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Extractive Industries as a Source of Greenhouse Gas Emissions and the Possibility of its Natural Sequestration under the Climatic Conditions of Central and Northern Eurasia

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ABSTRACT

The Paris Agreement came into force in 2016. Now, there are 196 parties to this Agreement, including Russia. The purpose of the accommodation is to hold the increase in the global average temperature below 2 °C and to make efforts to limit the temperature increase to 1.5 °C. Another important goal of this Agreement is to reduce greenhouse gas emissions, according to UNFCCC-2015. Each participating country at the national level plans special activities that will help to achieve these goals. In general, this should reduce the rate of global warming. The goals of the Paris Agreement can be achieved either by introduction of new technologies that exclude the formation of a large amount of carbon footprint or termination of the usage of fossil fuels for electricity production. The formation of a carbon footprint is observed at all mining enterprises, regardless of the extracted raw materials. In this case, the amount of carbon footprint depends only on the extraction technologies and the success of ecological measures.

Keywords: carbon footprint; coal phase-out; energy transition; resource nexus

INTRODUCTION

All stages of mineral extraction influence the formation of a carbon footprint: from the extraction of ore to its transportation to further consumers. The mining industry makes a large contribution to the formation of the carbon footprint. Figure 1 shows the role of coal in the global energy sector. The main greenhouse gases produced because of the coal industry are methane and carbon dioxide. According to experts, 40% of the global CO_2 is generated by the coal industry [Alyabyev et al. 2020]. Among the enterprises of the mining sector, it occupies a leading place in this area. The coal mining industry accounts for about 11% of global methane emissions. However, some scientists suppose that current estimates of methane emissions are understated. For example, according to one of the forecasts, the actual methane emissions from fossil fuels are 60–110% higher than current estimates [Kholod et al. 2020].

Coal mines constitute one of the largest anthropogenic sources of methane release. The main sources of greenhouse gas emissions from coal mining are blasting as well as loading and unloading operations, drilling rigs, boiler pipes, rock dumps, traffic/parking of automobile and railway transport, conveyor work, etc. [Korobova 2014].

In the Russian Federation, the coal industry is developing dynamically. In 2019, the volume of coal production reached 400.2 million tons, which is 0.5% higher than the year before. However, the consumption of this mineral in the home market is decreasing due to the high prevalence of natural gas-a cheap and environmentally friendly type of fuel. Nowadays, the greater part of the coal is directed to power plants (about 52%) [State report 2020].

The production of coal in Russia and the coal export are growing annually. In the period from 2013 to 2019, the volume of export increased by 1.5 times [State report 2020]. The coal from the Russian basins is sent to the countries of the Asian region (mainly brown and coking coal), as well as to the countries of the western direction.

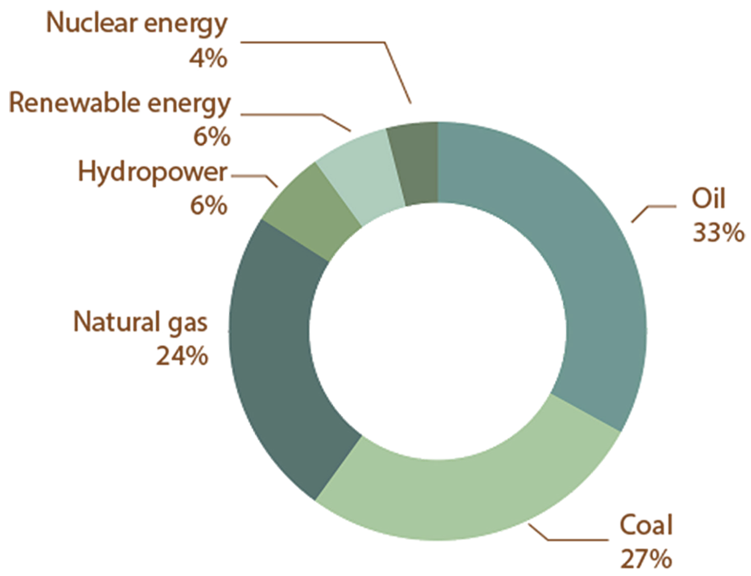

Figure 1. The structure of the world energy balance [Pankov and Afanasiev 2020]

In general, there is no stable dynamic of greenhouse gas emissions into the atmosphere from the coal industry enterprises in Russia. There was a decrease in emissions of carbon dioxide and methane in 2009. However, in 2017 the volume of emissions began to rise again and exceeded the volumes of 2016 up to 9.6% [Blinovskaya and Mazlova 2019]. Coal is used actively in power plants. During the production of one kilowatt-hour of electricity, Russian coal-fired thermal power plants emit 1.7 times more greenhouse gases than gas-fired thermal power plants [Kharyonovsky and Danilova 2017].

The data from the Federal State Statistics Service shows that 55.8 million tons of CO_2 equivalent were released into the atmosphere during the extraction of solid fuels in 2010. Afterwards, an increase in this indicator was almost annual. In 2018, emissions reached 68.5 million tons of CO_2 equivalent, and in 2019 they decreased and amounted to 68.2 million tons of CO_2 equivalent [Federal State Statistics Service 2022].

According to the Paris Agreement, Russia pledged to reduce greenhouse gas emissions by 30% compared to the 1990 figures by 2050. However, the realization of this goal in the mining industry is quite complicated due to the mining and geological conditions of coal production and the lack of appropriate technologies [Blinovskaya and Mazlova 2019].

Currently, there are a lot of measures that can be applied to reduce the formation of greenhouse gases. However, not all of them are advisable for use in Russia. In any case, two large groups must be noted:

1) Cessation of the extraction of traditional fuels, and the widespread introduction of different types of alternative energy, replacing the established traditions;
2) Continuation of mining and use of minerals, as well as the introduction of modern technologies that will help to reduce the volume of harmful gases.

Obviously, the combination of these two approaches is the most suitable option for any country. In this case, the complexity will allow abandoning traditional energy sources and switching to alternative ones. In Russia, a complete abandonment of coal is not expected in the near future, so it is advisable to develop technologies for the reduction of greenhouse gas emissions [Smirnov and Penezeva 2023].

The following mining and geological factors influence the choice of measures of greenhouse gas emissions reduction: the depth of coal beds, their gas content, the shape and features of the dump, the tendency of coal to spontaneous combustion, the size, as well as shape of fractions. Among the technological factors are the method of field development and the type of coal. Environmental factors include the quality of atmospheric pollution, the concentration of harmful substances, and the climatic features of the area. It is clear that economic factors are the cost and the expediency of a particular event, as well as final planned results [Petrov and Mihajlov 2019].

Taking into account all these factors will allow choosing the most appropriate measures to reduce the emissions of harmful pollutants into the atmosphere. The principle technologies are presented further.

Prevention and extinguishing of burning rock dumps are the simplest and the most common measures aimed at reducing the release of harmful substances into the atmosphere. It can be achieved by increasing the isolation of exposed areas, reducing the possibility of coal to accumulate thermal energy, extinguishing with water and anti-pyrogens, as well as reshaping the dumps [Petrov and Mihajlov 2019].

About 1.3 billion m^3 of methane enters the atmospheric air from Russian mines during the year. The experience of other countries (USA, Canada, China, India) shows that the extraction and use of methane is a prospective opportunity of its reduction [Ivanov et al. 2021]. However, this technology will not be implemented in Russia in the coming years because the methane potential of even highly gas-bearing regions is less than 2% of the energy potential of coal. The availability of other energy sources hinders the development and extraction of coal mine methane for economic reasons [Oberemok 2017].

The expansion of the spheres of methane use is a rather prospective direction. The economic feasibility and the volumes of air masses that contain methane are determined by the profitability of gas recovery machines of each specific mine.

Methane can be used to produce methylene chloride and its derivatives: chloroform, carbon tetrachloride, ammonia, acetylene, hydrogen, methanol, nitric acid, formalin, etc. [Alyabyev et al. 2020]. In Russia, the majority of gas-bearing coal beds are located in the Kuznetsk and Pechora coal-bearing basins. In general, Russia has good prospects in the development of this direction.

Another method of reducing the volume of greenhouse gases is to increase fuel efficiency. The greenhouse effect decreases in proportion to the increase in this coefficient. It is important to understand that during such processes, it is necessary to use more solid fuel, and also to use high-strength materials [Shpirt and Goryunova 2019].

In many developed countries (for example, in the USA, Germany, Great Britain), electricity generation at the coal-fired thermal power plants occurs mainly without the useful use of heat. As a result, a large amount of carbon dioxide is released into the atmosphere [Shpirt and Goryunova 2019]. In Russia and in some other countries, electricity production is carried out together with the production of heat (hot water and steam), which helps to reduce the CO_2 emissions.

Even after the mine closes, methane continues to infiltrate into the atmosphere. It is believed that the volume of methane remaining in the mined-out spaces is 2–3 times greater than the volume released during coal mining. Nowadays, there are various technologies for its extraction. A well-known technology has been consisting in drilling wells from the surface directly into the old worked-out space and subsequent extraction of methane with their help has been considered promising [Slastunov et al. 2021, Petrov and Yakusheva 2022].

After the signing of the Paris Agreement in 2016, a widely discussed topic was the proposal to create a carbon-free zone in Eastern Siberia. However, it is now clear that this was not a solution to the problem of greenhouse gases. It could lead to serious economic problems in the region, including the increase in electricity prices. The implementation of such a project requires a lot of material resources, and it is impractical nowadays.

European countries have a goal: to reduce the use of fossil fuels (especially coal) in the consumption of the energy industry. The European Union is divided into three groups:

- Countries that have already stopped using coal for electricity generation (Belgium);
- Countries that will exclude it by 2025 (Austria, France, Ireland, Italy, and Sweden);
- Countries that are rich in coal reserves. They do not plan stopping the extraction and use of coal (Germany, Poland, Czech Republic). These countries account for about 57% of all European coal consumption.

A slight reduction in coal consumption in the 3rd category of countries is explained by the phenomenon of “carbon lock-in”. It implies the inability to pass from existing technologies to technologies that produce fewer greenhouse gases. Table 1 shows the largest coal producers and the changes in the volumes of coal production in the period from 2012 to 2020.

Methane is used for the production of electrical and thermal energy in many countries. Sometimes this index can reach 50% of the total methane extracted by degassing. Such technologies

Table 1. Coal extraction in some countries, million tons (BP Statistical Review, 2021)

Country	2012	2013	2014	2015	2016	2017	2018	2019	2020
China	3945.1	3974.3	3873.9	3746.5	3410.6	3523.6	3697.7	3846.3	3902.0
India	605.6	608.5	646.2	674.2	689.8	711.7	760.4	753.9	756.5
Indonesia	385.9	474.6	458.1	461.6	456.2	461.2	557.8	616.2	562.5
USA	922.1	893.4	907.2	813.7	660.8	702.7	686.0	640.8	484.7
Australia	448.2	472.8	505.3	503.7	502.1	487.2	502.0	504.1	476.7
Russia	358.3	355.2	357.4	372.5	386.6	412.5	441.6	440.9	399.8
South Africa	258.6	256.3	261.4	252.2	249.7	252.3	250.0	258.4	248.3
Kazakhstan	120.5	119.6	114.0	107.3	103.1	112.3	118.5	115.0	113.2
Germany	196.2	190.6	185.8	184.3	175.4	175.1	168.8	131.3	107.4
Poland	144.1	142.9	137.1	135.8	131.0	127.1	122.4	112.4	100.7

cannot be used in the cases when methane content is 1% or less. It is very expensive and impractical due to the availability of other energy sources. Nevertheless, such projects are at the stage of technical testing. For example, a 5 MW power plant operating on an air mixture with a methane content of 0.9% is being tested at one of the mines in Australia [Kharyonovsky and Danilova 2017]

Germany is a good subject of research. It has the largest coal reserves in Europe and volumes of its production. Despite this, Germany is developing green energy successfully. In the period from 1990 to 2015, the volume of electricity generated from renewable energy sources increased to 171 TWh per year. However, it is not accompanied by a significant decrease in coal consumption: by 2017, the amount of electricity produced using coal decreased only by 38 TWh compared to the same indicator in 1990 [Rentier et al. 2019]. About half of the electricity produced in Germany was based on coal and lignite until 2010. Another half accounted for the energy from natural gas, nuclear power, and renewable energy sources. After 2010, there were some changes in the structure of energy production: nuclear energy reduced the volume of energy production, while renewable energy began spreading rapidly throughout the country. Electricity production using coal remained at the same level [Renn and Marshall 2016]. Coal-fired thermal power plants produced 44% of the country's electricity in 2014 [Heinrichs and Markewitz 2017].

The German authorities plan to stop using coal by 2038 [Osička et al. 2020]. Researchers propose several ways of industry development to achieve this goal and the goals of the Paris Agreement. However, unlike Russia, it all comes down to the final cessation of the production and use of coal [Heinrichs and Markewitz 2017].

To summarize, the most significant differences between the approaches of Russia and the countries of the European Union to reducing greenhouse gas emissions from coal industry enterprises are:

- Russia does not have the plans to stop coal extraction in the coming years and, as a result, the use of coal for various purposes will continue. The authors think that only the improvement of ecological measures will take place soon. European countries, on the contrary, are trying to turn to more environmentally friendly fuels, as well as to develop alternative energy;
- One of the long-term areas in Russia is the industrial extraction of methane from coal seams, but the development of this technology needs time;
- Germany and Poland are the largest countries in Europe in terms of the extraction and use of coal. However, these countries plan to abandon this type of fuel and to stop its production.

Assessment of the carbon footprint of metal mining companies in Russia and the world

In addition to the coal industry and the FES as a whole, the metallurgical sector of industry is one of the most affected by climate policy. For metallurgy in the EU, the results of reducing greenhouse gas emissions are trends such as a decrease in competitiveness, dissipating of sector assets and production facilities to developing economies, limited capacity growth and creation of new enterprises [Galenovich 2021].

In 2010, the Intergovernmental Panel on Climate Change (IPCC) reported that the metallurgical sector accounts for about 20% of global greenhouse gas emissions. Most of the emissions are related to the production of energy required for pyrometallurgical processes [Muller et al. 2020]. Carbon gases are also released during the extraction of ores and their direct reduction with coke or methane.

It is important that Russia traditionally occupies a leading position in the world in metallurgical production, and a high proportion of raw materials as well as products are exported. For example, in 2019, Russia ranked 3rd in terms of net exports of steel products, the 1st place was the sale of semi-finished steel products, 1st place – export of aluminum nickel, and 4th place – copper export [Khokhlov 2020]. According to the Federal State Statistics Service, the metallurgical sector in Russia produced 107 940 thousand tons of CO_2-eq. in 2017, and 104 940 thousand tons of CO_2–eq. greenhouse gases in 2019 [Federal State Statistics Service 2022]. In 2017, the main share of greenhouse gas emissions was associated with ferrous metallurgy (production of pellets, cast iron, steel and iron of direct reduction) – 95 134 thousand tons of CO_2-eq. This is lower than in 1990, but higher than in 2000 (113 563 and 86 388 thousand tons of CO_2-eq. respectively). In the second place, there is the production of aluminum – 6 136 thousand tons of CO_2-eq. This value is higher than in 1990, but lower than in 2008–2012 [Romanovskaya et al. 2020].

The coronavirus pandemic in 2020 temporarily caused a decrease in metallurgical production as well as extraction of iron ores and ores of other metals. However, by the end of the year, metallurgical companies have already recovered and showed growth. Nevertheless, with the introduction of various carbon taxes, the profitability of exports will fall, and the growth of the metallurgical industry will slow down.

In fact, the mining industry of the metallurgical sector includes quarries, mines and concentrating mills. At the same time, it is necessary to consider the extraction of iron ores and ores of non-ferrous metals separately [Eremeeva et al. 2023].

It is obvious that the problem of carbon dioxide release during the development of deposits is typical not only for coal mining, but also for other mining industries. During coal mining, greenhouse gases (CH_4, CO_2) are formed during the operation of internal combustion engines (ICE) and during the oxidation of exposed coal beds and release of gases from them. However, when mining ores, only ICE are the main source of greenhouse gases. In addition, the release of carbon in the composition of gases (mainly CO, CO_2) occurs during fuel and air explosions [Matvienko and Pihlak 2016]. For example, one ton of iron ore extracted by open-pit mining accounts for more than 100 kg of carbon dioxide [Lisienko et al. 2021]. The possible ways to reduce the carbon footprint during mining can be the use of mining machines with electric drive and the use of new effective explosives with reduced release of pollutants.

Russia has the largest reserves of iron ores. In 2018, iron ore production in the Russian Federation amounted to 105.1 million tons (5th place in the world). The export of ores and concentrates for 2016 amounted to 18.5 million tons [Lobacheva and Dzhevaga 2021]. The main mining companies are Metalloinvest Management Company, Evraz Group S.A., NLMK JSC, Severstal JSC. These companies in total produce more than 80% of iron ore in Russia (Iron ore production in the world and in Russia, 2020).

The world's largest iron ore miner is Australia (907.8 million tons) – the company "BHP Billiton", the Australian-British concern "Rio Tinto". Also Brazil (460.0 million tons) – the company "Vale". China (220.0 million tons) – the companies "Shougang Group", "Gangcheng Group" and others. India (200 million tons) – state mining Corporation "NMDC" [Khokhlov 2020, Top steel-producing 2021].

Each of the listed companies has complexes of mining and concentration plants. For example, Stoilensky GOK (NLMK Group), Karelian Okatysh JSC (Severstal), WAIO complex (BHP Billiton). These enterprises develop iron ores and produce various enrichment products: agglomerate and iron ore pellets.

Each of the types of iron ore raw materials has a different carbon footprint. The integral CO_2 emission in the production of agglomerate is 319 kg/t of product, in the production of pellets – 56.3 kg/t of product [Lisienko et al. 2016]. This iron ore raw material (IORM) is supplied to metallurgical plants for the production of cast iron and steel. Of course, the emission of carbon dioxide during the production of IORM cannot be compared with the release of carbon during the blast furnace process (1551 kg/t of product) [Lisienko et al. 2016, Gan and Griffin 2018]. However, when taking into account the carbon footprint of the final products for export, these values have a certain weight.

The formation of carbon oxides in the production of IORM is associated with the reduction of iron from iron ore using coke in the production of agglomerate. Carbon gases are also formed when burning fuel oil or gas in the production of iron ore pellets and during the decomposition of carbonate fluxing stones. Today, the production of iron ore pellets is a more advanced and environmentally friendly process than the agglomeration of iron ore. Pellets have a greater proportion of iron in their composition than agglomerate, with relatively low CO_2 emissions.

Technologies with fundamentally lower greenhouse gas emissions represent a coke-free reduction of iron from ore. These are Midrex, Energiron and Hyl processes. These technologies are based on the production of a mixture of CO and H_2 by the catalytic reaction of methane gas and water steam. Subsequently, iron is recovered from oxide ores by the gases obtained. The result of the reaction is spongy iron with a small (up to 5%) carbon content [Bhaskar et al. 2020]. This method is slightly more energy-intensive than the blast furnace process. However, it can significantly reduce the release of greenhouse gases into the atmosphere. Research in this direction has been conducted since the 1950s. Today, processes based on these technologies show high efficiency [Pauluzzi and Martiniz 2018]. Lebedinsky GOK (owned by Metalloinvest Management Company) is the only processing plant in the CIS engaged in direct reduction of iron. The volume of direct reduced iron production in 2020 amounted to 40.4 million tons. In Europe today, this process is employed for iron production at one plant owned by ArcelorMittal in Hamburg. In 2018, it produced 0.56 million tons [World direct reduction statistics 2018].

At the current stage of technology development, the reduction of the carbon footprint during extraction and enrichment is possible due to a full-fledged transition to the pelletizing of iron ore instead of the production of agglomerate. additionally, it is possible to reduce the CO_2 emissions during the production of pellets by reducing the consumption of carbonate fluxes and fuel. This step is part of NLMK climate strategy.

The flows of raw materials and products of primary processing, taking into account the specific release of greenhouse gases, can be depicted in the form of a graph of CO_2 emissions. Figure 1 shows two options for the production of reduced iron: the blast furnace process and HYL-3 [Lisienko et al. 2021, Lisienko et al. 2016].

It is obvious that in the future, iron ore mining companies need to develop hydrogen technologies to further reduce greenhouse gas emissions. Direct recovery of iron ores using pure hydrogen will be the next step in achieving carbon neutrality. However, today the problem is the reduction of the iron content in the ore. It is possible that by the time of the development of pure hydrogen generation, the production of concentrates in the form of pellets will become a necessity.

Russia occupies a leading position in the reserves of nickel, copper ores, platinum group metal ores, and in the production of this metals. In addition, Russia is a leader in the production of aluminum, also from imported raw materials [Khokhlov 2020]. A huge number of non-ferrous metallurgy products from the Russian Federation are exported. Therefore, it is also necessary

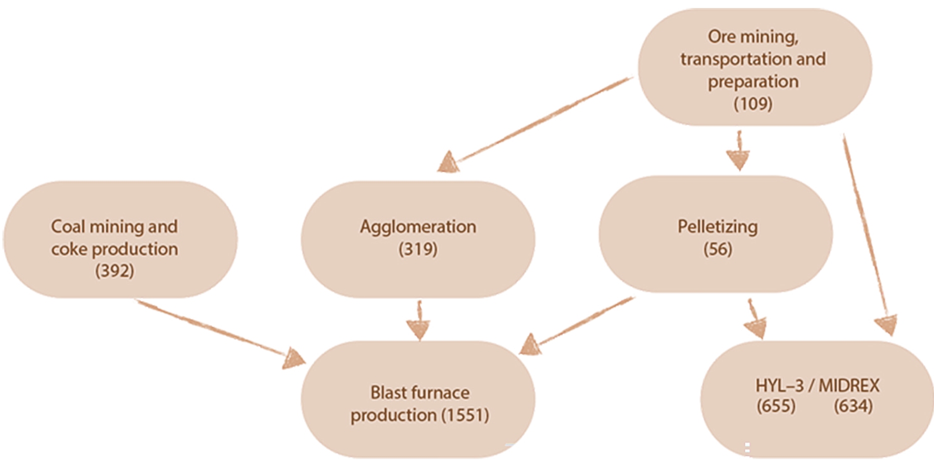

Figure 2. Graph of carbon dioxide emissions of iron reduction processes and products (specific CO_2 emissions per 1 ton of products are indicated in parentheses)

to take into account the carbon footprint of non-ferrous metals and their row materials produced in the country.

The largest producers of non-ferrous metal ores in the Russian Federation are such companies as MMC Norilsk Nickel, Rusal, and UMMC. They are engaged in the extraction, enrichment and production of metals such as copper, nickel, aluminum, lead, platinum group metals and others. Such Russian companies as Norilsk Nickel and Rusal have their own production sites abroad.

Unlike ferrous metallurgy, for most non-ferrous metals, recovery using coke or methane from ores is of little use. In this regard, the greatest emission of greenhouse gases during extraction and enrichment is associated more with obtaining energy for extraction and various enrichment processes. For example, the total CO_2 emission in the production of bauxite is 80 kg/t [Lapteva et al. 2020].

Considering the process of enrichment of aluminum ore (bauxite), for the production of alumina (enrichment product) according to the Bayer method, 280 kWh of electricity is needed. At the same time, 90 kg of caustic soda is consumed per ton of alumina, the total CO_2 emission during the production of soda is 3 200 kg/t. Such a high value is associated both with the processing of limestone and with the use of fuel oil and coke in production [Lapteva et al. 2020]. Electricity for alumina production can be supplied by both green energy with a low carbon footprint and thermal power plants. For example, for Rusal plants, about 90% of the energy is produced by hydroelectric power plants. According to this indicator, the company occupies a leading place in the world, and by 2025, it is planned to raise the provision of green energy from hydroelectric power plants to 95% [ALLOW 2021].

When talking about the production of copper, then the process of copper enrichment is similar to the production of cast iron. The product of the enrichment of copper sulfide ores is matte – an alloy of iron, copper and related metals sulfides with a useful component content of 6–20%. Matte is obtained by melting copper ore with coke in mine, reflecting furnaces and Vanyukov furnaces. For example, 1 ton of copper in the production of 10% matte accounts for 420 kg of CO_2 [Anufriev et al. 2019].

In general, most Russian metallurgical companies have strategies to reduce the carbon footprint of their products. In particular, it is necessary to reduce the CO_2 emissions at the stage of ore extraction and enrichment. Non-ferrous metal manufacturing companies rely on the use of energy sources with a low carbon footprint (hydroelectric power plants, gas thermal power plants). For ferrous metallurgy companies, the transition to the enrichment of iron ores without the use of coke is promising.

MATERIALS AND METHODS

Mining and processing enterprises

According to the State Report "On the State and Protection of the Environment of the Russian Federation in 2019", the share of the category "manufacturing industries" in the scope of emissions from stationary sources was 33.9%, or 5,865 thousand tons, which is the largest indicator among the categories. Compared to 2018, these values increased both in absolute terms (3,756.2 thousand tons in 2018) and in relative terms (22% of total emissions in 2018) [On the state and protection of the environment … 2021]. It is noted that this increase is associated with the growth of the industry, although according to the same report, its growth was 1.1%.

Metallurgical production makes the largest contribution to atmospheric emissions among manufacturing enterprises. According to Rosstat, the share of metallurgical enterprises in emissions from stationary sources was 47.86% for 2018 and 64.65% for 2017. At the same time, the absolute reduction of emissions in 2017–2018 (2,047.3 thousand tons) by 95.47% provides an absolute reduction in the industry (1,954.5 thousand tons), which creates a significant reduction in the share in emissions [Paris Agreement 2015]. Carbon dioxide emissions account for the largest share among the emissions in genera;. In 2019, this value was 27.75% of the sum of emissions from stationary sources.

Assessment of carbon-containing emissions from ferrous metallurgy enterprises

Calculation of the carbon footprint of various products is necessary to determine the baseline values of this footprint for the normative conditions of production. This will allow formulating the criteria of the best available technologies (BAT) [Changing of the climate 2022]. Determination of the carbon footprint of the products of various industries will identify the conditions affecting it.

In ferrous metallurgy, the carbon footprint of liquid steel production refers to the emission of carbon dioxide in the processes of mining, transportation and preparation of resources [Changing of the climate 2022].

As it was mentioned earlier, the carbon footprint of products is determined by the emission of carbon-containing gases in all processes used to produce these products. Carbon monoxide emission is unacceptable, for this reason it is burned in aggregates or in a candle, and methane is used as a secondary energy source. As a result, the carbon footprint of metallurgical products should be defined by carbon dioxide emissions. The carbon footprint is further referred to as end-to-end CO_2 emission. There are three types of emissions [Lapteva et al. 2020]:

- direct emission its value is determined by the mass of the burned carbon-containing fuel in the process or the resource that forms carbon dioxide during decomposition;
- transit emission defines a share of the total mass of carbon dioxide emission formed in the previous processes. Transit emission is determined by the sum of the products of the values of through emission of the incident vertices by the weights of the corresponding arcs;
- the end-to-end emission is equal to the sum of the emission of the process itself and the transit emission.

Technologies of production of a given product consist of many processes interconnected in a complex way. The most obvious form of their representation to calculate the carbon footprint (end-to-end emission) is a signal graph [Chesnokov et al. 2014]. The graph corresponds to the technological scheme. An example of such a graph of steel production is shown in Figure 3.

The vertices correspond to the processes producing the required resources (coke, sinter, oxygen, etc.). Process emissions and end-to-end process emissions through the slash are shown in parentheses. The values of the end-to-end emissions are treated as signals in the signal graph. On this basis, the transit emission of a process is equal to the sum of the products of the through emission indicated in the vertices, from which the arrows (arcs) to the vertex of this process run, by the costs of the corresponding resources, which are indicated on the corresponding arrows.

There are studies that determine the specific carbon dioxide emissions of ferrous metallurgy enterprises in various types (distribution by units/products produced). The data are presented in Tables 2–3 [Filantropova and Sham 2021].

On the basis of Table 2, it can be concluded that the production of electric furnace steel is the priority method for carbon dioxide emissions.

Assessment of opportunities to reduce the carbon footprint of the metallurgical industry in Russia

Choosing the possible most effective ways to reduce the carbon footprint in the iron and steel industry requires an understanding of the basic ways of producing steel. There are two main technologies:

- steelmaking, based on the process of reduction of iron ore in a blast furnace (BF) followed by carbon burnout from the pig iron in an basic oxygen furnace process (BOF);
- remelting in an electric arc furnace (EAF) using scrap metal or using direct reduction iron (DRI) [Hasanbeigi et al. 2014].

The largest part of carbon emissions occurs during iron reduction, where there is a chemical reaction between carbon monoxide, carbon and iron oxides. In the end, almost all of the carbon in the process chain is converted into CO_2, and only a small fraction remains in the finished metal products.

Table 2. Carbon dioxide emissions from ferrous metallurgy units

The process	CO_2 emissions, kg/t
Sintering machine	319
Iron ore pellet production	65
Coke and by-products plant (indirect emissions)	392
Blast furnace with natural gas injection	1398
Blast furnace with natural gas and pulverized coal	1439
Oxygen converter	144
Electric arc furnace	88,9
Electric energy production	1,084

Table 3. End-to-end emission of various products

Products	CO_2 emissions, kg/t
Pig iron	2170
Converted steel	2166
Electric furnace steel	1401

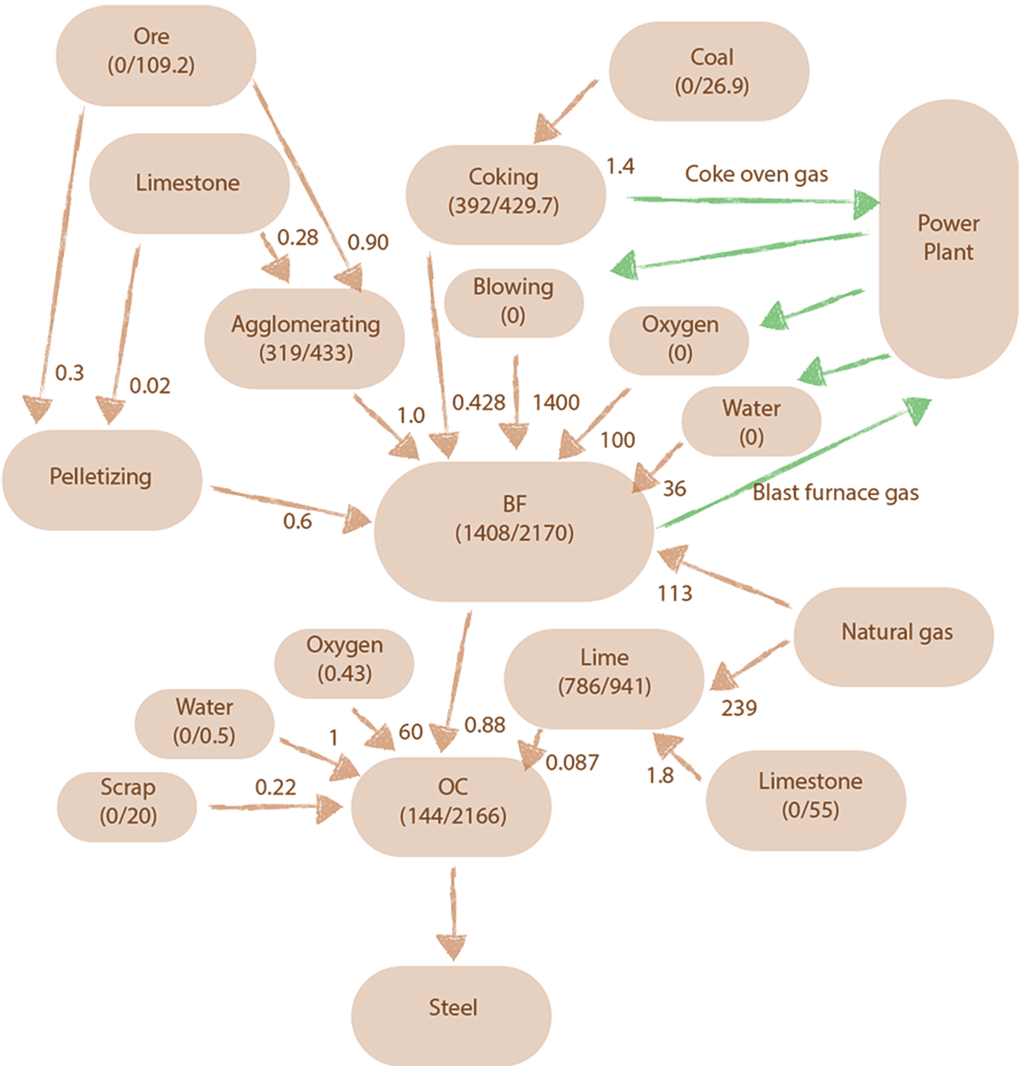

Figure 3. Emissions graph of CO_2 processes and products (end-to-end) for tandem blast furnace (BF) - oxygen converter (OC)

As an example of determining the carbon footprint, the data from the report of Metals and Mining Int. Ltd will be used [Nedelin 2021].

Direct costs and movement of carbon along the technological chain from mining to rolling in the production of one ton of iron as rolled products are shown in the scheme (Figure 4).

Thus, almost all of the carbon coming into the production scheme of a full-cycle steelmaking plant ends up being converted to CO_2.

A comparison of the two steel production schemes in terms of specific resource consumption and specific emissions is shown in Figure 5.

According to the presented diagrams, it can be concluded that steel production using the EAF technology is more profitable in terms of the load on the environment. Other studies also show similar results (Figure 6) [Hasanbeigi et al. 2017].

In summary, the first steps to reduce CO_2 emissions are:

- increasing the share of electrometallurgical production;
- reducing carbon consumption in the BF-BOF chain.

Reducing carbon emissions by increasing the share of electrometallurgy

Despite the obvious effectiveness of this production method, there are a number of limitations that hinder the active implementation of the method. In addition to the need for significant capital investments to re-equip existing production chains, the quality of the feedstock has a great influence on the wide application of this technology.

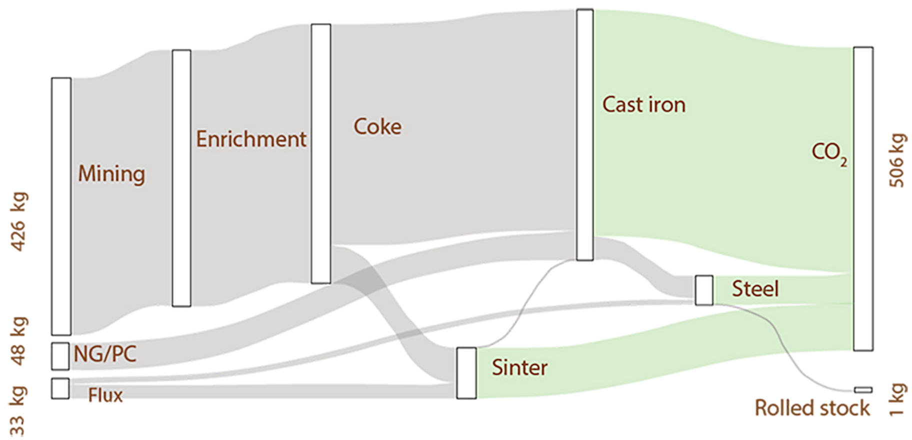

Figure 4. Movement of carbon in the production of one ton of iron in the form of rolled products under the scheme BF-BOF

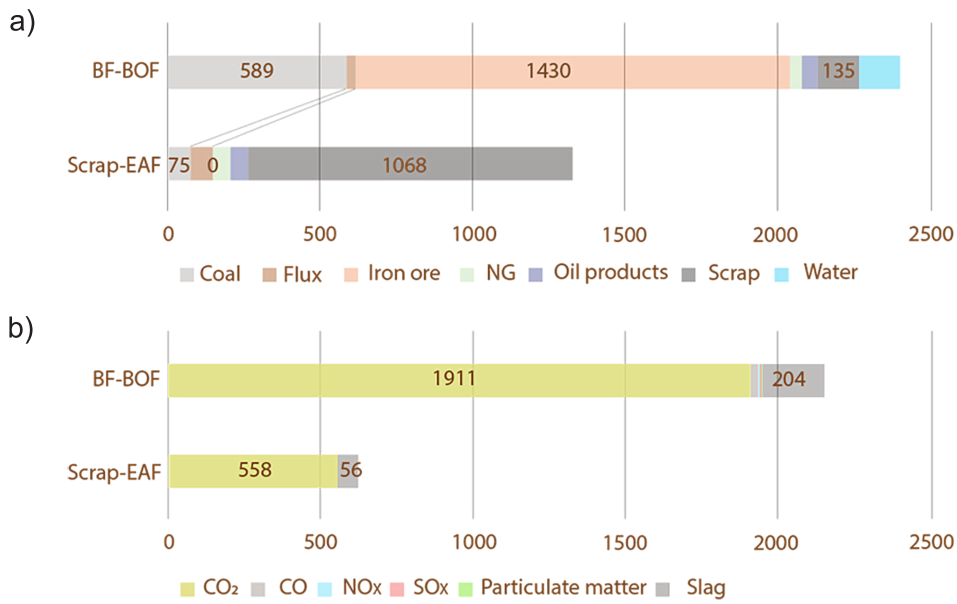

Figure 5. (a) Resource consumption in the production of 1 ton of steel (kg) (b) Emission from the production of 1 ton of steel (kg)

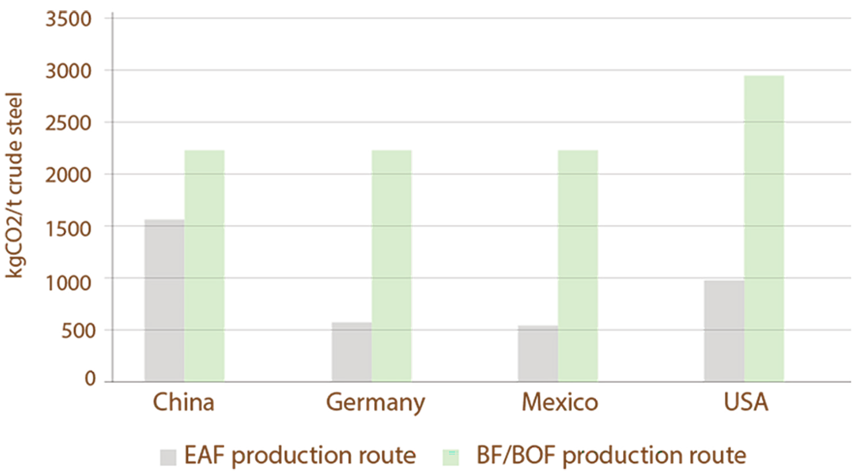

Figure 6. CO_2 intensity of EAF and BF/BOF steel production in China, Germany, Mexico and the USA in 2010

An important limiting factor is the lack of a sufficient quantity of scrap metal of the required quality and grade, since the quality of recycled scrap has a natural tendency to deteriorate due to the accumulation of impurity elements [Yang et al. 2017]. In addition, the reuse of steel scrap requires the implementation of schemes for its collection, sorting and preparation.

The process of involving secondary resources in the production cycle is a very significant advantage. The global trend is the development of circular economy with the maximum involvement of secondary raw materials in the production processes in order to save natural resources and reduce the burden on the environment. On this issue, there is a lag of domestic enterprises in terms of planning, organization and implementation of return schemes of secondary metal resources. The second option for using the EAF technology is smelting using direct reduced iron.

To produce high quality DRI, high quality iron ore is required. Otherwise, the productivity of DRI plants suffers and the efficiency of DRI use in electric steelmaking drops due to lower quality composition of the metallized raw materials. A decrease in the quality of the initial iron ore raw materials is accompanied by a decrease in the degree of metallization and a high proportion of waste rock, which significantly worsens the efficiency of the use of direct reduced iron in electric furnaces [Kirschen et al. 2011].

To produce high-quality special grades of steel from scrap with different quality and chemical composition, compliance with high purity levels is sometimes only achieved by diluting undesirable elements, such as Pb, Cu, Cr, Ni, Mo and Sn with high-purity substitute materials of direct reduced iron and hot metal. For example, high quality tire rope with less than 0.05% Cu is economically produced by remelting a mixture of scrap steel and 50–100% DRI [Hornby-Anderson 2020]. Due to rising scrap prices worldwide and in regions with limited availability of high-quality steel scrap, a combination of low-grade scrap and high-purity scrap substitute materials is a cost-effective option [Hornby-Anderson 2014].

Taking into account the limited opportunities to significantly increase the share of electrometallurgy, it turns out that a significant potential to reduce carbon-containing emissions lies in sinter and blast furnace production. At the same time, the opportunities for domestic enterprises to reduce carbon emissions in the technological chain BF-BOF are more significant than in Europe due to technological and furnace differences.

Use of hot briquetted iron in blast furnace production

According to Voestalpine's estimates, the optimal amount of hot briquetted iron (HBI) in the blast furnace charge is a specific consumption of 100–150 kg/t pig iron. During the experiment, hot briquetted iron was supplied from Voestalpine's plant in the USA and used in blast furnaces No. 5 and No. 6 in Linz, Austria, during 2017–2018. The diameter of BF#5 and BF#6 hammers is 8 m and the capacity is 2.5–2.7 thousand tons of pig iron per day. Carbon consumption in the form of coke is reduced by 25–35 kg/t pig iron. Decrease in specific coke consumption is accompanied by reduction of the bell furnace gas output and reduction of CO_2 content in it [Buergler and Kofler 2017].

The potential of using HBI in BF-BOF steelmaking, and not just in EAF steelmaking, with which DRI is usually associated, could be an advantage for future European iron and steel production in line with the CO_2 reduction goal. The use of HBI also works with limited hot metal capacity, and the smaller carbon footprint of an integrated steelmaking plant using HBI could prove attractive to other steelmakers around the world [Dzhevaga and Borisova, 2021].

The limiting factor for the use of direct reduced iron in blast furnace production is economic, due to the higher cost of HBI relative to iron ore raw materials. At present, economically efficient use of HBI is possible in the intracorporate segment, when the producer of HBI is in one integrated holding company with the producer of pig iron. However, with the introduction of a "green tax" or "carbon duty" on steel imported into Europe, the use of HBI in blast furnaces may become more common and economically advantageous, given its lower "carbon footprint" on the environment [Lungen 2014]. This method also has the advantage that no additional capital costs are required. The use of HBI can be cost-effective when the metallurgical production is short of liquid metal, or when one of the blast furnaces is suspended for overhaul.

Blowing of coke oven and blast furnace gas

Coke oven and blast furnace gases, which are co-products of pig iron and ferroalloy production in blast furnaces, can be used as secondary energy resources in production processes. In particular, coke and blast furnace gases can be used to reduce the specific consumption of coke in the production chains of ferrous metallurgy [Tovarovsky 2017].

Among all sectors of the traditional BF-BOF process, blast furnaces have the largest share of energy consumption and CO_2 emissions, which account for more than 50 and 70 percent of the total iron and steel production, respectively [Wang 2009]. Therefore, reducing energy consumption and CO_2 emissions in the blast furnace is important for the entire steel industry.

There are known studies, where reduction of carbon emissions and energy consumption of blast furnaces was achieved by injection of both coke oven gas and ladle furnace gas. Depending on the injection device, the state of equipment wear and operating parameters, the values of the mentioned parameters reached 40% and 16%, respectively [Wang 2016].

In addition to the obvious positive effect of applying such technologies in the areas of direct reduction of carbon dioxide emissions and energy savings, the recycling of by-products and waste can be used by manufacturers as a reason to receive preferential tax treatment and payment for negative impact on the environment.

Coke oven and blast furnace gas processing

The direct use of coke and blast furnace gases in the main production chain is not their only application. One example of their alternative use is the production of methanol.

There are technologies that allow this process with a number of advantages [Deng and Adams 2020]. These include the solved problem of gas desulfurization. The presence of thiophene and other sulfur compounds creates many difficulties for many conventional disposal methods. When considering the technical and economic parameters of production, it was determined that the implementation of these methods leads to significant benefits in the area of energy/carbon cost savings.

Although this analysis has focused on steel production, there are other applications of the proposed process. For example, there are many plants that produce coke from coal for the purposes other than steel production. Disposal of coke oven gases from these plants could also follow this path of modernization. In addition, if one considers methanol as a CO_2 “storage” (e.g., converting methanol to a stable solid product instead of fuel), this method, which provides potential CO_2 capture and storage, is itself a potential mechanism for regulating the carbon footprint. This direction coincides with the main trends to reduce greenhouse gas emissions. In general terms, they can be formulated as follows:

- capture and storage;
- capture and utilization.

As a major source of environmental pollution, the metallurgical industry nevertheless has great potential for qualitative improvement in reducing its carbon footprint. However, many of the “green” solutions require substantial investments in changing production structures.

Consideration of the problems of ferrous metallurgy is the first step in the study of processes to reduce the carbon dioxide emissions in chemical production, because in this industry has the largest scale. In non-ferrous metallurgy, the carbon footprint is largely determined by related industries, such as power generation, mining and transportation. Nevertheless, there is a high dependence on the composition of the initial ore. Reduction of carbon dioxide emissions in copper smelting, for example, can also be achieved by changing the basic technological process. Application of autogenous production stages results in reduction of CO_2 emissions by 15 t per 1 t of copper cathode compared with the stages using a shaft furnace [Climate: Greenhouse gas emissions management 2018].

RESULTS

Oil and gas enterprises

The issue of the carbon footprint formation at production facilities of the extractive and processing industry is caused by the emission of a significant amount of greenhouse gases at various process stages while crude oil and gas are treated in order to obtain finished products supplied to the consumer. The reason why the world community is focused on greenhouse gas emissions in the oil and gas industry is also that the oil and gas sectors account for almost half of all global emissions if considering the emissions resulting from the commercial product end use (transport, electricity and heat production) [CO_2 abatement 2020].

Research by the UCLA Institute of the Environment and Sustainability found that limiting the average global temperature rise to 2 °C means that 33% of the global oil and 50% of gas will remain untapped by 2050. If the trend for oil and gas production is retained over the next 30 years at the level of the previous 3 decades, then by the end of the century, the average global temperatures will rise by about 4 °C above the pre-industrial levels. It is emphasized that the plans of the hydrocarbon fuel producers are strongly not in line with the goals of the Paris Agreement, while the countries plan to produce about 50% more fossil fuels by 2030 [Al-Kuwari 2021].

The fossil fuel industry, which includes the oil and gas industry, differs from most other industries in that more than three-quarters of its impact on global warming come from the combustion of the products derived from the production process, rather than from the production processes themselves. Therefore, oil and gas companies must focus not only on direct production emissions.

For the energy sector, there is a standard classification used all over the world to determine the amount of greenhouse gas emissions associated with the activities of the oil and gas industry:

- Scope 1: direct greenhouse gas emissions due to operational emissions from production facilities and production vehicles; emissions due to own fuel consumption, flaring and emissions from irregular contamination sources (burst emissions).
- Scope 2: indirect greenhouse gas emissions imported from heat and power energy (i.e. related to the production energy supply).
- Scope 3: indirect greenhouse gas emissions associated with use of products made by oil and gas companies, for example, consumers driving cars and using fuels, as well as emissions from the equipment production for the oil and gas industry [Guilherme et al. 2021].

Scopes 1 and 2 account for about 12% of the global total anthropogenic greenhouse gas emissions, while Scope 3 accounts for the largest greenhouse gas emissions of the entire oil and gas sector (about 33% of global emissions), and for some large oil companies, the volume of Scope 3 emissions is generally 7 times the emissions of Scopes 1 and 2, on average. Another specific feature of the oil and gas sector is the high (up to 45%) share of methane emissions in its total greenhouse gas emissions [Decarbonization of the oil and gas industry 2021].

Recently, the amount of global greenhouse gas emissions from the oil and gas sector has increased, which is due to an increase in oil and gas production due to high demand for hydrocarbon processing products. Thus, over the period from 2005 to 2019, emissions almost doubled from the values of 2 900 to 5 250 million tons of CO_2-eq [Decarbonization of the oil and gas industry 2021].

The data on the amount of specific greenhouse gas emissions from the oil and gas industry vary for individual companies in particular. Table 4 shows the volumes of greenhouse gas emissions by the scope of coverage of some international oil and gas companies [Meziane et al. 2020].

According to the published data of some Russian companies in 2018, direct emissions (Scope 1) from Gazprom Group facilities totaled 239.9 million tons of CO_2-eq, and from LUKOIL Group facilities – 36.4 million tons of CO_2-eq [Craig 2014, Lancon and Berna 2018]

Figure 7 presented by the staff of the Bartlett School of Environment, Energy and Resources, UCL, shows a pattern of greenhouse gas emissions from all the Scopes, while the Scope 3

Table 4. Greenhouse gas emissions by scope of coverage of some international oil and gas companies

Oil and gas company	Greenhouse gas emissions in coverage areas 1 and 2, million tons of CO_2-eq.	Greenhouse gas emissions in the scope of 3, million tons of CO_2-eq.
BP (Great Britain)	55	360
Conocophillips (USA)	20.5	173.4
ENI (Italy)	43	252
Total (France)	41.5	410
Shell (multinational company)	116	576
Chevron (USA)	57	639
Exxon Mobil (USA)	120	570
Repsol (Spain, Latin America)	25.2	180

emissions, which are mainly driven by the use of refined oil and gas products, are considered by the authors to be about 90% of total emissions associated with the oil and gas production and use. Figure 8 presents the estimates of emissions from the oil and gas sector compared to the total volume of greenhouse gases [Guilherme et al. 2021].

Excluding Scope 3, it can be said that the significant direct contribution to greenhouse gas emissions is observed at the stages of extraction, production and transportation of hydrocarbon raw materials as well as products of their processing, while the indirect contribution is mainly due to the fact that the fuel used is processed during the production of heat and electricity from oil and gas. Figure 9 shows a diagram of the types of activities and sources of greenhouse gas emissions by enterprises of the oil and gas production as well as oil and gas processing industry, presented by the Russian company PJSC Gazprom Neft [Safe development 2016].

The volume of greenhouse gases coming from production facilities of the extractive and processing industries directly depends on the volume of production and is an individual indicator for different countries. Oil and gas production accounts for at least 10% of greenhouse gas emissions in the United States energy sector, according to the Environmental Protection Agency (EPA). However, emissions occur during production, flaring, ventilation and as fugitive emissions from fugitive sources. The possibility of emissions at each stage depends on many factors, such as quality of the oil and gas produced, methods of extraction, preparation, transportation, etc. For example, the US oil and gas industry contributes 3% to greenhouse gas emissions from direct extraction, about 0% from combustion and ventilation, as well as

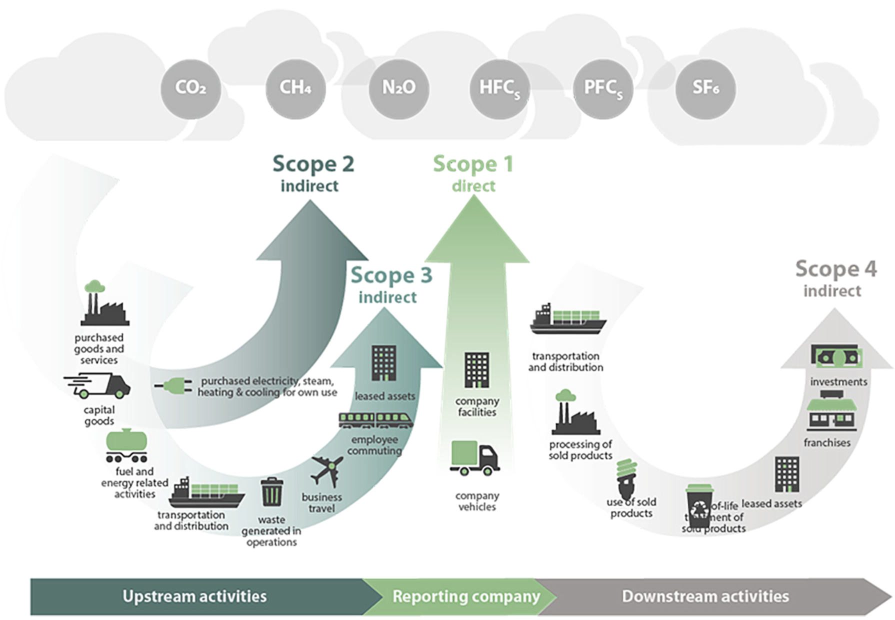

Figure 7. Diagram of greenhouse gas emissions by the Scopes

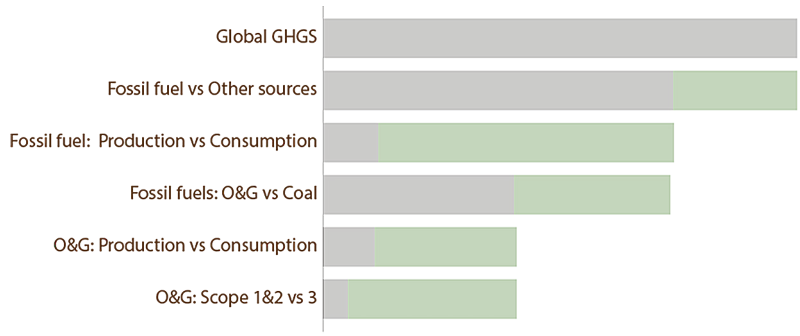

Figure 8. Illustrative estimates of oil and gas sector emissions versus total volume of greenhouse gases (~53 Gt of CO_2-eq.)

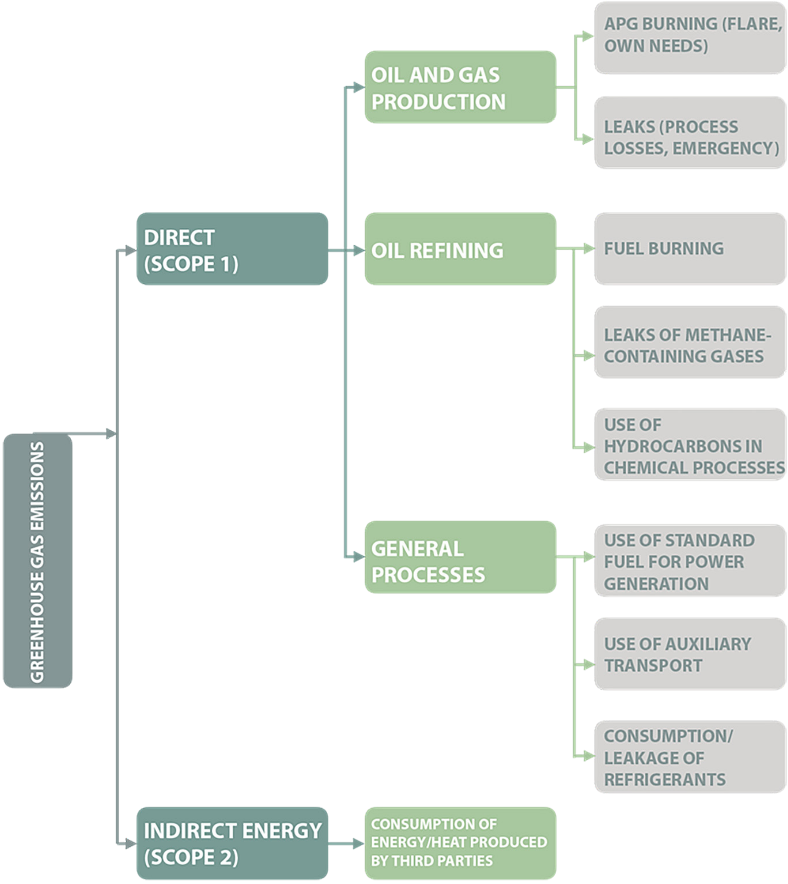

Figure 9. Diagram of activities and sources of greenhouse gas emissions by enterprises of the oil and gas production and oil and gas processing industry

0% from fugitive emissions. The rest of the US greenhouse gas emissions is approximately 88% from refining and 9% from transportation. However, these figures can be very different for Canadian oil sands, Venezuelan heavy oil, Arab light oil, or Indonesian gas condensate. For example, in terms of heavy oil production, one of the most common production methods is steam injection; however, this process is accompanied by the large amount of greenhouse gases when steam is generated and released from the reservoir [Lancon 2018, Raimi 2020, Jungin and Tayfun 2021].

Speaking about the United States, it should be noted that the Environmental Protection Agency has developed a list of regulations to control greenhouse gas emissions from stationary sources based on the Clean Air Act, which also covers activities of production facilities of the oil and gas complex [Ritchie 2013].

Globally, the GHG emissions from the oil and gas industry are in the order of 10% from production, 19% from flaring and ventilation, 6% from fugitive emissions, 4% from transportation, and 61% from refineries, according to the University of Texas. It is also stated that less than 3% of global greenhouse gas emissions are from the oil and gas industry, excluding Scope 3. According to other information, when taking into account Scope 3, the oil and gas industry accounts for one third of global greenhouse gas emissions. Approximately 85% of these emissions come from the end use of products, such as fuels and combustible materials, 15% of emissions are generated by the extraction, processing and transportation of hydrocarbons [Lancon 2018, Akimova et al. 2019].

According to other data released to the public in January 2021 by specialists of the Skolkovo Innovation Center, global greenhouse gas emissions from the oil and gas sector amount to 5.7 billion tons, or 12% of the total anthropogenic greenhouse gas emissions, and continue to grow. At the same time, the observed growth in greenhouse gas emissions from the oil and gas sector is due to share growth of unconventional oil and gas production [BP Statistical Review of World Energy 2021].

According to the official information provided by the Ministry of Energy of the Russian Federation, by the beginning of 2021, more than

280 organizations carried out activities for the production of hydrocarbons in oil, gas and oil and gas condensate fields, and the volume of national production in 2020 was estimated at 512.8 million tons [Climate agenda in the oil and gas… 2021].

The absolute largest contribution (83%) to the total greenhouse gas emissions is made by the energy sector of the Russian Federation, while about 20% is accounted for by the emissions from the oil and gas industry. Emissions of methane (CH_4), carbon dioxide (CO_2) and dinitrogen oxide (N_2O), being the main greenhouse gases, accompany the stages of exploration, production and preparation of hydrocarbons [Nikonova and Dryagina 2018].

At the exploration stage, main operations are drilling and testing wells, which may emit very small amounts of greenhouse gases. Drilling operations are a source of short-term air pollution by greenhouse gases. Preparation of well sites generates emissions from trucks and heavy equipment. During drilling, well gases and rock debris can enter the drilling fluid, which is designed to protect the drill bit and borehole walls. The drilling fluid is degassed and sieved to remove cuttings, while the resulting gases, including carbon and nitrogen oxides as well as methane, are released into the atmosphere or burned in flares. At the completion of drilling and construction, prior to installation of high pressure control valves, a test is performed to measure the potential flow of oil or gas, which is also either burnt or vented to the atmosphere, being another source of greenhouse gases [Environmental threats of hydrocarbons 2019, Eduardo 2017].

At the production stage, the hydrocarbons recovered from productive wells are sent to integrated treatment units for cleaning and separating associated fractions (in oil production – associated petroleum gas, in natural gas production – liquid fraction, gas condensate). When carrying out these operations, leaks in the equipment, as well as purging and venting of gaseous hydrocarbon raw materials, provided for by various technologies, are sources of greenhouse gas emissions into the atmosphere. Additional potential risk of spontaneous and uncontrolled greenhouse gas emissions also corresponds to the possible development of such processes as gas saturation of permafrost in the territory of the Arctic zones while drilling wells – this can lead to craters of uneven freezing. In general, most crude oil and natural gas treatment processes require the use of temporary storage facilities, sulfur recovery equipment, pumps and generators, which poses a potential hazard from ventilation flows and fugitive emissions containing methane, H_2S, SO_2, NO_x and CO. Emissions can also occur at the direct production stage due to leaks from high pressure valves or during process failures, such as overpressure blowouts. Potential sources of greenhouse gas emissions are spherical or horizontal separators used to separate natural gas from liquid hydrocarbons and water. Repair and maintenance work can also lead to emissions from trucks and heavy equipment. In long-running gas wells, insufficient reservoir pressure can lead to accumulation of fluid that must be removed for the well to operate smoothly – this leads to methane emissions. Unexpected process failures, as well as planned maintenance, start-ups and shutdowns of oil and gas facilities can lead to large temporary emissions, known as burst emissions [Himenkov 2020, Eduardo 2017].

It should be noted that accounting for all sources of greenhouse gases at the stages of exploration, production, preparation and processing of hydrocarbon raw materials is a complex process and requires constant research, for example, a group of scientists conduct research to assess the greenhouse gas emissions from helicopters that are used in exploration as well as production of oil and gas companies in Brazil, which, although being indirect emissions, contribute to the total share of emissions from oil and gas companies [Mendes et al. 2020].

Speaking about oil refineries, it should be noted that in addition to the emissions generated directly during processing hydrocarbon raw materials, such as separation of raw materials into fractions by boiling point, chemical transformation and obtaining commercial products using various additives, there is a risk of emissions associated with the use of obsolete equipment. The refineries built in the early stages of oil and gas industry approach or exceed the design life, which is a factor contributing to emergency and constant technological leaks [Climate: Greenhouse gas emissions management 2018].

In relation to refineries, particular attention is paid to reducing greenhouse gas emissions through the use of such technologies as cogeneration of heat and electricity, carbon capture in fluid catalytic cracking and steam methane reforming units, as well as alternative technologies for hydrogen production. Research results show that implementation of these technologies contribute to reduction of total annual CO_2 emissions from 2 to 24% per barrel of crude oil [Decarbonization of the oil and gas industry 2021].

According to many scientists and many years of experience of oil and gas enterprises, the main contributor to the carbon footprint due to the high share of greenhouse gas emissions is associated petroleum gas combustion [Bulaev 2015, Kurbangulov et al. 2016, Sattarov and Tukhfatov 2016].

During exploration, production and preparation of hydrocarbon raw materials, a part of gaseous hydrocarbons is formed that cannot be used, and is therefore burned in flares. As a result, greenhouse gases enter the atmospheric air as components of both combustion products (i.e. carbon dioxide and dinitrogen oxide) and incomplete combustion products (methane).

It is practically impossible to give the exact data on associated petroleum gas flaring, while information from domestic and foreign authors differs by hundreds of percent. Gas flaring is the main contributor to the global greenhouse gas emissions burden, with a total volume of flaring being 100 billion cubic meters annually, according to British scientists from the Coventry University. Russia accounts for 35.5 billion cubic meters per year, while Nigeria burns 18.27 billion cubic meters. According to Russian sources, the volume of burning does not exceed the limit of 21 billion cubic meters on an annualized basis, NASA cites figures of about 50 billion cubic meters on an annualized basis, based on its photographs from space. Experts from the Skolkovo Innovation Center attribute this discrepancy in volumes to the low accuracy of satellite surveys and the shortcomings of metering devices installed on flares. Another problem in accounting for greenhouse gas emissions when flaring associated petroleum gas is called low technical support when establishing the total the nature of their operation which leads to impossibility of tracking all flares, of which there are at least 1,500 in the oil fields of the Russian Federation, with an irregular and uneven nature of their operation [Bulaev 2016, Knizhnikov and Kutepova 2015, Ojijiagwo 2017].

According to some data, for each billion cubic meter of associated gas when burning in flares, 2 million tons of carbon dioxide are emitted into the atmosphere, while the financial losses for the Russian Federation amount to more than $5 billion per year due to the low use of resource and energy potential of associated petroleum gas. Some deposits in oil fields are accompanied by emissions of more than 1000 cubic meters of associated gas containing high concentrations of sulfurous methane and anhydride, with the production of one ton of oil, which is caused by high gas factors. Impossibility of associated gas transportation due to corrosive effect on the pipeline walls and impossibility of its further use due to high concentrations of toxic components aggravate the situation at such fields. As a result, forced flaring occurs [A Guide to the Restoration Opportunities 2014].

Considering the potential amount of carbon dioxide that can enter the atmospheric air when flaring associated gas at the stage of exploration, production and preparation of hydrocarbon raw materials, special attention is paid to the introduction of rational approaches to treatment and disposal routes, including the use of associated gas for re-injection into the reservoir (cycling process), the use of associated gas for power generation and processing of associated gas at gas processing plants. The cycling process has become widespread in the territory of the Russian Federation, as it contributes not only to the reduction of greenhouse gas emissions and the carbon footprint decrease, but also allows for saving methane inside the reservoir for subsequent use. For example, Irkutsk Oil Company and Gazprom Neft utilize associated petroleum gas by injecting it into the reservoir, for which various integrated gas treatment units have been built and put into operation [Gorbachev and Gorlenko 2019, Drozdova and Sukovatikov 2017, Extraction of oil raw materials 2021].

The leading oil and gas companies of the Russian Federation implement the climate agenda concerning for the environment, taking into account the Russia's Energy Strategy-2035 and goals of the Paris Agreement. JSC Gazprom is constantly developing its capabilities to reduce greenhouse gas emissions through the use of the best available technologies, commissioning associated gas compressor stations and gas turbine power plants. In 2020, Rosneft approved the Carbon Management Plan-2035, which has become the basis of the company's environmental agenda in terms of low-carbon economic development, including climate risks management and identification of opportunities related to future energy demand [Motazedi et al. 2017, Purtova and Koryakina 2014, Plan for carbon management… 2020.].

Despite the upward trend in the use of associated petroleum gas in the exploration, production and primary treatment of hydrocarbon raw materials, the carbon footprint problem remains urgent due to the lack of proper control and technical support, as well as high production volumes, which is associated with the constantly growing demand of enterprises operating oil products to one degree or another.

Currently, digital technologies have been developing in the world to control the greenhouse gas emissions resulting from activities of the oil and gas industry. For example, researchers from the Federal University of Rio de Janeiro found that when using dynamic systems in modeling the inventory of greenhouse gas emissions, it becomes possible to adjust all the variables individually or together, creating an infinite amount of information output. Thus, taking into account each source of emissions as a variable, determining the significance of each of them in the aggregate of emissions will allow in the future to pay attention and resources to certain processes of exploration and production of oil and gas, the most problematic ones in terms of greenhouse gas emissions [Fernandes and Santos 2022].

The greenhouse gas emissions during well drilling, leaks of equipment used in the fields, flaring of associated gases, arising at the primary stages preceding direct processing of hydrocarbons and transportation of the resulting processed products to the direct consumer and their operation contribute to an increase in the share of greenhouse gases of anthropogenic origin. It should be noted that the additional contribution to the hydrocarbon footprint is also made by emergencies with oil and oil products spills, as well as gas leaks, especially in the event of fire and explosive situations.

DISCUSSION

Plant communities are one of the largest natural sources of carbon dioxide absorption on the planet nowadays. In terms of vegetation reproduction as the main way of sequestering carbon dioxide, one can confidently speak of an increase in the intensity of carbon dioxide absorption with an increase in vegetation biomass [Di Vita et al. 2017]. However, full-scale scientific studies carried out in this area in the last decade suggest that, in addition to the natural biomass of vegetation, the absorption capacity of certain species of plant communities also affects the intensity of absorption of carbon dioxide from the atmosphere [Fedorov et al. 2018]. In this case, speaking of a forced increase in the intensity of sequestration of carbon dioxide by plant communities, one can rely not only on an increase in the projective cover of green spaces and an increase in their biomass, but also on the choice of certain species of plant communities with the maximum absorbing capacity [Akita and Ohe 2021].

More than 11,000 species of vascular plants grow on the territory of the Russian Federation, while there are also over 10,000 species of algae and about 5,000 species of lichens, which are also capable of absorbing carbon dioxide from the atmosphere, but in a much smaller amount [Petrova et al. 2022]. To consider the absorbing capacity of each individual plant species is an impossible and unnecessary task, since, depending on a number of territorial, climatic and soil characteristics, a wide species diversity of plants grows in a particular territory. In this regard, to assess the absorptive capacity of plant communities, the most logical way is to evaluate the absorptive capacity of the main natural ecosystems characteristic of different climatic zones of Russia, and not of each individual plant species [Krasutsky 2018].

The territory of the Russian Federation by latitudinal division covers 7 basic natural zones: arctic desert, tundra, taiga, mixed and deciduous forests, steppe, desert and subtropics. In addition, due to the smooth transition from one region to another, 3 subzones are also distinguished: forest-tundra, forest-steppe and semi-desert. Plant communities growing in each of the above-mentioned natural and climatic zones can differ significantly in different territories of the country; however, each zone has common basic plant species that are the basis of a particular natural zone [Koroleva 2016].

It is advisable to assess the intensity of carbon dioxide sequestration by plant communities only in those natural zones where green spaces have a significant projective cover and significant biomass. As a result of which, on the territory of the Russian Federation, the research on this topic is carried out mainly for 5 natural zones – tundra, taiga, mixed and deciduous forests, steppe and subtropical forests [Petrova et al. 2022] – as well as for artificial forest plantations, for example, for reforestation in technologically disturbed areas [Pashkevich and Danilov 2023].

In the Arctic deserts and deserts, green spaces are practically absent, and therefore the intensity of carbon dioxide absorption by vegetation in these natural areas tends to absolute zero, which makes it inappropriate to study the intensity of carbon dioxide absorption by natural ecosystems in these areas [Krasutsky 2018, Nauta et al. 2015].

A sufficient number of scientific studies have been carried out in order to assess the absorptive capacity of plant communities and entire ecosystems on the territory of various countries today. Most scientists agree that the species with the most developed specific gravity have the greatest absorptive capacity in relation to carbon dioxide that is woody plants [Chimitdorzhieva et al. 2015).

In the work of Fedorov et al., the specific absorption capacity of some species of woody plants for 1 vegetation period is given. Thus, spruce absorbs 6.6 t CO_2/ha, aspen – 7.1 t CO_2/ha, birch – 8.1 t CO_2/ha pine – 11 t CO_2/ha, linden – 16.5 t CO_2/ha, oak – 29.7 t CO_2/ha, poplar – 46.2 t CO_2/ha [Fedorov et al. 2018].

Also, among the many scientific works of Russian scientists, one can find the data on the average specific absorption of CO_2 in the regions of Russia. In the forests of the Urals, the annual capture of carbon dioxide is estimated at 6.1 t CO_2/ha, in Eastern Siberia – 5.7 t CO_2/ha, in the forests of Western Siberia and the Far East – 4.95 t CO_2/ha [Zamolodchikov et al. 2014, Titlyanova and Shibareva 2017].

Having performed a large-scale analysis of the studies carried out by Russian and foreign scientists, it is possible to present summary data on the specific absorptive capacity of plant communities in accordance with the natural and climatic zones of Russia, which will be taken as a basis for further research. Hence, in the tundra, the annual value of carbon dioxide capture is 0.003–1.4 t/ha [Petrov et al. 2018, Van Huissteden and Dolman 2014], in taiga – 3.8–9.4 t/ha, in the mixed forest zone - 4.2–11.6 t/ha [Krasutsky 2018, Zamolodchikov et al. 2014, Xu et al. 2021], in the subtropical – 5.7–17.5 t/ha [Koroleva 2016, Mancini et al. 2016, Adamovich et al. 2018], and in the steppe – from 1.1 t/ha in desertified steppes to 6.4 t/ha in the meadow steppe zone [Kurganova 2013, Petrov et al. 2018, Van Huissteden and Dolman 2014].

In addition to the species diversity of vegetation in a certain area, the rate of CO_2 absorption is significantly influenced by the age of woody vegetation. Young woody plants store carbon 3 – 6 times more efficiently than middle-aged and aging trees [Mancini et al. 2016]. Thus, to correctly determine the absorptive capacity of plant communities, it is necessary to take into account not only the regional specifics, but also the age structure of forest stands, which is a rather difficult task, since natural plantations are often very heterogeneous in composition, age groups, and status categories.

In addition to species diversity, mainly dictated by natural and climatic conditions, an important factor affecting the intensity of absorption of carbon dioxide by plant communities from the atmosphere is the biomass of vegetation. In this case, the determination of the biomass of vegetation can be carried out directly in the field by destructive sampling, as well as by the non-destructive method of remote sensing.

Remote sensing of the earth is currently the most preferred method to use, since it provides real-time monitoring of vegetation, allows regular updates of data on the area of distribution of plant communities and their biomass, and is also applicable for mapping biomass heterogeneity [Xu et al. 2021, Yude et al. 2011]. The use of satellites and unmanned aerial vehicles is especially important when obtaining characteristic data of vegetation from large areas, as well as hard-to-reach areas [Calders et al. 2020, Zamolodchikov et al. 2014].

Remote monitoring acquired wide application in the study of vegetation, including forest plantations, after the launch of the Landsat satellite. Currently, monitoring is carried out on the basis of a significant number of satellite systems, such as IKONOS, Quickbird, Worldview, ZY-3, SPOT, Sentinel, Landsat, and MODIS [Chen et al. 2020]. Table 5 presents the main technical characteristics of the imaging equipment of the listed satellite systems.

The undoubted advantage of remote monitoring using satellite images, as mentioned earlier, is the study of large areas with an estimate of the biomass of trees on a global scale [Xu et al. 2021]. However, the implementation of this type of shooting is limited by the low ability to penetrate through the clouds, as well as low image detail. In recent years, it has been possible to solve the penetration problem with the help of radar remote sensing. An additional advantage of this method is obtaining more detailed information about the structure of vegetation. Since the beginning of the 21st century, not only onboard radar systems have been actively involved, but also space systems, such as Terra-SAR, RADARSAT, ALOS and PALSAR [Ferwerda et al. 2015).

If it is necessary to individually assess the trees of the forest under study to determine the

Table 5. The main technical characteristics of the imaging equipment of the listed satellite systems

Name of the satellite system	Visibility, km	Frequency, days	Spatial resolution, m/pix	Spectral characteristics*
IKONOS	11	3	3.2	B, G, R, NIR
QuickBird-2	16.5	3–4	2.5	B, G, R, NIR
Worldview	17.6	2–4	0.5	PAN
ZY-3	50	1–3	5.8	B, G, R, NIR
Spot 5	60	1–4	10	B, G, R
Sentinel	290	10	20	B, G, R, NIR
Landsat 7	185	16	60	G, R, NIR
MODIS	2300	<1	250–1000	B, G, R, NIR

Note: List of spectral channels of imaging equipment: B – blue; G – green; R – red; NIR – near infrared; PAN – panchromatic.

vertical structure of the forest or the size of individual specimens, which is directly related to the biomass value, the lidar remote sensing method can be applied. Owing to this method, it is possible to accurately measure the density of the stand, the height and the density of the crown. Lidar sensing technology provides 3D information on the structure of a forest and, when used in conjunction with other remote monitoring methods, it can increase the accuracy of biomass estimates [Xu et al. 2021].

Mapping and other characteristics of vegetation using remote sensing methods are based on the data of the reflected radiation spectra. Such spectra are due to different absorption of radiation of different wavelengths by biological pigments, in particular, chlorophyll. The physiological state of vegetation changes in parallel with the concentration of pigments in its cells and tissues as well as the level of moisture supply; therefore, these indicators characterize plant health [Adamovich et al. 2018, Lalit and Mutanga 2017].

To quantify vegetation, in particular its aboveground biomass, the pictures obtained by remote sensing are processed using vegetation indices. Vegetation indices are values of arithmetic combinations of spectral brightness coefficients in individual spectral channels of an aerospace image. These expressions are derived on the basis of empirical observations and are aimed at increasing the signal informativeness in individual channels for vegetation studies while reducing the influence of side factors: the influence of the atmosphere, soil brightness, saturation effect, dependence on the geometry of observations [Seward et al. 2018]. At the moment, there are about 160 indices that are calculated for wide and narrow spectral zones, depending on the spectral brightness of objects. Figure 10 shows a graph of the dependence of the spectral brightness of the main natural objects on the wavelength [Xu et al. 2021].

Spectral vegetation indices are calculated from the values of the most stable parts of the spectrum, namely the red and near infrared. The

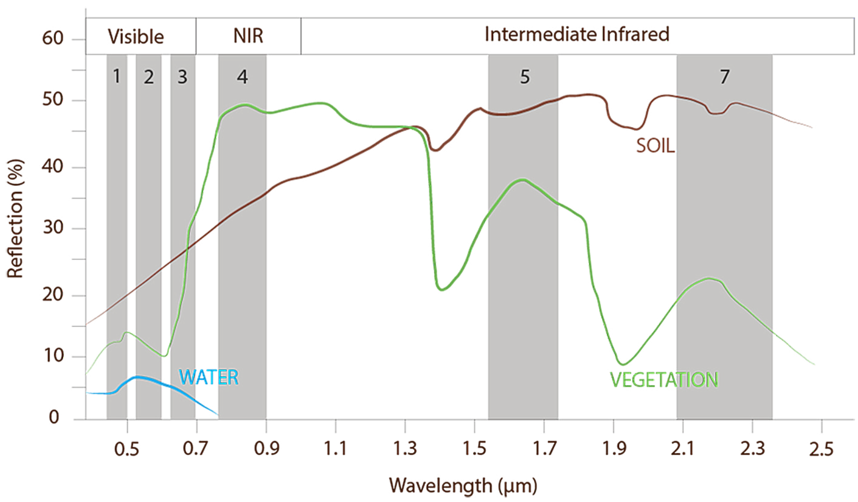

Figure 10. Dependence of the spectral brightness of the main natural objects on the wavelength

first spectrum region (of 0.62–0.75 μm) is characterized by a maximum absorption of solar radiation by the green pigment of plants, and the second (0.75–1.3 μm), the maximum reflection energy [Adao et al. 2017].

Assessment of vegetation condition, as well as identification of territories occupied or free of plantings, is possible with the help of Broadband Greenness group indexes. The most popular index is NDVI (Normalized Difference Vegetation Index), which allows quantifying the biomass of plants and is determined by the formula:

$$NDVI = (NIR - RED) / (NIR + RED) \quad (1)$$

where: *NIR* is a reflection in the near infrared, *RED* is a reflection in the visible region.

This index takes positive values for vegetation, and the larger it is, the higher the value of biomass [Sozina and Danilov 2023, Adamovich et al. 2018]. There are many researches who use NDVI as a biomass estimate. This index has been successfully applied in its modeling on seasonal wetlands, forests and agricultural lands [Guerra et al. 2020]. There is a stable correlation between the NDVI indicator and productivity for various types of ecosystems, as shown in Figure 11 [Zamolodchikov et al. 2014].

More often, the calculation of NDVI is used on the basis of a series of multi-temporal (various series) pictures with a specified temporal resolution, enabling to obtain a dynamic picture of the processes of changes in the boundaries and characteristics of different vegetation types (monthly variations, seasonal variations, annual variations) [Kusumaning et al. 2021].

Being an artificial dimensionless indicator, NDVI is designed to measure the ecological and climatic characteristics of vegetation, but at the same time it can show a significant correlation with some parameters of a completely different field: productivity (temporary changes), biomass, moisture and mineral (organic) saturation of the soil, evaporation (evapotranspiration), precipitation volume, power and characteristics of snow cover, etc. [John et al. 2022].

In some cases, only NDVI may not give a correct evaluation of the data obtained from the pictures, for example, upon reaching a certain threshold of plant development index loses sensitivity. If the plant develops very actively, NDVI cannot distinguish an abnormally green plant from the "usual" green [Laefer 2019].

In this regard, in addition to interpreting pictures based on NDVI, four vegetation indices are often used when assessing carbon emissions reduction by restoring agricultural land: RVG (Ratio Vegetation Index), SAVI (SOIL Adjusted Vegetation Index), GCC (green Chromatic Coordinate) and fc (Fractional green vegetation cover). For example, SAVI was chosen by the authors to reduce the influence of soil when interpreting the results, since not all of the studied area was covered with vegetation [Liu et al. 2017].

There are also other vegetation indices, which are an alternative to the NDVI index. Thus, for example, if it is not possible to use a camera with an infrared channel for shooting, then the VARI index (Visible Atmospheric Resistant Index) is often used as an indicator of photosynthetic activity designed specifically for working with RGB cameras, which is determined by the formula:

$$VARI = (Green - Red) / (Green + Red - Blue) \quad (2)$$

where: *Green* – denotes the pixel values from the green channel, *Red* – corresponds to the pixel values from the red channel, *Blue* – includes the pixel values from the blue channel [Chevrel and Bourguignon 2016].

Of course, the aboveground biomass of plantations is characterized by the most dynamically changing carbon content. The applicability of remote monitoring to the determination of this type of biomass allows using it to predict the efficiency of carbon dioxide uptake [Mancini et al. 2016].

To date, methods for assessing carbon uptake by binding it inside the forest are already known. Thus, in the Guidelines of Good Practice of the Intergovernmental Panel on Climate Change (IPCC), the calculation of the carbon uptake efficiency is based on the use of the biomass value of forest plantations, followed by the conversion of this value into carbon mass, based on the assumption that biomass contains 49% carbon. In the future, it is possible to recalculate the result into CO_2 units by multiplying the value by 3.67, which is the ratio of the atomic mass of CO_2 and C, respectively [A Guide to the Restoration Opportunities… 2014]. A similar technique for determining captured carbon and carbon dioxide was used by scientists from India, New Zealand and South Africa to study the ability of carbon dioxide capture by specific plant species [Iron ore mining in the world 2020]. However, Asner et al. in the study of the Amazon forests noted that

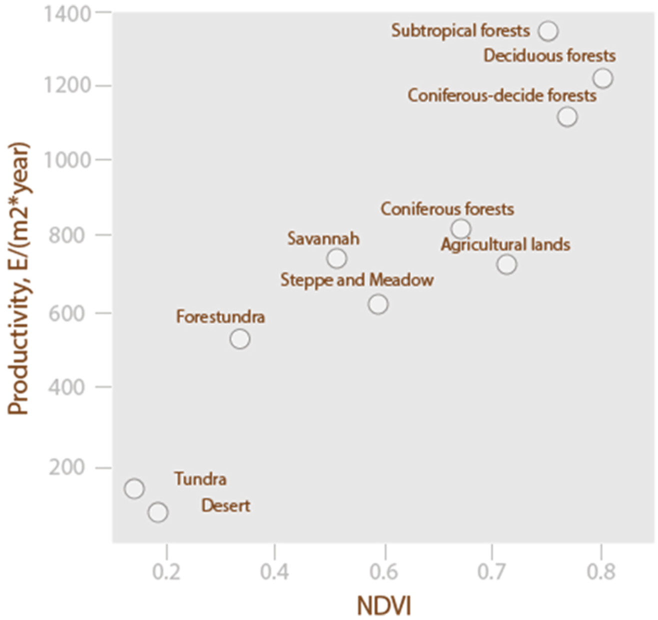

Figure 11. Correlation between NDVI and productivity for different types of ecosystems

the difference between the values calculated using this method and those obtained using airborne LiDAR is more than 30%. One of the probable reasons for this difference is the heterogeneity of carbon density in forests at different scales [Asner et al. 2010].

Forecasting the efficiency of carbon dioxide absorption by a forest should be based not only on the obtained value of biomass. It should be noted that the course of this process depends on climatic and temporal characteristics, as well as the type of vegetation growing [Pankov and Afanasiev 2020]. One species, growing in different regions, may exhibit differing rates of carbon absorption. In the study of Blank et al., 1,197 stand points were analyzed around the world in order to determine the carbon absorption coefficient depending on the climatic conditions of growth. As a result, scientists found that the rates of absorption by coniferous, oak and broad-leaved tree species in tropical regions were characterized by the highest rate. At the same time, eucalyptus showed a consistently high absorption coefficient regardless of growing conditions (Figure 12) [Bernal et al. 2018]. Along with predicting the efficiency of carbon absorption, it is possible to forecast its release when analyzing pictures from areas of deforestation, degradation or destruction of vegetation.

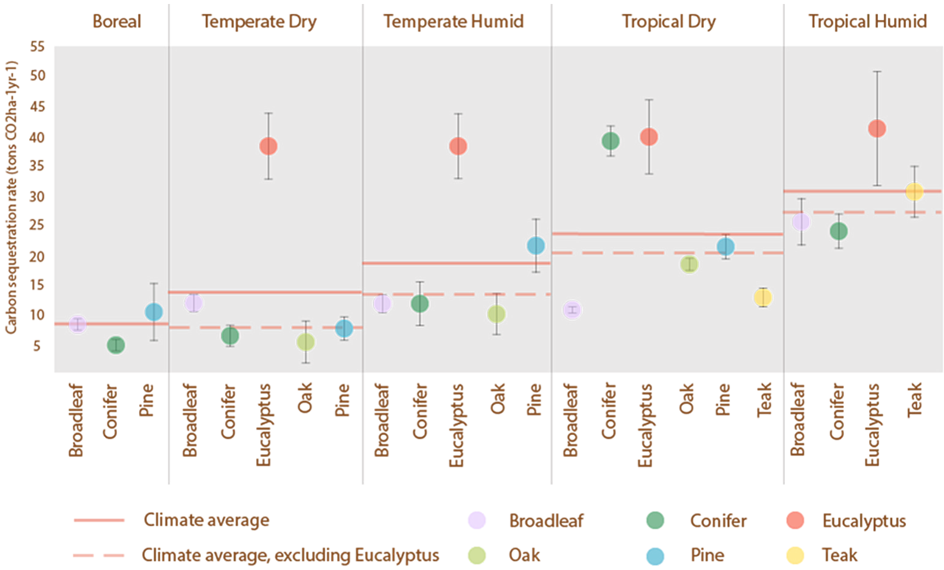

Figure 12. Dependence of carbon dioxide absorption by vegetation under different climatic conditions

When conducting remote monitoring, it is necessary to pay attention to the age structure and growth pattern of trees. There are studies of old-growth trees in terms of their ability to absorb carbon. Some of them point to the lack of such ability due to a decrease in biomass production and the loss of trees due to natural disturbances, such as lightning strikes, diseases and fungi. At the same time, representatives of the young-aged forest are characterized by the production of biomass at a high level for a long time, which contributes to effective absorption [Mancini et al. 2016]

The growth patterns of species in a forest community, namely their density and spatial location relative to each other, are an important factor in predicting absorption. For example, a report by the International Union for Conservation of Nature said that in order to bind the largest amount of carbon, it is necessary to produce mosaic tree planting using a lower tree planting density. In this case, the maximum land area will be involved, which ensures efficient carbon sequestration over a larger area [A Guide to the Restoration Opportunities … 2014]. However, in the studies of Pan et al., the main reason for the increase in carbon absorption in temperate forests, along with a significant increase in forest area, is called an increase in the density of its planting [Pankov and Afanasiev 2020].

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