Industrial Revolution (around 1750) has led to an increase in the concentration of carbon dioxide in the atmosphere by more than 50 % by now. The planet has become increasingly warm, and the threat of global warming has loomed.

At the current rate of GHG emissions, the Earth's temperature could increase by 2 °C by 2050, which, according to the UN Intergovernmental Panel on Climate Change (IPCC), is the upper limit that still allows avoiding "dangerous" levels of atmospheric heating [1]. It is necessary to reduce carbon emissions so that the observed increase in the average temperature of the Earth's atmosphere does not exceed the critical 1.5 °C. To do this, the global average human CF (in t CO_2-eq./person·year) must be reduced to 2.5t by 2030 and to 0.7t by 2050. Today, according to statistics from the Global Carbon Project [2], the CF of a US resident is 16.4t, the EU – 6.8t, China – 7.4t, and Russia – 12.5t. The global average is about 5 tons of CO_2-eq./person·year.

Signs of a climate crisis include heat waves, fires, floods and powerful storms, flooding of cities, extinction of biological species, drought and other natural disasters. If the situation is not changed, then very soon we will experience an increase in the frequency of natural disasters, the planet will have significantly reduced supplies of drinking water, existing desert zones will expand, outbreaks of epizootics, epidemics, infectious diseases, and famine will occur in many regions. In the most negative forecasts, all life on Earth may be under threat.

The anthropogenic factor has a huge impact on the manifestation of natural emergencies. Human activity disrupts the balance in the natural environment. Already now, the features of the global ecological crisis caused by the growth in the scale of use of natural resources are noticeably manifested. The main causes of natural hazards are:

- increasing anthropogenic impact on the environment;
- irrational placement of economic facilities;
- settlement of people in areas of potential natural hazard;
- insufficient efficiency and underdevelopment of hazard monitoring systems;
- absence or poor condition of hydraulic engineering, anti-landslide, anti-mudflow and other protective engineering structures, as well as protective forest plantations;
- lack and low rates of earthquake-resistant construction, strengthening of buildings and structures in seismically hazardous areas.

Currently there is a general understanding that natural disasters are a global problem that causes profound humanitarian shocks and are one of the most important factors determining sustainable economic development. Climate change increases the frequency and extremeness of severe weather events, which remain a major obstacle to sustainable development in cases where economic incentives for the development of hazardous areas do not exceed the expected disaster risks.

Extreme weather caused by climate change has pushed nearly 100 million people into hunger and increased heat-related deaths by 68 % among vulnerable groups. Globally, burning coal, oil, natural gas and biomass causes air pollution that kills 1.2 million people each year.

According to a new report published by the UN Office, the financial losses on global markets between 1998 and 2017 due to natural disasters increased by 251 %. In just 20 years, there were 7,255 major natural disasters in the world (i.e. one disaster per day). The most common disasters, based on the data in Fig. 1, are floods (43.4 %) and storms (28.2 %) [3]. Today, the concentration of CO_2 in the atmosphere is 0.04 % and this figure is growing. Global carbon dioxide emissions have reached 36 gigatons per year, and the average global temperature has already increased by 1.1 °C (in some places on the planet by 1.5 °C) [4].

III. Global carbon budget

The world's carbon budget includes all CO_2 emissions and absorption that are the direct or indirect result of human activity. The largest component of emissions comes from the combustion of fossil fuels (coal, oil and gas), which accounts for almost 90 % of all CO_2 emissions. The next smallest component comes from cement production. The remaining emissions come from land use changes (e.g. deforestation).

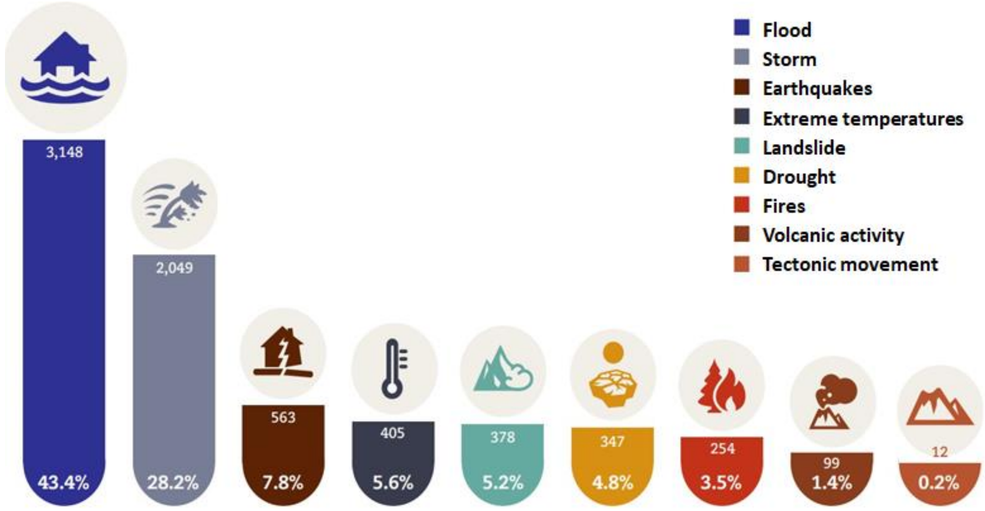


Figure 1: *Statistics of natural disasters in the world in the period 1998-2017*

The good news is that of all the CO_2 emitted by humans into the atmosphere, only about half remains in the atmosphere, causing climate change; the other half is removed by CO_2 sinks on land (vegetation through photosynthesis) and the oceans (through diffusion). The impact on climate change is therefore only half of what it would be without the help of these natural CO_2 sinks. Monitoring and predicting the evolution of CO_2 sinks allows to quantitively estimate the speed of climate change.

The assessment of the global carbon budget is carried out by the Global Carbon Project (GCP), which unites more than 50 research institutes around the world that collect observations, maintain statistics, and develop global models for annual updating and improvement of the carbon budget. The key point of the GCP Global Carbon Budget 2023 report [2] is the conclusion:

- If current CO_2 emissions levels continue, the remaining carbon budget for a 50 % chance of limiting warming to 1.5 °C could be exceeded in 7 years, and for 1.7 °C in 15 years;
- Returning global temperatures below these thresholds once they are crossed will require a massive increase in carbon dioxide removal after net-zero global emissions are achieved.

IV. The Role of the global infrastructure associated with climate change

Anthropogenic heating of the Earth's atmosphere has led to the intensification of existing and the emergence of many new climate phenomena that threaten the sustainable development of regions, territories, countries and continents, as well as to the destabilization and destruction of the Earth's ecosystem. This heating has already affected the astronomical parameters of the Earth as a planet. Typical examples of such phenomena are:

- Rising sea levels caused by melting Antarctic and Greenland glaciers will eventually flood coastal regions and cause the disappearance of a number of Pacific island-states.
- Changes in precipitation patterns, leading to desertification and an increase in floods, hurricanes and tsunamis.
- Decreased crop yields and, consequently, a food crisis and famine.
- Lack of drinking water.
- Death of flora and fauna.
- Slowing down of the Atlantic Meridional Overturning Circulation (AMOC) conveyor belt as new freshwater flows from melting Greenland ice upsetting the existing balance of salt and fresh water in the circulation. Scientists fear that if the engine slows too much, it could stall, changing weather patterns (for the worse) for billions of people in Europe and the tropics. The

timing of such a tipping point is not yet predictable.

- A decline in the West African monsoon could transform tropical forests into grassy savannas.
- The thawing of the Arctic tundra, accompanied by the appearance of *batagaykas* – giant funnels (craters) in the Siberian tundra, which were apparently caused by huge bubbles of methane from melting clathrates (methane ice) erupting onto the surface. The first of these craters, discovered in 2014, was 30 meters in diameter and more than 70 meters deep, which gives some idea of the force of the eruption and the pressure of the methane accumulated beneath it. Batagayka is a newspeak, comes from the word Batagay – the name of a city built in the Chersky Ridge area in the Verkhoyansk region of Yakutia (Russia) for tin deposit developers. In 1969, geologists discovered the largest Batagay permafrost crater in the world near this city, or Batagayka (nicknamed in the media – Gates of Hell) [5].

As the soil thaws, the methane ice melts quite fast. Scientists believe that of all the possible events that could push the world toward abrupt, catastrophic, and irreversible climate change, only one—clathrate release—poses an immediate potential threat. Extraction of methane from seafloor clathrates could trigger massive underwater landslides and subsequent tsunamis.

To have a real chance of avoiding catastrophic climate change, it is not enough to slow the process; we must find a way to reverse it. This means removing CO_2 from the atmosphere and, ideally, returning the planet's atmosphere to pre-industrial CO_2 levels.

Effective carbon capture and storage can provide zero-emissions electricity, as renewable energy does now. But this is not enough to stop the runaway climate change that climate scientists believe may be underway. More must be done, namely (1) removing carbon from the atmosphere and (2) breaking the vicious cycle of methane release from the melting permafrost.

Virgin Enterprises founder Richard Branson launched the largest $25 million science prize ever in 2007 for a way to extract one gigaton (a billion tons) of carbon from the atmosphere each year. There are currently 11 finalists working toward that goal [6].

One of the fastest ways to capture atmospheric carbon is to grow fast-growing algae that can be turned into biochar through pyrolysis. This could go beyond zero human emissions and reduce methane emissions in the Arctic, but it would require a significant increase in the price of the carbon sequestered in this way to make it possible. The funds needed to do this, according to the Paris Agreement, could come from the developed world, which must raise (according to the COP 29 Resolution) $300 billion a year (by 2030) to help poorer nations achieve sustainable development.

On a planetary scale, the permafrost layer of the Earth contains about 1.6 trillion tons of CO_2—about twice as much as the Earth's atmosphere currently contains. Scientists call this carbon, made up of plants and animals that froze before they could decompose, *deep legacy carbon* [7]. All of this creates a new, previously non existing threat of collapse for the entire Arctic infrastructure: port facilities, railways, roads, airports, oil and gas pipelines, LNG plants, buildings and structures

(Figs. 2, 3, a, b [8]):

- Thermal domes (islands), not only in countries with a hot climate, but also in regions with a moderate climate (for example, East Canada), where the temperature reaches +50 °C and + 40 °C and higher, respectively, and lasts for several weeks, including at night. This leads to a decrease in human cognitive abilities, and to a mass manifestation of subresilience of people living under such a dome (on such an island), and corresponding expenses to cure this illness;
- Change in the relief of the Earth's surface;
- Change in the tilt of the Earth's rotation axis due to the melting of Antarctica ice;
- Increase in the time of the Earth's daily rotation (yet, by several milliseconds);
- Change in the dynamics of the Earth's crust, its interaction with the mantle and the Earth's surface, which must be considered for achieving needed accuracy of space navigation;
- Rising ocean temperatures are causing corals to expel the symbiotic algae that live inside their tissues. This bleaching is fatal to corals. Scientists predict that even if humanity quickly takes action to curb global warming, 70 to 90 percent of today's reef-forming corals could die in the coming decades. If not, the loss could be 99 percent or more;
- Deforestation of the Amazon could reduce rainfall in the region, causing the remaining forest to degrade and turn into grassy savannah. Researchers estimate that by 2050, a good half of today's Amazon forests could be at risk of this fate.

I. Classification of environmental emergencies associated with changes in

Land conditions:

- intensive soil degradation;
- catastrophic subsidence, landslides, collapses of the earth's surface due to subsoil development or mining;
- the presence of heavy metals and other harmful substances in the soil more than maximum permissible concentrations;
- depletion of non-renewable natural resources;
- overflow of storage facilities (landfills) with industrial and household waste, pollution of the environment by them.

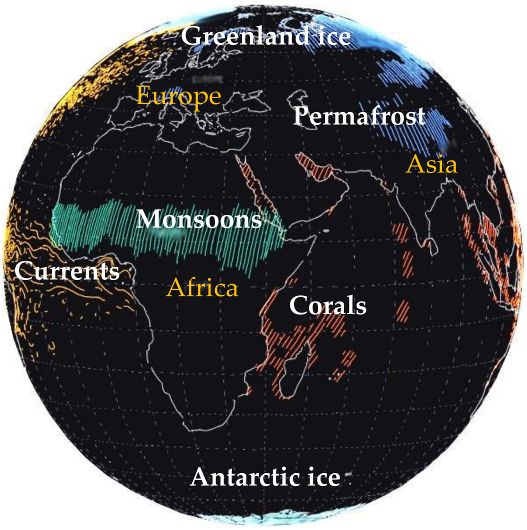


Figure 2: *Changes in the Earth's ecosystem because of global warming*

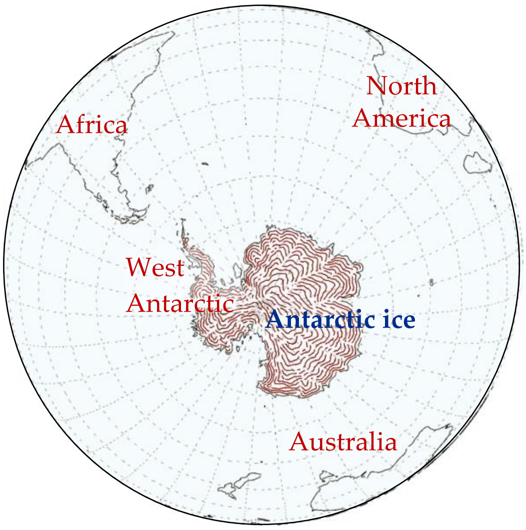


Figure 3: a. *Changes in the Earth's ecosystem because of global warming*

Figure 3: b. *Changes in the Earth's ecosystem because of global warming*

Composition and properties of the atmosphere:

- abrupt changes in weather or climate because of anthropogenic activity;
- temperature inversions over cities;
- severe oxygen starvation in cities;
- significant excess of the maximum permissible level of urban noise;
- exceeding the maximum permissible concentrations of harmful impurities in the atmosphere;
- formation of a vast zone of acid precipitation;
- destruction of the ozone layer of the atmosphere;
- significant change in the transparency of the atmosphere.

Composition of the hydrosphere:

- a sharp shortage of drinking water due to the depletion/ pollution of water sources.

II. The global carbon footprint (GCF)

The main emitting sectors in both the global and national economies are: (1) energy, (2) industry (non-energy processes), (3) agriculture, forestry and land use, and (4) waste disposal and recycling. The contributions of each sector, as well as the shares of subsectors of industries, to global emissions (according to World Resources Institute (WRI) data for 2016 [9]) are graphically presented in Figs. 4, 5.

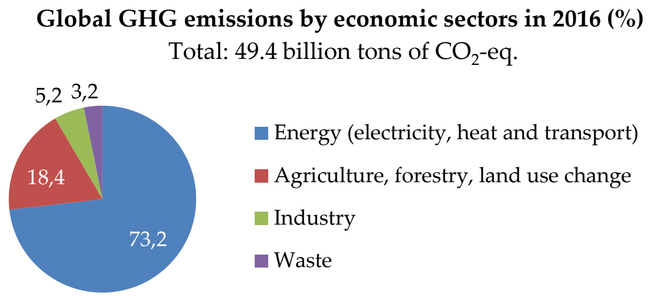


Figure 4: *Distribution of global greenhouse gas emissions (GGHG) by economic sectors in 2016 (%)*

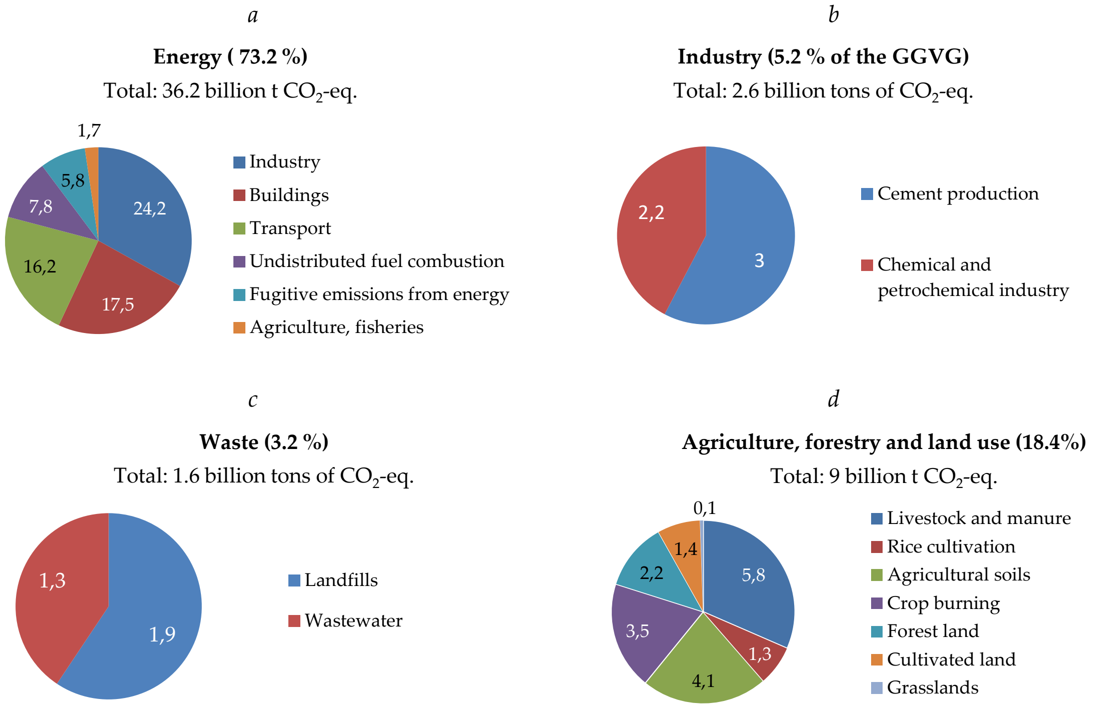


Figure 5: *Distribution of GHG emissions in 2016 (% of the GGHG):*
a – in the energy sector; b – in the industrial sector; c – in the waste sector; d – in the agriculture, forestry and land use change

The global carbon footprint of the world for a period t is the sum of the carbon footprints of all countries for the same period *t*:

$$CF_{\text{glob.}} = \sum_i CF_{\text{country}} , \tag{1}$$

where $CF_{\text{glob.}}$ is the global CF, CF_{country} is the CF of the *i*-th country.

According to the European Commission's GHG data (EDGAR – Emissions Database for Global Atmospheric Research), in 2023 the global economy produced 52.9629 billion tons of CO_2-eq. [10]. The distribution of countries' contributions to the global CF is presented in Fig. 6.

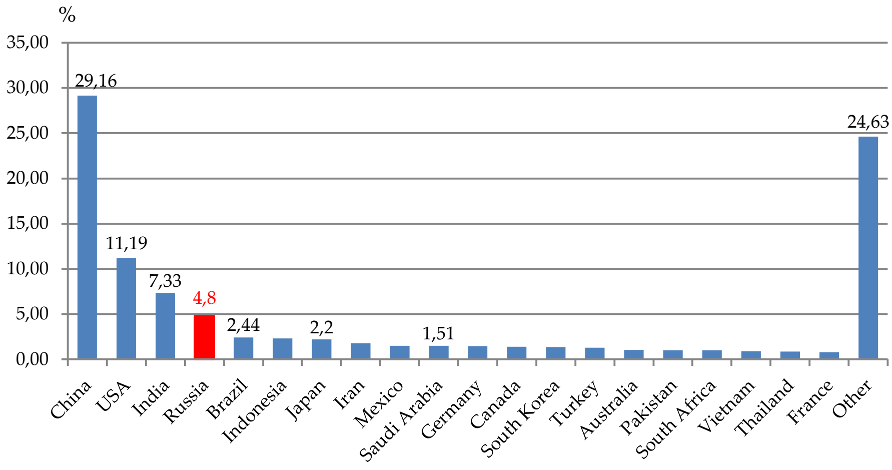


Figure 6: *GHG emissions by country in 2022 (% of global emissions)*

The GCF can also be represented as the sum of emissions from all sectors of the global economy:

$$CF_{\text{glob.}} = \sum_i CF_{\text{sector}}\ , \tag{2}$$

where CF_{sector} is the CF of the i-th sector of the world economy.

A country's GHG emissions are formed from emissions from all sectors of its economy:

$$CF_{\text{country}} = \sum_i CF_{\text{s},i}\ , \tag{3}$$

where $CF_{\text{s},i}$ is the GHG emission of the i-th sector of the country's economy.

The GCF, expressed in terms of country sector emissions, can be written as

$$CF_{\text{glob.}} = \sum_i \sum_j CF_{i,\text{s},j}\ , \tag{4}$$

where $CF_{i,\text{s},j}$ is the GHG emission of the j-th sector of the economy of the i-th country.

The contributions of economic sectors of Russia, as well as the shares of subsectors of industries, to total country emissions are graphically presented in Figs. 7, 8 [11].

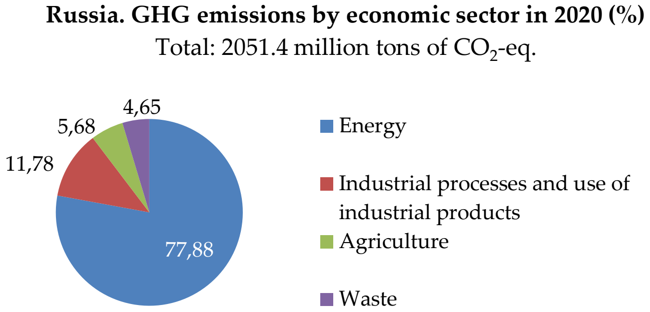
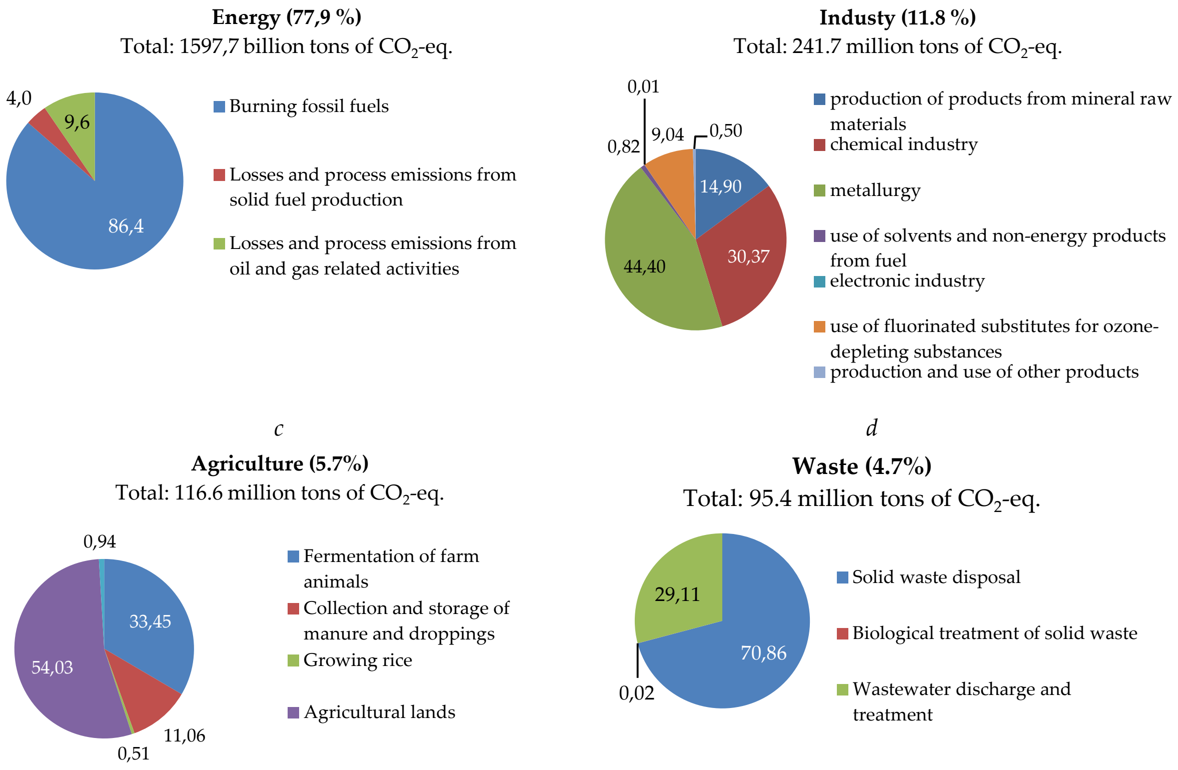


Figure 7: *Distribution of GHG emissions by economic sectors of Russia in 2020 (%)*

a

b



Energy (77,9 %)
Total: 1597,7 billion tons of CO_2-eq.

Industy (11.8 %)
Total: 241.7 million tons of CO_2-eq.

c

Agriculture (5.7%)
Total: 116.6 million tons of CO_2-eq.

d

Waste (4.7%)
Total: 95.4 million tons of CO_2-eq.

Figure 8: *Distribution of GHG emissions of Russia in 2020 (% of total CF):*
a – in the energy sector; b – in the industrial sector; c – in the agriculture; d – in the waste sector

V. Tasks of modern risk analysis of infrastructures in the context of climate change

The awareness that any human action is inevitably accompanied by an ecological trail, carbon emissions, economic and social footprint, allows setting and solving tasks of modern risk analysis in a new way. First, the CF must be considered as a planetary/country/industry boundary/maximum permissible condition (BC/MPC) acceptability of creating and operating each specific socio-technical system/infrastructure.

Infrastructure design must explicitly consider the impact of climate change on the magnitude of loads, impacts and any other stressors on the system being designed to prevent future incidents and accidents due to failure to consider increased impact values due to climate change. It is necessary to develop:

1) stochastic load and impact models, in the context of considering king-dragon events using heavy-tailed PDFs, as well as advanced degradation models of materials and structures;

2) risk-based design and maintenance standards for buildings and structures for thermal, wind, wave loads and impacts, and

3) full life cycles that consider climate change and the size of the carbon (as well as economic and digital) footprint of each infrastructure.

Particular attention should be paid to thermal loads in the Arctic Zone of the Russian Federation (AZRF), where the rate of warming is twice as high as the rate of global warming. Maintaining the reliability, resilience and safety of critical and strategic infrastructures in the context of global warming requires ever greater resources. This objectively reduces the economic efficiency of the oil, gas and transport sectors located in the AZRF.

A feature of modern risk analysis is that more and more attention is paid to the integrated economic consequences (damage) from undesirable events associated with a decrease in the physiological, cognitive and social abilities of an individual (and the affected community as a whole) over time from such stressors as active radiation, mass poisoning with chemicals (i.e., pesticides used in Vietnam), post-traumatic syndrome, etc. This problem is studied in the theory of sub-resilience.

I. Full life cycle (FLC) of the infrastructure

In the context of climate change, risk analysis must be carried out based on the FLC of the infrastructure/system/network. This relatively new task has a short history of its development.

In essence, the FLC is a forecast scenario for the entire period of the system's existence – from conception to disposal. The exception is infrastructures that have no visible end to operation. They exist almost forever: large cities, railways and highways, seaports, etc.

For a qualified and consistent assessment of the ecological/carbon footprint of the global artificial nature (GI), it is necessary to conduct a specific FLC analysis of each global infrastructure component (GIC) to assess (1) the magnitude of the ecological footprint and CF of the GIC as a random function of time and (2) its contribution to the global CF, influencing climate change on the planet.

The full life cycle of any GIC consists of following stages:

I) production of materials from which the GIC will be manufactured (extraction of raw materials to produce materials is usually not considered in the calculation of the CF);

II) production of the GIC;

III) construction of the GIC, including transportation, welding, installation of equipment, protection from external influences, acceptance tests;

IV) operation of the GIC in a stationary mode, including scheduled and unscheduled diagnostics, monitoring, technical repairs, maintenance, as well as restoration of the infrastructure after each accident, emergency or disaster;

V) recycling/disposal of the GIC after the end of its operation.

The infrastructure CF is an indicator of the environmental efficiency of its use at all stages of its LC and is therefore of great interest to the public and investors. Decision makers (DMs) when deciding on GI operation methods should (in the context of the Paris Protocol) separately consider the sizes of the current and the cumulative CF they create and the discounted cost of their neutralization, considering the impact of climate change.

In the conditions of dynamic multifactorial uncertainty of the modern world, the management of the GIC is carried out according to safety and risk criteria. In this case, the target function (TF) of risk management is reduced to minimizing the generalized cost of operating the GIC over the period "from conception/cradle to grave".

The problem of managing the GIC risk is posed as a problem of optimizing the target function, which should adequately reflect the total NPV of costs during its entire LC for:

1) creating and disposing GIC;
2) technical maintenance, repair and restoration due to possible emergency situations;
3) restoring the disturbed (due to system operation) ecological balance of the environment;
4) compensating the system's CF;
5) restoring lost human health and monetary compensation for the possible loss of lives and limbs during the GIC operation.

In the most general case, the problem of determining the man-made risk, interpreted as the product of the probability of failure (POF) and its consequences (losses/damage), expressed in monetary form, is formulated as a problem of Pareto-optimizing the target function, which is reduced to the integral cost of owning the GIC over its FLC:

$$_{\mathrm{GIC}}C_{\Sigma} = C_{\Sigma,c} + C_{\Sigma,in} + C_{\Sigma,r} + C_{\Sigma,cf} + C_{\Sigma,hl}\,. \tag{5}$$

Here $C_{\Sigma,c}$ is the total cost of design, construction and commissioning of the GIC, as well as its disposal after the end of its service life; $C_{\Sigma,in}$ is the total cost of all inspections on the GIC life cycle; $C_{\Sigma,r}$ is the total cost of all repairs/restorations during the life cycle of the GIC, including after accidents and disasters; $C_{\Sigma,cf}$ is the total costs of compensation for damage from CF; $C_{\Sigma,hl}$ is the cost of restoring lost human health and the amount of monetary compensation for possible loss of lives and limbs during the GI life cycle.

When solving the problem of assessing and minimizing the CF size, it is necessary to consider following circumstances.

The size of the CF when creating the GIC is determined by the facility design goals; at the same time, the CF size is subordinated to these goals and cannot be a limiting factor. It follows from this that compensation for the CF caused by the construction and commissioning of the GIC may require the use of special financial instruments (for example, planting a certain number of fast-growing and highly CO_2 absorbent tree species). At the same time, the size of the CF when utilizing such a GIC is also a certain function of its original goal.

The main CF occurs during the operation of the GIC. It is a function of the volume and quality of diagnostics, monitoring, maintenance, as well as the consequences of GIC pipelines and vessels depressurization because of incidents, accidents and disasters.

Since all these operational events are modeled when constructing a set of GIC life cycle scenarios required to assess and minimize operational risk, the value of the CF is obtained as a natural consequence of the scenario under consideration. In this case, minimization of the CF for each virtual violation of the integrity of the GIC pipeline or vessel is possible in the process of making the next decision. This allows for effective management of the CF size by selecting optimal system design, inspection technologies, scheduled repairs, and restoration of GIC after depressurization or accident.

II. General algorithm for assessing the carbon footprint of a GIC over its life cycle

Since the sectoral CF is formed by individual infrastructures of companies/states, its reduction is accomplished by reducing the CF of each infrastructure that comprises the sector, starting from the initial stage of the GIC life cycle – the production of its structural components and the construction itself. By analogy with the name of the life cycle stage, the emissions of this stage are called initial CF of the GIC.

The design CF of an infrastructure is the CF emitted during its construction and normal operation, without accounting for any unplanned emissions due to accidents and subsequent restorations. For newly designed facilities, this value will be legislatively reduced. This will demand using new low-carbon technologies for building the structures, improved risk-oriented methods of facility operation, and advanced technologies for capturing the carbon emitted by the GIC.

In general, the calculation of the GIC CF considers emissions of all types of GHG, as well as indicators of energy expended per unit of production generated at all stages of its LC.

VI. Methods for reducing atmospheric carbon masses

There are two ways to decarbonize the Earth's atmosphere: through natural CO_2 absorbers and through technical and economic measures.

Natural CO_2 absorbers are:

- Healthy forests;
- Marsh and peat ecosystems (main absorbers of atmospheric CO_2);
- Brown algae.

Technical and economic measures are:

- Sequestration directly at plants and enterprises emitting GHGs;
- Minimization of fugitive gas leaks;
- Renewable energy sources;
- Alternative (low-carbon hydrogen) fuel;
- Use of electric vehicles, electric and hydrogen aircraft;
- Technologies for removing CO_2 from the atmosphere;
- Policy of "green" loans.

VII. Nuclear power carbon footprint

In nuclear power, the fulfillment of the undertaken obligations to reduce CO_2 emissions and achieve carbon neutrality is realized by replacing *dirty* electricity with *environmentally friendly* electricity.

The production of 1 kWh of electricity by burning coal produces 1700 g of GHG; when burning natural gas, the emission is about 900 g; at a hydroelectric power station – about 50 g; at a wind power plant – about 50 g; at a solar power plant – about 100 g; for nuclear energy – from 2 to 130 g CO_2-eq./kWh, with an average value of 29 CO_2-eq./kWh [12].

I. Recommendations for reducing the nuclear fuel cycle emissions

- When mining uranium, it is recommended to carry out underground leaching (characterized by the lowest energy and material costs).
- In the process of ore enrichment, gas centrifugation is more environmentally friendly than gas diffusion, since electricity from renewable energy sources is used.
- When choosing a site for the construction of a nuclear power plant (NPP), the potential loss of carbon by vegetation should be considered. During the construction period, the amount of materials and energy used can be reduced by reducing design redundancy, optimizing the design and shortening the construction period.
- During operation, it is recommended to use 5G and artificial intelligence (AI) technologies to enhance the digital transformation capabilities of the NPP, so that it can be operated with less dependence on personnel and, consequently, with lower emissions. At the end of the nuclear fuel cycle, a closed fuel cycle (CFC) strategy is recommended, where the spent nuclear fuel is reprocessed to extract unburned uranium U and accumulated plutonium Pu, which are then used to manufacture new fuel elements.

Effective management of carbon forests can potentially provide Russian nuclear power plants with conditions in which up to 20–25 % of all carbon emissions will be offset by an increase in phytomass in forests located within the sanitary protection zones of NPPs [12]. According to the statement by Russian Prime Minister M. Mishustin at the UN COP 29 conference on November 13, 2024 in Baku, Russian forests make up 20 % of the world's forest lands and absorb one billion tons

CO_2 per year.

VIII. Hydrogen energy carbon footprint

In hydrogen energy, the fulfillment of the undertaken obligations to reduce CO_2 emissions and achieve carbon neutrality is realized through the production of low-carbon hydrogen [13]:

- from fossil raw materials, including using CO_2 capture technologies;
- based on a nuclear power plant (with CO_2 capture);
- by water electrolysis based on a NPPs, hydroelectric power plants and electricity from power systems, subject to ensuring a low-carbon footprint, as well as
- based on renewable energy sources in those regions where the cost of hydrogen produced based on such sources is competitive.

IX. Carbon offset measures

1) Purchasing emission quotas from oil and gas transportation companies that have been able to reduce their emissions below established limits;
2) Investing in emission reduction projects (e.g., renewable energy sources) or offset projects (reforestation);
3) Purchasing certificates from specialized organizations that finance GHG emission reduction projects.

X. Measures to prevent accidental emissions

To prevent malfunctions and emergency situations of the GIC such as oil and gas pipelines, pressure and temperature monitoring are carried out – the main operational parameters of pipelines and pressure vessels, as well as their regular diagnostics and inspection to detect and assess deformations, welding defects, dents, damage to the protection of pipelines, pressure vessels, as well as possible leaks of natural gas.

The main reason for the cumulative growth of the CF of the gas-oil complex is the depressurization of its pressure vessels and pipelines, accompanied by the release of gas condensate or crude oil due to corrosion or crack formation. To reduce the likelihood of these risks passive or active preventive barriers are used.

Preventive barriers (i.e., corrosion allowance, external anti-corrosion coating, cathodic protection) reduce the probability of risks and the severity of their consequences. Since they (even all together) do not guarantee the GIC against depressurization, they are supplemented by parry barriers (i.e., leak detection system; emergency shutdown, accident elimination plan), which are designed to reduce the consequences of GIC depressurization [14].

The task of minimizing the CF of a specific infrastructure during its life cycle to achieve the planetary planned CF values (based on the Paris Protocol of 2015) is solved using the target function, which includes direct and indirect GHG emissions as a function of time. The CF value is managed by the Pareto optimization method based on risk-oriented monitoring and maintenance, with given values of the initial and final (considering climate change) CF permissible values. This formulation of the optimization problem allows each enterprise to implement the task of reducing CF, the likelihood and consequences of incidents, accidents and disasters.

XI. The agro-industrial complex carbon footprint

The CF of the agribusiness sector has its own specifics. When forests are cleared for agriculture (and land use changes occur), the carbon stored in the trees is released into the atmosphere as CO_2. These emissions need to be considered in life cycle assessment (LCA) studies of agricultural production. In Europe, CF and LCA information is becoming increasingly important for feed and food producers (in some countries, providing this data is already mandatory).

In addition, in recent years, soil security has emerged as a new paradigm for addressing sustainable soil management. Soil security is defined as maintaining and improving the world's soil resources so that they can continue to provide food and freshwater, make significant contributions to energy and climate sustainability, and support biodiversity conservation and the overall protection of ecosystem goods and services [15, 16].

The European Commission has identified the following seven soil functions that should be protected:

- Biomass production, including in agriculture and forestry;
- Storage, filtration and transformation of nutrients, substances and water;
- Biodiversity pool (habitats, species and genes);
- Physical and cultural environment for humans and their activities;
- Source of raw materials;
- Carbon pool;
- Archive of geological and archaeological heritage.

Food and nutrition security (FNS), like soil security, has its own parameters: availability, access, utilization, and stability.

Food security is becoming increasingly challenging over time due to changes in supply and demand caused by population growth, climate change and environmental conditions. For a nation, community or individual to be food secure, it must *always* have access to sufficient, safe and nutritious food to support an active and healthy life.

Accessibility is the physical availability of sufficient food of adequate quality. This aspect of food security is directly linked to agricultural management and the availability of land for crop production.

XII. Conclusions

- To achieve a zero-carbon balance on a planetary scale, it is necessary, using the Paris Agreement limits on country emissions, to establish maximum permissible emissions (MPEs) within each country for each industry and life activity.
- Within each economic sector, it is necessary to establish MPEs for each and every network infrastructure and system. These MPEs are limitations that must be considered when designing new and operating existing infrastructures. This introduces a limitation on the CF during diagnostics, monitoring, maintenance, recovery after an accident and disposal of infrastructures and their components. In addition, it becomes possible to estimate the CF size of each incident, accident and man-made disaster. All these values must be optimally minimized.
- Considering the Paris Protocol on reducing the carbon load and achieving carbon neutrality by all countries to reduce the temperature of the atmosphere by two degrees, risk analysis procedures carried out at the design stage of the GIC should not only assess their level of safety, but also provide an assessment of the project CF.
- At the stage of risk-oriented operation of the GIC, it is necessary to plan and implement organizational and technical measures to minimize the CF, by ensuring high reliability of the GIC according to its integrity criterion.
- The initial and boundary conditions on the infrastructure CF organically converge social and cognitive sciences with engineering mechanics, computer science and artificial intelligence, forming a MABICS-technology, under the umbrella science of infranetics.

- In connection with the above, it seems appropriate to initiate a research topic on assessing the magnitude of the emissions arising from leaks and accidents of the GIC, which do not currently fall under the Order of the Ministry of Natural Resources and Environment of the Russian Federation dated 05/27/2022 No. 371 [17].
- It is advisable to introduce mandatory certification of each GIC for its emissions. This certificate must be confirmed annually. This certificate allows monitoring emissions of all sectors of the national economy and the rate at which the country (and global) emissions approach zero emissions.
- Certification of all lands from the viewpoint of (1) the safety of their soils and vegetation, (2) biocapacity/productivity and (3) CF will allow forming of a "reference point" for assessing the population quality of life, and the quality of services and industries. Completion of the first point will allow assessing (apparently for the first time) the country's bioproductive capacity and its ultimate capacity to absorb pollution as a function of time.
- When assessing the financial availability of food, it is necessary to consider the region's life quality index (LQI); when assessing its transport accessibility the reliability of transport networks (primarily highways) has to be considered, and when assessing the availability of food in a store it is necessary to assess the reliability of the supply chain and the level of reserves over time with random demand.
- The *supply–demand problem* (analogous to the classical *load-resistance* problem of the structural reliability theory) as applied to the food security problem has its own specific characteristics: the demand for civilization products, primarily food, can be regulated by social instruments; supply (production of edible biomass) is solved by ensuring agricultural soil reliability and safety, using advanced AI-based agricultural technologies and probabilistic forecasting of crops.
- Risk managers and risk analysts must be prepared for climate change shocks (and their implications for artificial intelligence, politics, finance, energy systems, food and water supplies, and pandemics) in the next few years, not at some unspecified time in the future.
- The largest emissions in the life cycle of a GIC are generated during its construction and operation phases.
- The main way to reduce GHG emissions is by using of energy-efficient technology and process equipment (e.g., new generation gas pumping units with low-emission combustion chambers).
- The Russan oil industry should: (1) lobby for a carbon price that will help it take market share from coal faster, (2) ask the government for financial incentives to capture Arctic methane emissions, produce and sequester biochar; (3) minimize methane leakage throughout the gas supply chain; (4) identify financial incentives that will make capturing methane leakage from permafrost profitable; (5) explore ways to convert atmospheric carbon dioxide into biochar for long-term storage and (6) identify financial incentives that will make this profitable [5].
- The super task of decarbonizing the Earth's atmosphere is the creation of nature-like, low-energy technologies and low-temperature processes that imitate the efficiency of those observed in nature.

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