ASSESSMENT OF THE CARBON FOOTPRINT OF INFRASTRUCTURES USING THEIR FULL LIFE CYCLE WITH ACCOUNTING FOR CLIMATE CHANGE

Sviatoslav Timashev[1], Tatyana Kovalchuk[1], Anna Bushinskaya[1], Gennady Shmal[2]
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[1] Science & Engineering Center «Reliability and Safety of Large Systems and Machines»
Ural Branch Russian Academy of Sciences, Russia, 620049, Yekaterinburg, RUSSIA
[2] Union of Oil & Gas Industrialists of Russia, Russia, Moscow, RUSSIA
timashevs@gmail.com

Abstract

The article examines from an interdisciplinary perspective the problem of quantitative accounting, assessment and minimization of the carbon footprint (CF) of the infrastructures of the oil and gas sector (OGS) of the fuel and energy complex (FEC) of Russia at all stages of their life cycle (LC), including diagnostics, monitoring, maintenance, recovery from accidents and disasters. The ultimate goal of the study is to develop a working algorithm that allows formulating a global carbon balance equation according to the top-down scheme, which shows the contribution of each infrastructure to the global carbon footprint, taking into account climate change according to the criterion of the need to achieve zero CO_2 emissions by 2060, in accordance with the obligations assumed by Russia under the Paris Agreement of 2015.

Keywords: global warming, global carbon budget, greenhouse gas emissions, carbon footprint of infrastructure, decarbonization, carbon offsetting.

I. Carbon Footprint of the Oil and Gas Industry: State of the Art

The oil and gas industry is not the most important emitter of greenhouse gases (GHG), operations for the extraction and production of hydrocarbon fuels (HCF) account for only 10 % of global emissions. However, further use of HCF provides an additional 33 % of emissions in end-use areas. Over the entire cycle from extraction to end-use, 57 % of GHG emissions from oil are concentrated in the transport sector; in gas, 72 % of emissions occur in generation, industry and public utilities. In the extraction, processing and transportation of oil and gas, methane plays a significant 42 % role, associated with the extraction of natural gas and associated petroleum gas, as well as the transportation of dry stripped gas [1].

In terms of hydrocarbon fuels, most companies agree that in the baseline scenario, the energy transition will not lead to an absolute reduction in demand in the next 10–20 years. Thus, according to forecasts, oil consumption by 2030 will grow by 0–15 % compared to 2019, while gas demand will grow at least until 2040 within the range of 25–52 % [1].

To date, all major Russian oil and gas companies have implemented carbon management systems, including greenhouse gas emission accounting systems. When preparing reports on greenhouse gas emissions, the national methodology for quantifying GHG emissions approved by the order of the Ministry of Natural Resources and Environment of the Russian Federation dated 27.05.2022 No. 371 [2] is used, as well as foreign guidelines: the corporate standard for accounting and reporting of the Greenhouse Gas Protocol (GHG Protocol) of the World Business Council for Sustainable Development and the World Resources Institute [3], the international standard ISO 14064-1:2018 "Greenhouse gases. Part 1: Specification with organization-level guidance for quantifying and reporting greenhouse gas emissions and removals" [4].

All major Russian companies provide data on GHG emissions as part of their periodic reporting (environmental report, or as part of a sustainable development report or annual report). The total GHG emissions in the oil and gas sector of the Russian economy in 2019 amounted to 297.6 million tons of CO_2-eq., the total GHG emissions of the largest companies in the sector (PJSC Gazprom, PJSC Rosneft, PJSC LUKOIL, PJSC Gazprom Neft, PJSC Surgutneftegaz, PJSC Novatek, PJSC Tatneft and PJSC Transneft) amounted to 236.2 million tons of CO_2-eq. [1].

II. Statement of the problem

For a qualified and consistent assessment of the ecological/carbon footprint of the OGS of the Russian fuel and energy complex, it is necessary to conduct a specific analysis of their full life cycle (FLC) to assess (1) the value of the carbon footprint of the OGS as a random function of time and (2) its contribution to the industry's CF, which affects climate change on the planet.

The full life cycle of any OGS infrastructure (OGI) consists of: (1) extraction of raw materials required for the creation of this infrastructure; (2) processing of materials, manufacturing of the OGI components; (3) construction of infrastructure; (4) hydro testing of the OGI pipeline to check for defects; (5) operation of the system, including its diagnostics, monitoring and scheduled maintenance; (6) restoration of the infrastructure after each accident and (7) its disposal after its useful life.

The carbon footprint of OG infrastructure is an indicator of the environmental efficiency of its use at all stages of its life cycle, and is therefore of great interest to the public and investors. Decision makers (DM) on the methods of operating OGI should (in the context of the Paris Agreement) separately take into account the size of the current and cumulative CF they create and the discounted cost of its neutralization, taking into account the impact of climate change on the CF of OG infrastructure.

In the conditions of dynamic multifactorial uncertainty of the modern world, OGI management is carried out according to safety and risk criteria – determining indicators of the quality of their functioning. In this case, the target function (TF) of risk management is reduced to minimizing the generalized cost of operating an OGI facility over the period of time “from conception/cradle to grave”.

From a mathematical point of view, the problem of managing the risk of OGI is posed as a problem of optimizing the objective function, which in the context of the problem under consideration should adequately reflect the total present value of costs during the entire life cycle for:

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

In the most general case, the problem of determining the man-made risk, interpreted as the product of the probability of failure (POF) and its consequences (losses/damage), expressed in monetary form, is solved as a problem of optimizing the target function of managing the risks of operating the OGI, which is reduced to the integral cost of owning the OGI over its full life cycle:

$$_{\mathrm{OGI}}C_{\Sigma} = C_{\Sigma,c} + C_{\Sigma,in} + C_{\Sigma,r} + C_{\Sigma,cf} + C_{\Sigma,hl}\ . \quad (1)$$

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

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

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

The main carbon plume occurs during the operation of the OGI. It is a function of the volume and quality of diagnostics, monitoring, pipeline maintenance, as well as the consequences of OGI depressurization as a result of incidents, accidents and disasters.

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

III. General algorithm for assessing the carbon footprint of OGI

Consider the general algorithm for assessing the carbon footprint of the OGI throughout its life cycle.

Since the sectoral CF is formed by individual infrastructures of companies/states, in order to reduce it, it is necessary to strive to reduce its carbon emissions at the level of each infrastructure, starting from the initial stage of the OGI life cycle – the production of its structural components and the construction itself. By analogy with the name of the life cycle stage, we will call the emissions of this stage the initial CF of the OGI.

The calculation of the natural gas transportation efficiency factor takes into account methane (CH_4) and carbon dioxide (CO_2) emissions, as well as energy consumption per unit of production generated at all stages of its life cycle. The share of other greenhouse gases (GHG) is no more than 1 % of all GHG emissions and they are not taken into account in the quantitative determination of the efficiency factor.

The OGI life cycle consists of the following stages:

I) production of materials from which the components of the OGI will be manufactured (extraction of raw materials for the production of structural materials is usually not considered in the calculation of the CF);

II) production of structural components of the OGI;

III) transportation, welding, laying of the OGI pipeline string and its protection from external influences, installation of all process equipment;

IV) operation of the OGI in a stationary mode, including scheduled and unscheduled diagnostics, technical repairs, maintenance;

V) processing/disposal of the OGI components after completion of its operation.

Now consider in general terms what the OGI's CF consists of and how it is calculated at each stage.

Stage I. Production of materials for the manufacture of components

At the stage of production of materials, the CF depends on the type of materials from which the structural components of the OGI are made, their weight and the GHG emission factors during the production of these types of materials.

$$CF_{\mathrm{I}} = \sum_i EF_i m_i \,, \tag{2}$$

where EF_i is the emission factor for the production of the i-th material; m_i — mass of the i-th material in the components of the OGI.

Examples include the production of steel or polymers needed to manufacture pipes and pipeline equipment, the production of concrete needed to construct compressor station buildings, the production of anti-corrosion materials used to protect pipes, etc.

Stage II. Production/manufacturing of structural components.

The components of the OGI include: oil and gas valves, taps, gas compressor station (GCS), oil pumping station (OPS), gas distribution station (GDS), gas control point.

At this stage, the energy consumption of the equipment used in the production of OGI components is generated by the energy consumption of the equipment and depends on the type, quantity, power consumption and operating time of this equipment.

$$CF_{\mathrm{II}} = \sum_i \sum_j EF_{ij} w_{ij} t_j \,, \tag{3}$$

where EF_{ij} is the emission factor when using the i-th energy source by the j-th type of equipment for the production of components; w_{ij} is the energy consumed (power) by the j-th equipment per unit of time (hour) from the i-th energy source; t_j is the operating time of the j-th equipment.

For example, in the production of steel pipes, emissions from energy consumption by equipment used to produce sheet steel from finished raw materials, subsequent calibration, stretching, cooling, cutting, welding and other technological processes are taken into account..

For gas (oil) pipelines, emissions from anti-corrosion coatings of pipe surfaces with special materials are also taken into account, which also have their own emission factors, and the emissions will depend on the area, thickness and density of these coatings. Emissions from the production of materials included in the coatings are calculated using formula (2), and from the coating process using formula (3).

Carbon emissions in OGI increase with increasing pipeline throughput: larger pipe diameters and wall thicknesses require more steel at the production stage.

The production of oil and gas pumping and other process equipment is also accompanied by carbon emissions, and OGI emissions at the stage of production of its components will depend on the design number of equipment of these types and are calculated based on the weight of the equipment and the average emission factor of the manufacturing industry in the region..

Stage III. Transportation to the site, welding, installation and laying of the pipeline and its protection from external influences, construction of compressor stations, oil pumping stations and other structural components of the oil and gas pipeline system.

The carbon footprint at this stage is calculated similarly to stage II, taking into account all types and quantities of energy-consuming machinery and equipment involved in the construction of the facility, and the time spent on their operation. For the construction of the OGI, it is necessary to perform:

- geological and geodetic studies of the area, preparatory work along the pipeline construction route (clearing vegetation, leveling the land plot, installing temporary roads for moving the construction equipment);

- transportation of OGI components and equipment to the construction site – pipes, pumps, compressors, shut-off valves, gas instruments, control and measuring devices, support structures, materials and structures for constructing a compressor station or a pumping station;
- excavation works for laying underground pipeline strings in trenches or construction of supports, columns, overpasses for ground oil and gas pipelines, measures to strengthen the soil and enhance its stability, construction works for the construction of industrial buildings and structures, installation of all technological units of the oil/gas pipeline;
- removal of construction waste;
- hydraulic testing, checking the tightness and functionality of systems and equipment before putting the entire system into operation.

Execution of all these works for the construction of an oil and gas pipeline require significant financial resources and the use of a large number of energy-intensive equipment, and therefore have significant GHG emissions already at the initial stage of the life cycle of the OGI before the start of its operation.

During the construction of a pipeline system on site, carbon emissions are generated by the equipment used, powered by various energy sources (fossil fuel, electricity): cranes, excavators, trucks, DC welding machines, electrode drying cabinets, etc., and are calculated based on the carbon emission factors from energy sources, power consumption and the time spent operating the equipment according to formula (3).

According to the source [5], the carbon emission level for the construction of large public buildings is set at 800.15–1296.44 kg/m^2, and to assess emissions during the construction of industrial buildings, such as oil pumping stations, gas compressor stations, an average value of 1000 kg/m^2 is selected.

Stage IV. Operation of the OGI.

At this stage, the largest emissions are generated in the entire life cycle of the infrastructure. (In many cases, the production stage is also characterized by large emissions.) A large number of emissions are due to significant energy costs, without which it is impossible to operate the infrastructure.

At the stage of operation of the OGI, the main emissions are formed during the operation of energy-consuming equipment. GHG emissions from the gas pipeline system are supplemented by emissions from:

- organized leaks from the pipeline system arising as a result of technological operations;
- unorganized leaks from technological equipment through connections and seals;
- emissions during emergency situations.

According to paragraph 3.3 of the Order of the Ministry of Natural Resources and Environment of the Russian Federation dated May 27, 2022 No. 371 "On approval of methods for quantitative determination of greenhouse gas emissions and greenhouse gas absorption" [2], fugitive emissions and emergency emissions are *not included* in the quantitative determination of fugitive greenhouse gas emissions in organizations.

In GI, the gas pumping units (GPU) installed at GCS are the main consumers of natural gas and sources of GHG emissions. The capacity of the GPU ranges from 6 to 25 MW, and from 1 to 10 GPUs, including backup ones, can be installed at each GCS. More than 80 % of the gas consumed for its own process needs during gas transportation is spent on fuel needs of the GPU.

GHG emissions generated during compressor operation are equal to

$$CF_{\text{comp.}} = \sum_{i=1}^{n} w_i EF_e t_i \,, \tag{4}$$

where w_i is the operating capacity of the *i*-th GPU; EF_e is the coefficient of conversion of electrical energy into CO_2 emissions; t_i is the operating time of the *i*-th GPU; *n* is the number of all operating GPU.

Carbon emissions increase with the increase in pipeline capacity due to the increase in energy consumption. During operation of the linear section of the main gas pipeline, fugitive emissions are also formed during repair work and maintenance, when technologically justified operations are carried out with the release of natural gas into the atmosphere. The quantitative determination of fugitive emissions of CO_2 and CH_4 for a time period *t* is carried out by a calculation method based on data on the consumption of the hydrocarbon mixture for the implementation of technological operations or the volume of their removal (bleeding, dispersion) without combustion or catalytic oxidation. The calculation is performed according to the formula [2, pp. 3.5, 3.6]

$$CF_{\text{fug}.i} = \sum_{j=1}^{n} \left(FC_j \cdot W_{i,j} \cdot \rho_i \cdot 10^{-2} \right), \tag{5}$$

where $CF_{\text{fug}.i}$ is the fugitive emissions of the *i*-th greenhouse gas for the period *t*, ton; FC_j is the consumption of the *j*-th hydrocarbon mixture for technological operations (volume of removal without combustion) for period *t*, thousand m^3; $W_{i,j}$ is the content of the *i*-th greenhouse gas in the *j*-th hydrocarbon mixture for period *t*, vol. %.; ρ_i is the density of the *i*-th greenhouse gas, kg/m^3; *i* is the CO_2, CH_4; *j* is the type of hydrocarbon mixture; *n* is the number of types of hydrocarbon mixtures used in technological operations (discharged without combustion).

The consumption of hydrocarbon mixture for process operations and the volume of hydrocarbon mixtures removed without combustion (FC_j) are determined based on actual instrumental or calculated data for the reporting period.

Stage V. Dismantling, transportation from the site, processing/utilization.

The dismantling process is similar to the construction process, but in reverse order, due to which carbon emissions at this stage can be considered similar to those at the construction stage. To them are added GHG emissions generated during the processing or utilization of infrastructure components at processing plants. The calculation of the CF at this stage is made using formula (3).

I. Compensation measures for CF infrastructure

Carbon footprint compensation measures for OGIs may include:

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

IV. Carbon footprint of an accident or emergency

It should be noted that currently the calculation of the CF in the event of an accident of the OGI pumping hydrocarbons is not performed, which is a serious omission, since it does not allow for the accounting of a significant portion of emissions that affect climate change. In the event of an accident, the size of the leaks is determined and the damage is assessed, including the amount of

GHG emissions.

In order to prevent malfunctions of oil and gas pipelines and emergency situations, their regular diagnostics and inspections are carried out to detect and assess deformations, welding defects, dents, damage to pipeline protection, as well as possible leaks of natural gas. Monitoring of operational parameters (pressure, temperature) of pipelines and pressure vessels is also carried out.

The main reason for the cumulative growth of the carbon footprint of the gas condensate is the depressurization of its pipeline under pressure, accompanied by the release of gas condensate or crude oil. Possible causes (risk factors) of pipeline depressurization and design and technological measures to reduce the likelihood of these risks are presented in table 1 [6]. These measures, in essence, are passive or active preventive barriers that reduce the likelihood of the depressurization of the gas condensate.

Table 1: *Preventive barriers for oil and gas pipelines that reduce the likelihood of risks occurring and the severity of their consequences*

Risk factors	Preventive barriers
External corrosion	• Corrosion allowance calculated for a 30-year service life of the pipeline; • External anti-corrosion coating of the pipeline; • Cathodic protection calculated for a 30-year service life of the pipeline; • Conducting an inspection to determine the thickness of the pipeline and the presence of defects caused by corrosion.
Internal corrosion	• Corrosion allowance calculated for a 30-year pipeline service life; • Internal protective coating of the pipeline; • Conducting an inspection to determine the thickness of the pipeline and the presence of defects caused by corrosion.
Mechanical damage	• Protection of the pipeline with a protective casing; • Monitoring of vessels passing the area of the laid pipeline, as well as marking the location of the underwater pipeline on the navigation chart; • Permission to carry out any operations near the pipeline.
Earthquake	• Design of a pipeline capable of withstanding the maximum seismic activity recorded in the area for the last 2,000 years; • Monitoring of seismic activity in the area of possible pipeline reach.
Ice impact (stamukhas, hummocks)	• Pipeline design capable of withstanding ice impacts throughout the entire service life; • Annual inspection of the pipeline to determine the impact of ice formations.
Internal erosion	• Anti-friction coating that provides protection for the internal steel surface of the pipeline; filtration of the transported product to remove as much erosive impurities as possible.
Exceeding the maximum permissible pressure level	• Pipeline design capable of withstanding increased pressure; • Control of the parameters of the transported product; • Training for operators servicing the pipeline; Strict control of all operations carried out with the pipeline; • Equipping the pipeline with a system of safety valves.

Risk factors	Preventive barriers
Operational errors, pigging, and restoration	• Pipeline design that ensures unimpeded passage of the projectile; • Work permit to perform an operation using intelligent pigs; • Performing operations by trained personnel.
Maintenance errors	• Conducting maintenance strictly according to the existing maintenance program; • Work permit to conduct relevant work of any maintenance; • Conducting maintenance by specially trained personnel.
Hidden defects of material and/or welds	• Assessment and quality control during pipeline construction; • Pressure testing of the pipeline before starting its operation; • Testing the pipeline using defect detection equipment.

None of these *preventive* barriers (or even all of them together) guarantees the OGI against depressurization, so in practice they are supplemented with *parry* barriers, which are designed to reduce the consequences of OGI depressurization [7]. As an example, Fig. 1 shows a "Bow-Tie" diagram (BTD) with *preventive* (left) and parry (right) barriers for the case of exposure to external and internal corrosion.

Figure 1. *Bow-Tie diagram for pipelines exposed to external and internal corrosion*

Note to Fig. 1: Preventive barriers: 1 – corrosion allowance calculated for a 30-year pipeline operation period; 2 – external anti-corrosion coating of the pipeline; 3 – cathodic protection, for a 30-year pipeline operation period; 4 – inspection to determine the pipeline thickness and the presence of defects caused by corrosion; 5 – corrosion allowance, for a 30-year pipeline operation period; 6 – internal protective coating of the pipeline; 7 – inspection to determine the pipeline thickness and the presence of defects caused by corrosion. Parrying barriers: 1 – leak detection system; 2 – emergency shutdown: pressure relief; 3 – fire warning and extinguishing system; 4 – leak elimination plan; 5 – accident elimination plan.

An emission from a gas pipeline may result in the formation of a cloud of fuel-air mixture (FAM) and its subsequent ignition, with the formation of a burning torch or a spill fire [8]. An emission of a multiphase hydrocarbon medium may cause serious damage to the environment and lead to the loss of production due to the blocking of the export channel during the period of eliminating the consequences [8].

In light of the Paris Agreement, the risk analysis procedures carried out at the design stage of the OGI should not only assess their safety level, but also provide an assessment of the project's CF. At the stage of risk-oriented operation of the OGI, it is necessary to plan and implement organizational and technical measures to minimize the CF, by ensuring high reliability of the OGI according to the criterion of its integrity.

V. Conclusions

- It is necessary to initiate a topic on assessing the magnitude of the emissions arising from leaks and accidents of the oil and gas industry, which do not currently fall under the Order of the Ministry of Natural Resources and Environment of the Russian Federation dated May 27, 2022 No. 371 [2].
- It is advisable to introduce mandatory certification of each oil and gas industry facility for its emissions. This passport must be confirmed annually. The presence of such passports will allow monitoring the country's emissions and the rate at which Russia's emissions approach zero emissions. To fill out the passport, it is necessary to conduct a regular analysis of GHG emissions throughout the entire life cycle of the OGI, with mandatory consideration of emergency emissions.
- The largest emissions in the life cycle of the OGI are generated at the stages of their operation and construction. With the growth of the length and throughput of the OGI, its emissions also increase.
- To reduce GHG emissions into the atmosphere, the use of energy-efficient technology and process equipment, the use of new generation gas pumping units with low-emission combustion chambers is becoming a priority.

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