Assessment of the contribution and measures to reduce the impact of the railway industry on the development of global warming

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Abstract. A review of current approaches to the assessment of the anthropogenic impact on global warming is presented. Measures to regulate greenhouse gas emissions are analyzed, including the introduction of a carbon tax and a system of national quotas for greenhouse gas emissions. The outcomes of the assessment of the contribution of the railway industry to gross greenhouse gas emissions are presented. The potential for the application of negative emission technologies at railway transport facilities is considered. Proposals are formulated to reduce the influence of the railway industry on the development of global warming. **Keywords:** global warming, railroad, negative emission technologies, greenhouse gases, sustainable development.

1 Introduction

The UN Conference on Environment and Development (Rio de Janeiro, 1992), affirming the Declaration of the UN Conference on the Human Environment (Stockholm, 1972) proclaimed as one principle that to achieve sustainable development, environmental protection must form an integral part of the development process and cannot be considered in isolation from it. However, another principal postulates that States have the sovereign right to exploit their resources according to their own environmental and developmental policies, and the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or areas beyond national jurisdiction. At the juncture of these two principles, we are now aware that the operation of several industries, especially given the obsolescence and obsolescence of technology, contributes significantly to global greenhouse gas emissions [1].

One of the outcomes of the development and adoption of the Kyoto Protocol to the UN Framework Convention on Climate Change (Kyoto, 1997) was the creation of the Intergovernmental Panel on Climate Change (IPCC), in addition, national governments are developing measures to improve energy efficiency in the relevant economic sectors and promote the introduction, development and wider use of new and renewable energy, carbon dioxide absorption technologies and innovative environmentally sound technologies [2-4]. Including the use of market instruments to stimulate these processes, such as the principle of quotas for

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greenhouse gas emissions (emission reduction units). The annex to the protocol defines a list of greenhouse gases (CO_2, CH_4, N_2O, HFC, PFC, SF_6) and emission source categories, including transport. At the same time rail transport includes power facilities where fuel combustion takes place. The Russian Federation has made commitments to limit or reduce emissions to the extent of 100% of the base year.

The next milestone event on climate change was the Paris Agreement (COP21). The 197 negotiators pledged to develop low greenhouse gas emission development strategies over the long term. This is the first global agreement to combat climate change. To date, it has been ratified by countries accounting for 96.98% of emissions, including Russia.

The COP-21 target is to limit average temperature increases to below 2 degrees from pre-industrial levels and to continue to implement actions to limit temperature increases to 1.5 degrees. To this end, the Paris Agreement stipulates that each country will review its commitments every five years to continue efforts to reduce greenhouse gas emissions. Funding is critical to support emerging economies and help them transition to a decarbonized economy. The agreement calls for $100 billion annually from public and private sources, starting in 2020, to fund projects that allow countries to adapt to climate change (rising water levels, drought, etc.) or reduce greenhouse gas emissions. This funding will need to be gradually increased, and some developing countries will be able to become donors voluntarily to help the poorest countries.

After six years of intense negotiations, in 2021, the open agenda items that had been impeding full implementation of the Paris Agreement on Carbon Markets and Reporting were agreed upon. The package of decisions from the 26th session of the Conference of the Parties to the UN Framework Convention on Climate Change (UNFCCC) (Glasgow, 2021) covers several agenda items on which an agreed position could be reached. These include efforts to strengthen climate resilience, reduce greenhouse gas emissions, and provide the necessary financing to combat climate change. States at COP26 called for reducing the share of unmodern zed energy capacity based on coal generation and inefficient fossil fuel subsidies. Analysis of climate change mitigation showed a persistent gap between actual emissions and the emissions needed to meet the goals of the Paris Agreement [5-9]. The parties agreed to work together to reduce this gap and ensure further progress during the current decade to keep the global average temperature rise within one and a half degrees Celsius relative to pre-industrial levels [10-11].

The ultimate goal of all agreements related to the FCCC is to stabilize the concentration of greenhouse gases in the atmosphere at a level that would not allow dangerous anthropogenic impacts on the Earth's climate system. Such a level should be achieved within a time frame sufficient for the natural adaptation of ecosystems to climate change and ensure further economic development on a sustainable basis [12-15].

2 Materials and methods

One of the mechanisms to reduce greenhouse gas emissions from non-modernized industries is the introduction of a transboundary carbon tax or a system of national emission credits. In this case, the expected size of the carbon tax, which can be imposed on suppliers of Russian goods and services with a large carbon footprint (production of iron, steel, aluminum, fertilizers) is estimated at least € 1.1 billion per year.

The essence of this method is that the additional costs are designed to encourage producers to reduce harmful emissions. The European Union (EU) sets import conditions that equalize the regulatory burden on importers and domestic producers. In this case, importing companies essentially pay for the implementation of the EU's climate expectations. The importing company is exempt from the purchase of carbon certificates if it can prove that it has paid a "price on carbon" for imported goods in its country. Currently, the preparation of national legislation in the field of decarbonization and its recognition at the international level is underway.

First of all, corporate decarbonization strategies must be formed. They must take into account the economically and technically achievable potential for reducing carbon intensity. This requires an inventory of the sources of greenhouse gas emissions, to assess the possibility of using the best available technologies, the application of technical solutions, and optimal regimes.

The second area is climate risk management. Managerial decisions in terms of responding and adapting to climate challenges are severely limited without a balanced assessment of transient climate risks. The Task Force on Climate-related Financial Disclosures (TCFD) methodology can be used for this purpose.

The third important aspect is interaction with Russian and international regulators and business associations.

The topic of climate change and carbon regulation, despite its relevance, is still poorly understood. Areas for improvement can be an understanding of industry specifics, analytics showing the impact of certain regulatory approaches on business and the outcomeing impact on reducing greenhouse gas emissions, and generally recognized methodological approaches-from calculating greenhouse gas emissions by individual production processes to account for the absorption of negative emissions by technologies. An important principle is that decarbonization strategies should take into account the economically and technically achievable potential of carbon intensity reductions.

Effective steps could include the active introduction of renewable energy sources; the development of low-carbon hydrogen energy; the creation of carbon-neutral territories that provide manufacturers with the necessary green infrastructure to reduce the carbon footprint of their products; and the formation of a market for direct contracts and "green" certificates.

The essence of the carbon reduction agenda is to build a more sustainable system, including transportation. On the one hand, it must satisfy consumers and, on the other hand, stimulate economic and social development without wasting resources. It is also important to build transparent processes to maintain trust with regulators, partners, service consumers, employees, and society.

The behavior of consumers of goods and services is changing very rapidly. It seems appropriate that the agenda should be defined rather than simply reacting to trends that have already taken shape. An example is the rapid entry of e-commerce into society during the pandemic. Many consumers are already forever in the habit of purchasing and receiving goods and services online. Society is beginning to become more waste conscious-so far mostly in large cities, but the trend is clear. Among other things, it is important to make the strategy of ignoring or not paying enough attention to the problems of sustainable development unprofitable for contractors, while encouraging responsible representatives of business and society.

Also, as part of the initiative to reach the goal of reducing greenhouse gas emissions by 55 percent by 2030 and reaching zero emissions by 2050, the European Commission presented a draft package of climate legislation on July 14, 2021, including both new proposals and amendments to existing laws.

In particular, among the proposed initiatives is planned to the introduction of a mechanism of cross-border carbon regulation (Carbon Border Adjustment Mechanism, CBAM), which provides for the sale of certificates for carbon-intensive goods imported into the EU by a specially created authorized body on the established list.

This measure aims to protect European businesses from environmental dumping and prevent so-called "carbon leakage" when companies based in the EU move their carbon-intensive plants to countries with less stringent climate and environmental policies to reduce production costs. CBAM should also create incentives for manufacturers in non-EU countries to green their production processes.

CBAM will cover both direct emissions - those emitted and consumed directly in the production process, including emissions from heat and cold production-and indirect emissions, such as electricity consumed. In this case, for products classified as "complex goods" (goods that require the inclusion of other simple goods in the production process), the carbon footprint of consumed raw materials and supplies is added.

Initiatives to create a carbon regulation are actively discussed in Russia and include the creation of a national market of carbon units. The development of national carbon regulation can help reduce the burden on Russian importers about CBAM.

Thus, on July 2, 2021, the Federal Law "On limiting greenhouse gas emissions" was adopted (entered into force on December 30, 2021), aimed at creating conditions for sustainable and balanced development of Russia's economy while reducing greenhouse gas emissions.

In particular, the law provides for: state accounting of greenhouse gas emissions; the establishment of targets for their reduction; support for activities to reduce emissions and increase the absorption of greenhouse gases, and the introduction of a market for the circulation and offsetting of carbon units.

In addition, the Ministry of Economic Development of Russia has submitted to the government a bill "On experimenting to establish a special regulation of emissions and absorption of greenhouse gases in the Sakhalin region. The purpose of the bill is to achieve carbon neutrality in the territory of the participant of the experiment until December 31, 2025. It is planned to experiment from January 1, 2022, to December 31, 2025, inclusive.

To reduce greenhouse gas emissions without harming the economy, it is necessary to create a stable regulatory environment, as well as to extend to these activities the benefits of special investment contracts, comprehensive programs to improve competitiveness, agreements to protect and promote capital investment, as well as to introduce subsidized loan rates for green projects. It is also worth noting that about 15% of the decarbonization potential can be realized with additional benefits for companies by modernizing production, forming a new product line, and reducing energy intensity. At the same time, there are effects-social, environmental, and production-that may arise from the revision of development plans and programs.

3 Outcomes

The analysis showed that existing technologies offer only limited potential for carbon dioxide removal from the atmosphere, i.e., only compensations and direct sequestration will not be able to achieve the goals set by the Paris Climate Agreement. At the same time, carbon dioxide removal technology is not yet used on a mass scale, so it is difficult to calculate its environmental effect of it. The method itself requires a large amount of energy and water resources, which may in the future simply offset the positive effect of CO_2 removal and cause the opposite outcome. Moreover, the large-scale construction of facilities to capture greenhouse gases can hurt terrestrial and aquatic ecosystems.

That said, the most effective way to combat climate change is to reduce emissions directly. However, transportation companies should not limit themselves to their direct emissions. Because if a company claims to be carbon neutral only in terms of its direct emissions, this can be perceived as greenwashing (masquerading as environmental friendliness). The carbon footprint includes all emissions associated with its activities: raw materials, production, supply, use, disposal, and recycling, i.e., the entire product life cycle.

Reducing emissions during production and transportation of the product and switching to renewable energy sources can be considered a priority, another direction is to invest in negative emission technologies to offset those emissions that cannot be removed for some reason.

As part of the EU's low-carbon strategy, a significant role is assigned to the development of rail transport as one of the «greenest» ways to transport goods. Rail transport, unlike other modes, consistently reduces emissions, despite the increase in the share of the transport sector in EU emissions from 15% in 1990 to 24% in 2020. The European Commission has calculated that rail's share of EU freight traffic should reach 30 percent by 2030. Thus, the EU shows a long-term commitment to the development of railroads.

Nevertheless, emissions from railroads depend on several factors. First, is the degree of electrification (in the EU about 55%, in Russia about 50%). Secondly, when estimating not only direct but also indirect emissions, the environmental friendliness of the energy source is of key importance. In the EU, the share of low-carbon energy sources is about 40%. The share of renewable energy sources is 20.7% (6.1% in 1990).

In addition to improving energy efficiency and introducing technological innovations, the development of intermodal transportation is important. In addition to reducing costs, intermodal routes can also reduce greenhouse gas emissions, as well as work for sustainability through load balancing, increased transportation safety, etc.

As the European experience shows, if other countries and regions follow the European example of environmental regulation in general and carbon regulation in particular, further extrapolation of these norms can strengthen the position of rail transport in other regions of the world, all other things being equal. In this case, such a "domino effect" is very possible, given the international climate regulation described above.

The key provisions of such regulation are the principle of material responsibility of the polluter pays and the principle of user pays. Using such regulation, the state (or a supranational institution) includes the costs of using the common resource in the costs of the pollution source.

According to the International Energy Agency, railroads are one of the most energy-efficient modes of transport: they account for 7% of international freight traffic, but only 3% of the energy used by the global transport industry. At the same time, the direct contribution of railroads to carbon dioxide emissions is only 0.3% of the global total.

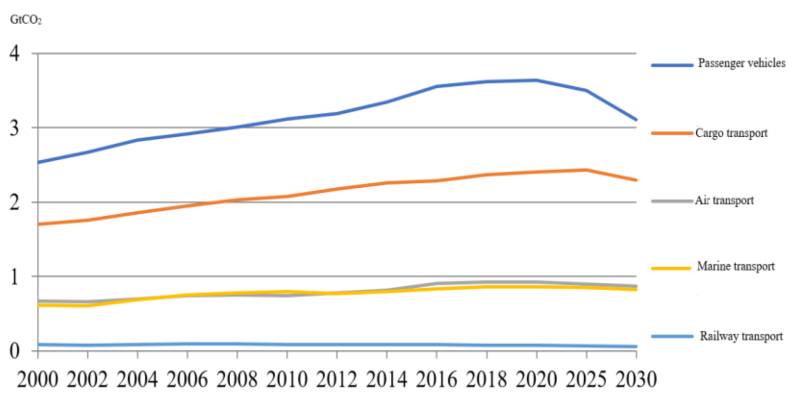

Fig. 1. Amount of CO_2 emissions by modes of transport (including forecast under sustainable development).

However, the objective advantages of rail freight transportation have their specifics. First, in terms of environmental friendliness, the energy source is important. Most freight transportation is carried out by diesel locomotives, i.e., autonomous locomotives with a diesel engine. Their use is due to the low degree of electrification on regional and local routes, high costs for electrification, and maintenance of such infrastructure on poorly loaded routes. Direct emissions from diesel locomotives range from 25 to 60 g CO_2 per ton-kilometer, depending on the characteristics of the locomotive. At the same time, the scatter of emissions from electric locomotives is about 10 to 25 g CO_2 per ton-kilometer. Nevertheless, even this spread, which is important for carbon regulation, preserves the objective environmental advantages of rail transport.

The following questions arise when using electricity:

1–The nature of the energy source (whether the electricity was generated by renewable or fossil resources);

2–Accounting for indirect emissions from railway infrastructure;

3–the costs of electrification and maintaining the corresponding infrastructure.

Obviously, due to the objective circumstances of low-load routes, full electrification is not economically feasible. In this regard, the second specific factor related to the environmental advantages of rail transport is the presence of transport corridors with a constant flow of goods. The development of railway infrastructure requires large expenditures compared to, for example, automobile infrastructure.

In addition, this development is often associated with political issues and political risks due to the international and continental nature of rail transport. The maximum economic and environmental advantages of rail transport appear on well-established routes with high loads and high predictability of commodity flows. In this case, an additional incentive is the development of intermodal transportation.

In the first half of 2020, freight transportation by rail caused direct CO_2 emissions in the amount of 14.9 thousand tons, which is almost five times less than if transportation was carried out by sea, 89 times less than by road transport, and 528 times less than by air transport.

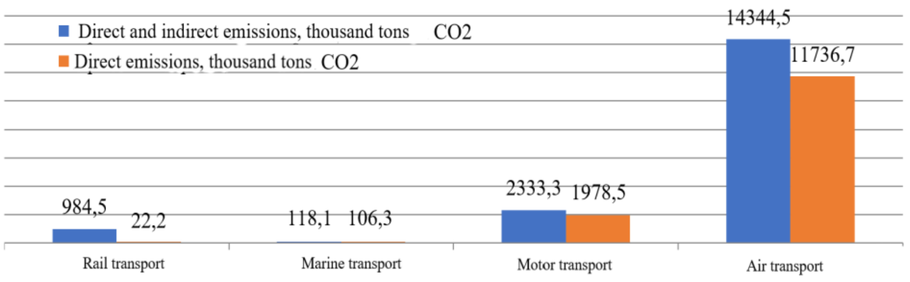

Fig. 2. Accumulated emissions from freight transportation on the China-Europe rail route in 2019.

Thus, the penetration of the environmental agenda, primarily in terms of carbon regulation, is changing the established competitive landscape in the field of international freight transportation. The trend toward "green" brings a competitive advantage to rail transport. However, this effect is discrete and depends on several other factors-for example, how successful other modes of transport are in responding to the green agenda. Additional opportunities for railroads are technological innovations that emphasize the objective environmental advantages of this type of transport.

Under the Paris Climate Agreement, signatory countries have made voluntary commitments to reduce greenhouse gas emissions. The strengthening of carbon regulation by several countries and associations makes it urgent to transform the global transport industry to transition to a low-carbon development model. Under these conditions, the inherent advantages of rail transport as the least carbon-intensive of all, all other things being equal, are outlined.

The development of railroads and the introduction of polluter pays and user-pays principles into regulatory mechanisms help accelerate the shift of freight flows from carbon-intensive sectors, such as trucking and air travel, to railroads. Nevertheless, innovations that will impact the rail industry are needed to maximize their impact.

The environmental agenda has a significant impact on secondary factors of production, such as infrastructure, rolling stock, and technology. The changes taking place are complex and interconnected. New technologies are designed both to increase energy efficiency and implicitly promote greening and the acquisition of additional environmental benefits.

As the structure of planned reductions in global CO_2 emissions from the energy sector shows, in the long term, the rail industry will be affected not only by electrification but also by the transition to new fuels. To date, the alternatives to diesel and electric locomotives being tested are liquefied gas and hydrogen.

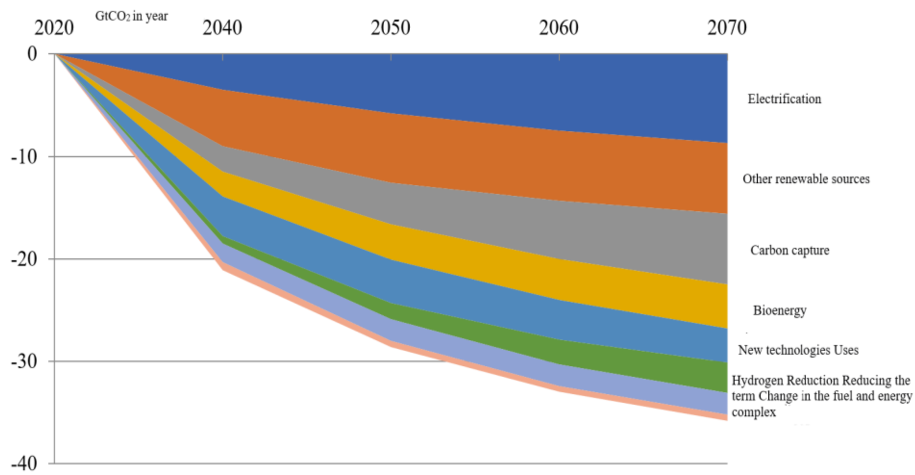

Fig. 3. Planned reduction of global CO_2 emissions from the energy sector by type.

Upgrading rolling stock, as well as infrastructure, in favor of greater environmental friendliness will reduce indirect emissions from railroads, thereby reducing the "carbon price. For the transformations noted to have the greatest economic impact, states must continue their policy of encouraging the transition to low-carbon development.

Finally, digitalization will indirectly help reduce the carbon footprint. The introduction of modern digital technologies optimizes operations and promotes better integration both within the rail system and with other modes of transport. Digital solutions can accelerate the decarbonization of rail transport and increase the attractiveness of railroads as a reliable and environmentally friendly mode of transport.

4 Analysis of outcomes

The environmental agenda and decarbonization policies provide new benefits to railroads, including the industry's adoption of negative emission technologies.

Types of negative CO_2 technologies can be categorized as follows:

1 Afforestation and reforestation absorb CO2 when forests grow. The upside is that it is an existing negative-emission technology that can be applied at a low cost. The downside is that to absorb gigatons of CO2

large (and ever-increasing) areas of forest are required. Estimates of global afforestation and reforestation potential range from 1.1-3.3 GtC/yr, given fairly large land areas. Potential problems exist in the release of stored carbon during disturbance of planting technology or land use change. In addition, nitrous oxide emissions are possible when fertilizers are used to accelerate forest growth. Carbon stored in living biomass may not be safe, and additional protection measures, including protection from wildfires, will be needed to protect and maintain expanding areas of forest. The need for water can also be an important constraint, especially in arid areas.

2 Land management for soil carbon sequestration and fixation. A major store of carbon is soil. Many cultivated soils have lost 50-70% of their original stored carbon (IPCC, 2000), so agricultural land management is an important part of soil carbon sequestration and fixation. Soil carbon content can be increased by growing cover crops, leaving crop residues in the field, applying manure or compost, using low-or no-till systems, and using other land management practices to stabilize soil structure. The mitigation potential of this approach is estimated to be in the range of 0.07 to 0.7 tCO2 eq/yr per hectare. Soil carbon accumulation can occur for decades before the content reaches a steady state. However, such measures need to be applied continuously, as they are easily offset if agriculture returns to more intensive tillage methods. Soils contain 1,500 GtC at depths of up to 1 meter and 2,400 GtC at depths of up to 2 meters.

3 Bioenergy production with carbon capture and storage (BECCS). Currently, this is the only negative emission technology included in the IPCC scenarios. The concept behind this technology is that biomass stores CO_2 during growth and stores it as organic material. The biomass is subsequently burned in a power plant (or converted to another form of energy), producing electricity (or another energy carrier). The carbon dioxide produced by burning biomass is captured and stored, thereby effectively removing CO_2 from the atmosphere. The use of biomass is not limited to the energy sector, but can also be integrated into other sectors, such as the production of hydrogen, biofuels, or biogas. This technology is currently implemented in demonstration models. The effectiveness of using this technology should be evaluated on a case-by-case basis.

4 Enhanced weathering. The natural carbon cycle includes processes that remove CO_2 from the atmosphere through inorganic transformations. The main mechanisms include the following:

• CO2 is dissolved in seawater and slowly mineralizes, sinking into the deep ocean sediments (it takes 2000-8000 years for this system to reach equilibrium). The critical factor is the calcium (or magnesium) carbonate minerals entering the ocean after weathering on land, where their alkalinity compensates for the initial acidification by the dissolution of CO2. Accelerating this process can increase the rate at which the oceans absorb CO2.

• The weathering of silicate minerals and the introduction of calcium (or magnesium) silicate into the oceans can also affect marine chemistry in a similar way to producing (biogenic, amorphous, or dissolved) silica and soluble bicarbonate. This is twice as effective at removing CO_2 as calcium (or magnesium) carbonate, but on a much slower time scale (usually hundreds of thousands of years). CO_2 can also react directly with calcium (or magnesium) silicate to form solid calcium (or magnesium) carbonate. These processes involve the carbonization of minerals and accelerating such natural processes is a potential means of increasing the rate of CO_2 removal from the atmosphere. The potential for sharing uptake through minerals is enormous, as the amount of suitable and readily available mineral silicates far exceeds the requirements for sequestering all conceivable anthropogenic coals. However, the time scale of these processes is rather large.

5 Direct captures of CO_2 from ambient air and storage (DACCS). About half of current anthropogenic greenhouse gas emissions come from distributed sources, such as transportation and residential heating. Capturing these emissions at the source is often impractical. However, it is possible to capture this carbon dioxide by capturing it directly from the ambient air. The ability to capture CO_2 anywhere opens up a wide range of possibilities for this technology. Carbon dioxide can be captured at the place of its formation and directed to the places of storage. On the other hand, direct capture technology requires a carbon-neutral energy and/or heat source for operation, which may limit the choice of suitable

locations to those areas where such a source is available. Direct capture uses a solid or liquid sorbent to bind CO_2. However, there is a limitation due to the low concentration of CO_2 in the air compared to the concentration of CO_2 in the flue gases. Once CO_2 is bound, the sorbent can be regenerated releasing high concentrations of CO_2 with onward transport to storage sites such as underground voids from which hydrocarbons are extracted for long-range injection into rock formations.

6 Fertilizing the ocean to capture CO2. The oceans are currently one of the largest natural CO2 sinks, with a "solubility pump" and a "biological pump". Both of these sinks could potentially be improved. The possibility of stimulating uptake by solubilization and mineralization is discussed in 4 technologies. Phytoplankton production rates in many parts of the oceans are limited by nutrient availability, and increasing them has long been seen as a potential way to increase CO2 uptake rates. Thus, the biological pump can be enhanced by providing additional needed nutrients where they are lacking to allow greater production of biological material that is food for other organisms. However, much of the carbon fixed in this way will be released again by absorption by other marine organisms and their respiration, but a small fraction of the particulate matter will eventually settle in the deep ocean, where it may persist for centuries as remineralize dissolved organic carbon or be deposited as particulate matter in sediments.

In addition, since carbon capture and storage (CCS) is a component in categories 3 and 5 above, as well as a direct mitigation technology for point sources of CO_2, this technology can be considered as a separate negative emission technology.

5 Conclusion

In visions of the future-a low-carbon transportation industry is seen as an important component, given the current high level of dependence on fossil carbon fuels and the inertia outcomeing from the long lifespan of fossil fuel infrastructure. Indeed, the more challenging climate goals under the Paris Agreement make it even less likely that renewable energy and energy efficiency alone can provide the necessary emission reductions without simultaneously limiting emissions from the embedded fossil fuel base in transportation. Analysis of IPCC reports shows that limiting atmospheric concentrations to about 450 ppm CO_2 equivalent by 2100 is either impossible or much more expensive without deploying negative emission technologies. Achieving a scenario in which average warming is limited to 2 °C above pre-industrial levels would require capturing and storing nearly 4 Gt of CO_2 per year by 2040. Without negative emission technologies, the required cost of reducing greenhouse gas emissions could be 40% higher than with negative emission technologies.

At the same time, the Transport Strategy of the Russian Federation to 2030 and the forecast for the period up to 2035 provide for the implementation of such long-term goals for the development of Russia's transport system as the digital and low-carbon transformation of the industry and accelerated implementation of new technologies. In addition, the strategy aims to meet the expectations of the main users and consumers of the transport complex ahead of time. Transport industry enterprises and their investors must be provided with conditions to reduce energy and carbon intensity.

As part of the reduction of greenhouse gas emissions by rail transport facilities, the following measures may be implemented: direct reduction of greenhouse gas emissions; introduction of negative emission technologies at rail transport facilities, taking into account the spatial distribution of facilities and their specifics (technologies 1, 3, 5); expanding the range of potential investors in "green" projects and providing access to cheaper financing; integration of decarbonization issues in the strategies of Russian transport companies; introduction of a mechanism for

References

1. T. Titova, R. Akhtyamov, E. Nasyrova, A. Elizaryev, Lecture Notes in Civil Engineering **49**, 473-478 (2020) DOI: 10.1007/978-981-15-0450-1_49
2. O.A. Bardyshev, V.A. Popov, S.K. Korovin, A.N. Filin, Occupational safety in industry **(1)**, 52-56 (2020) DOI: 10.24000/0409-2961-2020-1-52-56
3. M. Baydarashvili, A. Sakharova, N. Shrednik, Lecture Notes in Civil Engineering **50**, 479-486 (2020) DOI: 10.1007/978-981-15-0454-9_
4. E. Nasyrova, A. Elizaryev, S. Aksenov, et al., E3S Web of Conferences **110**, 02045 (2019) DOI: 10.1051/e3sconf/201911002045
5. V.M. Ulyasheva, A.M. Grimitlin, N.A. Chernikov, Water and Ecology **(4)**, 92-97 (2018) DOI: 10.23968/2305-3488.2018.23.4.92-98
6. S. Miloslavskaya, A. Panychev, A. Myskina, P. Kurenkov, IOP Conference Series: Materials Science and Engineering **698(6)**, 066059 (2019) DOI: 10.1088/1757-899X/698/6/066059
7. M.J. Bryn, D.A. Afonin, N.N. Bogomolova, Procedia Engineering **189**, 386-392 (2017) DOI: 10.1016/j.proeng.2017.05.061
8. M. Baydarashvili, Procedia Engineering **189**, 616-621 (2017) DOI: 10.1016/j.proeng.2017.05.098
9. L.D. Terekhov, S.B. Mayny, N.A. Chernikov, Water and Ecology **24(4)**, 71-78 (2019) DOI: 10.23968/2305-3488.2019.24.4.71-78
10. T. Titova, R. Akhtyamov, E. Nasyrova, A. Elizaryev, MATEC Web of Conferences **239**, 06003 (2018) DOI: 10.1051/matecconf/201823906003
11. A.M. Uzdin, M.V. Freze, M.Y. Fedorova, Y. Guan, Soil Mechanics and Foundation Engineering **55(3)**, 201-208 (2018) DOI: 10.1007/s11204-018-9526-0
12. S. Ershova, T. Orlovskaya, E. Panfilova, IOP Conference Series: Materials Science and Engineering **463(4)**, 042040 (2018) DOI: 10.1088/1757-899X/463/4/042040
13. O.I. Dudkina, N.V. Gribkova, Vestnik St. Petersburg University: Mathematics **53(3)**, 282-286 (2020) DOI: 10.1134/S1063454120030061
14. A. Kolos, V. Alpysova, G. Osipov, I. Levit, Lecture Notes in Civil Engineering **50**, 295-306 (2020) DOI: 10.1007/978-981-15-0454-9_
15. R.V. Vvedenskij, S.G. Gendler, T.S. Titova, Magazine of Civil Engineering **79(3)**, 140-149 (2018) DOI: 10.18720/MCE.79.15