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MONITORING OF GREENHOUSE GAS EMISSIONS AT MINING AND PROCESSING PLANTS IN UKRAINE UNDER EUROPEAN INTEGRATION CONDITIONS

Purposes. To develop a scientifically substantiated approach to greenhouse gas emissions monitoring at mining and processing enterprises in Ukraine in the context of European integration and industrial decarbonization, ensuring compliance with European Union Emissions Trading System standards and Carbon Border Adjustment Mechanism requirements.

Methods. The mass balance methodology and the risk matrix through probability and impact assessment are employed.

Results. For calculating greenhouse gas emissions based on analysis of material flows at one of Ukraine's leading mining and processing enterprises, sequential technological process analysis is conducted to identify emission sources, including pellet drying and firing zones, bentonite drying drums, mill circuits, and boiler installations. Material flow mapping covered input flows (natural gas, coal, limestone, bentonite, iron ore concentrate, biomass) and output flows (pellets, CO_2 emissions). A comprehensive risk matrix was developed for assessing monitoring data quality threats based on probability and impact criteria. Analysis of greenhouse gas emission dynamics in Ukraine over recent decades revealed significant reduction compared to baseline levels, primarily resulting from economic crises and armed conflicts rather than purposeful climate policy. For the examined enterprise, total annual CO_2 emissions were calculated, with natural gas accounting for the dominant share, followed by limestone decarbonization, iron ore concentrate processing, and bentonite. International practice analysis demonstrates that leading global producers achieve substantially lower emission levels per tonne of pellets through effective monitoring systems and decarbonization strategies.

Conclusions. The mass balance methodology proves optimal for mining and processing enterprises, ensuring comprehensive accounting of all significant emission sources, including process emissions from carbonate material decarbonization. The developed risk matrix enables systematic threat management through probability and impact assessment. Implementation of certified monitoring systems is critically necessary for

Ukrainian mining enterprises to maintain competitiveness in international markets and comply with European climate requirements.

KEYWORDS: *climate commitment, material flows, decarbonization, monitoring, greenhouse gases, industrial ecology*

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Introduction

Global greenhouse gas emissions demonstrate critical trends, having reached historical peaks of 59±6.6 $GtCO_2$-eq in 2019, representing a 54% increase over 1990 levels [1]. Analysis of data from the Sixth Assessment Report Synthesis Report (IPCC 2023) reveals significant regional disparities in climate system impacts. This results from the uneven nature of industrialization, and these disparities persist under current global economic conditions. The growth of greenhouse gas emissions over recent decades demonstrates a rapid acceleration of anthropogenic influence on the climate system, particularly after the 1950s, when the period of the so-called "Great Acceleration" of industrial development began.

The regional distribution of cumulative CO_2 emissions from 1850 to 2023 demonstrates significant inequality in historical responsibility for climate change. North America holds the dominant position in historical cumulative emissions, accounting for 23% of all anthropogenic CO_2 emissions since 1850. Europe demonstrates the second-largest contribution (16%), reflecting its role as the center of the Industrial Revolution and early development of the fossil fuel economy. East Asia, despite its significant contemporary contribution, accounts for 12% of historical cumulative emissions, indicating the relatively late inclusion of this region in industrialization and urbanization processes [2].

Figure 1 reveals a fundamental restructuring of Ukraine's greenhouse gas emission profile from 1990 to 2023. While total emissions decreased 28.6% (964 to 688 Mt CO_2-eq), the composition shifted dramatically. Traditional gases declined substantially - CO_2 by

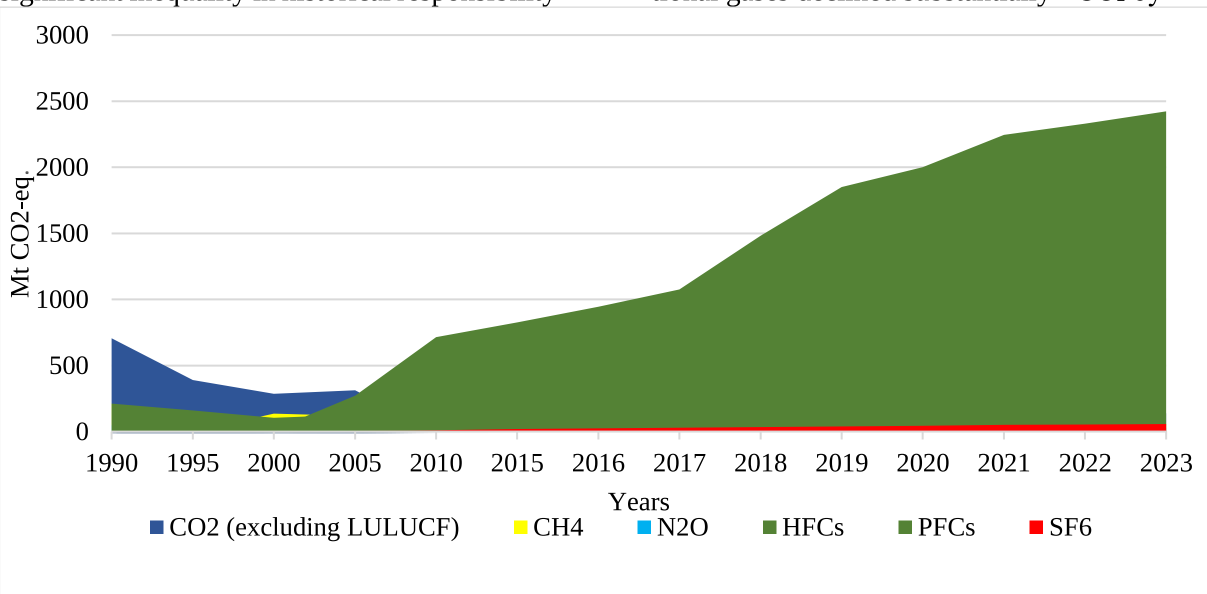

Fig. 1 – Dynamics of greenhouse gas emissions in Ukraine from 1990 to 2023 (developed by the authors based on [3])

80.3% (706 to 139 Mt), CH_4 by 70.0% (209 to 63 Mt), and N_2O by 41.2% (49 to 29 Mt)- primarily due to economic transformation and industrial restructuring. Conversely, HFCs increased exponentially from near-zero to 2,423 Mt CO_2-eq (352% of traditional gas emissions), reflecting Montreal Protocol implementation. This structural transformation necessitates comprehensive monitoring at mining and processing enterprises that accounts for both declining combustion-related emissions and emerging fluorinated gas sources [4].

Analysis of greenhouse gas emissions by economic sectors in Ukraine reveals the dominant contribution of energy production and heavy industry to the national carbon footprint. According to the National Inventory of Anthropogenic Emissions, the energy sector consistently accounts for the largest share of total greenhouse gas emissions, representing approximately 64% of national emissions (excluding the Land Use, Land-Use Change and Forestry - LULUCF sector) in recent years (Fig. 2) [3]. The industrial processes and product use sector constitutes the second-largest emission source, contributing approximately 18% of total emissions, with a historical peak of over 200 Mt CO_2-eq in 1990 declining to approximately 60 Mt CO_2-eq by 2023 following economic restructuring and industrial modernization.

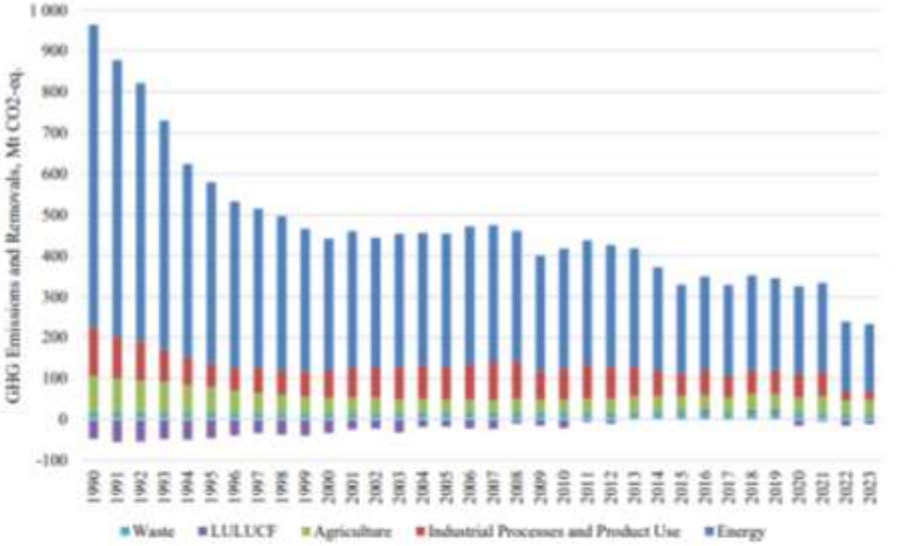

Fig. 2 – GHG emissions and removals by sector in Ukraine, Mt CO_2-eq. in Ukraine from 1990 to 2023 [3]

Within the industrial processes sector, metallurgy traditionally dominates with approximately two-thirds of sectoral emissions, followed by chemical industry (approximately 17%) and mineral products manufacturing including cement and lime production [3]. Mining and processing enterprises constitute a critical component of both the energy and industrial processes emissions profile. Statistical data for 2020 demonstrates that metallurgical production generated 729,854 tonnes of pollutants and greenhouse gases from stationary sources, while extractive industry and quarrying operations contributed 365,586 tonnes. These figures underscore the substantial carbon intensity of mining and processing operations, which generate emissions through multiple pathways: direct combustion of fossil fuels in technological processes, process emissions from ore beneficiation and pelletization, and chemical transformations during mineral processing.

Therefore, in Ukraine, emissions reduction occurred through the destruction of industrial infrastructure as a result of Russia's full-scale war, which takes on particular significance in the context of European climate requirements Ukraine's commitments under the Paris Agreement on emission reductions, combined with European integration requirements, necessitate harmonization of national monitoring systems with EU standards, specifically the European Union Emissions Trading System (EU ETS) and the Carbon Border Adjustment Mechanism (CBAM) [5]. The implementation of CBAM from 2026 creates direct economic incentives for accurate emissions accounting, as Ukrainian exporters of iron ore products will have to pay carbon charges when importing to the EU [6].

Mining and processing enterprises (MPEs) form the backbone of the Ukrainian economy, providing approximately 85% of iron ore raw material exports and a significant portion of foreign currency earnings, while being characterized by high specific CO_2 emissions resulting from energy-intensive pelletizing and ore beneficiation processes. The complexity of technological processes at MPEs creates methodological challenges for accurate determination of greenhouse gas emission sources and volumes, requiring consideration of both direct emissions from fuel combustion and process emissions from decarbonization of carbonate materials [7]. Ukrainian MPEs need to invest 2-3 billion euros by 2030 to achieve decarbonization goals, while the destruction of industrial infrastructure due to Russian aggression creates a unique opportunity for implementing modern, energy-efficient technologies instead of restoring outdated energy-intensive industries [8].

Leading global iron ore producers demonstrate significant progress in implementing effective carbon monitoring systems, creating a methodological foundation for strategic decarbonization planning in the industry. Swedish company LKAB has set global efficiency standards, achieving an emission level of 31 kg CO_2 per tonne of pellets in 2013, representing an 84% reduction compared to 1960 [9]. ArcelorMittal has developed a comprehensive monitoring system as part of its strategy to achieve net-zero emissions by 2050, setting an interim target of 30% emission reduction by 2030 for European operations [10]. Chinese metallurgical companies demonstrate experience in large-scale monitoring with an average emission level of 58.5 kg CO_2 per tonne of pellets and have achieved emission reductions of over 60% for automotive products [11]. Modern systems are characterized by the implementation of digital technologies and integration with international reporting standards [12].

The main centers of mining and processing industry are Kryvyi Rih, where the largest iron ore mining and processing enterprises are located, such as Pivdennyi (Southern), Pivnichnyi (Northern), Tsentralnyi (Central), Inguletskyi, Poltava - Poltavskyi Mining and Processing Plant, and other mining and processing enterprises of Ukraine - Bilanivskyi Mining and Processing Plant, Verkhnodniprovskyi Mining and Metallurgical Plant, Yerystivskyi Mining and Processing Plant, Komysh-Burunskyi Iron Ore Plant, Marganetskyi Mining and Processing Plant, and others. These enterprises ensure the extraction and beneficiation of iron ore, producing concentrate, pellets, and agglomerate for the metallurgical industry [13].

Mining and processing enterprises are subject to Ukrainian regulations governing the monitoring, reporting and verification of greenhouse gas emissions, with legal frameworks defined by the Law of Ukraine "On the Principles of Monitoring, Reporting and Verification of Greenhouse Gas Emissions" and related subsidiary legislation that incorporates European climate policy standards. The classification of mining and processing enterprises as subjects of the monitoring, reporting and verification procedure is determined by the nature of their production activities, which generate significant volumes of greenhouse gases through fossil fuel combustion in technological processes, electricity consumption, blasting operations, operation of quarry transport, and functioning of beneficiation facilities. In terms of technical parameters and capacity, most mining and processing enterprises in Ukraine exceed the emission threshold values established by legislation, which automatically includes them in the list of installations subject to mandatory monitoring [14].

Analysis of international experience confirms the relevance of addressing greenhouse gas emissions monitoring at mining and processing enterprises in Ukraine, which is determined by the need for integration with European standards and achieving competitiveness in international markets. However, analysis of scientific research reveals significant gaps regarding the adaptation of international monitoring methodologies to the specifics of Ukrainian MPEs, comprehensive approaches to material flow mapping, and practical aspects of implementing monitoring, reporting and verification systems in the context of environmental safety and sustainable development. Ukrainian scientists have explored various aspects of emissions monitoring and the sustainable utilization of the country's natural resources in their research [15]. Performed an extensive examination of innovative strategies for sustainable natural resource management in Ukraine, evaluating contemporary trends and obstacles within the European integration framework [16]. However, these studies do not examine specific methodological aspects of emissions monitoring at mining and processing enterprises and practical challenges of material flow mapping in the context of CBAM requirements.

Purpose is to develop a scientifically substantiated approach to greenhouse gas emissions monitoring at mining and processing enterprises in Ukraine in the context of European integration and industrial decarbonization, ensuring compliance with European Union Emissions Trading System standards and Carbon Border Adjustment Mechanism requirements.

Materials and Research Methods

The study was conducted at one of Ukraine's leading mining and processing enterprises, which specializes in iron ore (magnetite) extraction, primary processing, ore beneficiation, and pellet production. The enterprise belongs to the category of large iron ore producers, providing a significant share of Ukraine's iron ore raw material exports. The enterprise comprises 29 workshops and subdivisions, the main ones being the mining workshop, railway workshop, crushing and beneficiation plant, pellet production workshop, beneficiation plant tailings management workshop, off-rail transport workshop, finished product dispatch workshop, and internal logistics service.

The selection of this enterprise was determined by its representativeness for the industry, the availability of a complete technological cycle for pellet production, and the possibility of obtaining technical data necessary for conducting emission assessments.

The study was based on analysis of the enterprise's production reports, technical documentation of technological processes, equipment specifications, and records of raw materials and fuel consumption for 2023. Additionally, official greenhouse gas emission factors published by the Ministry of Environmental Protection and Natural Resources of Ukraine and data from the National Inventory of Anthropogenic Emissions by Sources and Removals by Sinks of Greenhouse Gases were used.

The regulatory framework for the study included the Law of Ukraine "On the Principles of Monitoring, Reporting and Verification of Greenhouse Gas Emissions," Resolution of the Cabinet of Ministers No. 960 "On Approval of the Procedure for Monitoring and Reporting Greenhouse Gas Emissions," as well as European regulations EU ETS and CBAM requirements [17].

Identification of activity types was carried out through sequential analysis of the enterprise's technological processes following the methodology recommended by the Ministry of Environment in the Recommendations for Interpretation of Installation Activity Types. At the first stage, a technical audit of the installation was conducted with determination of installation boundaries in such a way as to maximally cover all equipment related to activity types included in the List of Activity Types or having technological connection with such activity types. At the second stage, an inventory of all fuel combustion equipment was performed, establishing each unit's nominal thermal capacity based on manufacturer technical documentation.

Sources of greenhouse gas emissions were determined via comprehensive examination of the enterprise's technological operations. Based on pellet production technological schemes, key stages accompanied by CO_2 emissions were determined: pellet drying and firing zones, bentonite drying drums, mill circuits, steam and hot water boilers.

Determination of material flows was conducted in accordance with mass balance principles with identification of input flows (natural gas, limestone, bentonite, iron ore concentrate, sunflower husks) and output flows (pellets, CO_2 emissions). For each material flow, consumption/production volumes and carbon content coefficients were determined.

Effective monitoring at mining and processing enterprises requires selecting an appropriate calculation methodology. According to the Cabinet of Ministers Resolution No. 960 "On Approval of the Procedure for Monitoring and Reporting Greenhouse Gas Emissions" and European regulations EU ETS, there are three main methodologies: standard calculation-based methodology, mass balance methodology, and continuous measurement-based methodology [18].

Examining MPE technological processes reveals challenges in identifying the most suitable greenhouse gas emissions monitoring methodology. Pellet production includes not only natural gas combustion, but also process emissions from decarbonization of carbonate materials, oxidation of organic components in iron ore concentrate, and thermal treatment of biomass. Energy-intensive iron ore processing processes are characterized by multiple CO_2 emission sources, requiring a comprehensive approach to their quantitative determination [19]. The standard methodology is unable to adequately account for the full complexity of these processes, as it is based only on fuel combustion factors and does not consider process emissions from chemical transformations of raw materials.

The continuous measurement methodology has significant limitations due to multiple emission points, requiring substantial capital expenditures, lack of qualified personnel, and complex operating conditions. Implementation of continuous monitoring systems at mining and processing enterprises faces technical challenges due to aggressive environments and the need for simultaneous control of dozens of emission points [20].

The mass balance methodology was adopted for greenhouse gas emissions assessment based on the analysis findings and Cabinet of Ministers Resolution No. 960 as this methodology is most appropriate for the following reasons: it ensures comprehensive accounting of all significant emission sources, including process emissions from limestone decarbonization; demonstrates optimal ratio of accuracy and economic efficiency; is based on existing production accounting data; ensures full compliance with European EU ETS standards; allows for phased implementation without disrupting the production process. In their studies of the carbon footprint of iron ore extraction, [21] confirm that the mass balance methodology provides the most accurate assessment of CO_2 emissions from technological processes with minimal implementation costs.

CO_2 emissions were calculated using the mass balance formula:

$$\mathrm{CO_2 emissions} = \left(\mathrm{C_{input}} - \mathrm{C_{product}}\right) \times 3.664 \quad (1)$$

where: $\mathrm{C_{input}}$ - mass of carbon in all types of fuel and carbon-containing materials consumed in activities during the year, t;

$\mathrm{C_{product}}$ - mass of carbon in all products resulting from activities during the year, t;

3.664 - conversion factor for converting the molar mass of carbon to CO_2.

The carbon content in input materials was calculated using the formula:

$$\mathrm{C_{input}} = \sum\left(V_{\mathrm{input}} \times \mathrm{CC_{input}}\right), \quad (2)$$

where: V_{input}- volume of carbon-containing materials consumed in activities, t,

$\mathrm{CC_{input}}$- carbon content in carbon-containing materials consumed in activities, t C/t.

The carbon content in products resulting from activities during the year, measured in tonnes of carbon, is calculated using formula (3):

$$\mathrm{C_{product}} = \sum\left(\mathrm{V_{output}} \times \mathrm{CC_{output}}\right), \quad (3)$$

where: $\mathrm{V_{output}}$ - volume of products resulting from activities, t,

$\mathrm{CC_{output}}$ - carbon content in products resulting from activities, t C/t.

For the identified material flows at the mining and processing plant, carbon content coefficients are used according to the detailed reference values of calculation coefficients published annually on the official website of the Ministry of Environmental Protection and Natural Resources, or in their absence, coefficients that were used for the latest National Report (inventory) on anthropogenic emissions by sources and removals by sinks of greenhouse gases submitted by Ukraine to the Secretariat of the United Nations Framework Convention on Climate Change and according to the data from the IPCC Guidelines for National Greenhouse Gas Inventories.

It is important to use current coefficients that ensure the reliability of the national greenhouse gas emissions inventory submitted to the UNFCCC Secretariat. Inaccurate coefficients can lead to significant distortion of total emissions data. Ukraine, as a Party to the Paris Agreement and the UNFCCC, is obligated to provide accurate information on greenhouse gas emissions. Regular updating of coefficients in accordance with annual publications by the Ministry of Environmental Protection and Natural Resources and national inventory data ensures adherence to methodological consistency and compliance with international reporting standards. Annual updating of coefficients for main fuel types (natural gas, coke, coal) and materials (limestone, steel, cast iron, ferroalloys) reflects changes in their composition and production technologies, ensuring the relevance of emissions calculations.

Emissions from fuel combustion are calculated separately according to the formula:

$$\mathrm{CO_2 emissions} = \mathrm{AD} \times \mathrm{NCV} \times \mathrm{EF} \times \mathrm{OF}, \quad (4)$$

where: $\mathrm{CO_2 emissions}$ - emissions from fuel combustion, t CO_2, AD - activity data: fuel consumption volume, t or thousand m³,

NCV - net calorific value of fuel, GJ/t or GJ/thousand m³,

EF - CO_2 emission factor for fuel, t CO_2/TJ,

OF - oxidation factor for fuel, dimensionless.

Data Quality Risk Assessment Methodology. A 5×5 risk matrix has been developed for managing monitoring data quality risks, based on the assessment of the probability of risk events occurrence and their potential impact on the accuracy of reported data. Probability was assessed from level 1 (0.5% per year) to level 5 (50% per year), while impact ranged from 28.3 t CO_2 to 11,329.6 t CO_2.

The integral risk assessment was calculated as the product of probability and impact, with subsequent classification into low, medium, and high risk levels.

Results and Discussion

Based on the conducted analysis of technological processes at the enterprise, two key activities have been identified that generate greenhouse gas emissions: roasting and sintering of metal ore (in the pellet production process) and fuel combustion in high thermal capacity installations.

The study showed that the predominant part of greenhouse gas generation processes is concentrated in the pellet production workshops, which is associated with the processing of carbon-containing materials: iron ore concentrate, limestone, and bentonite. Analysis of the pellet production workshop structure revealed the presence of a pelletizing and firing building, transfer nodes, limestone grinding building, bentonite receiving, crushing and drying building, limestone solution preparation section, and filtration and pelletizing facilities. Investigation of the technological cycle established that the process begins with the supply of iron ore concentrate in the form of pulp from the crushing and beneficiation plant, followed by thickening and dewatering on vacuum filters. In parallel, preparation of charge materials – limestone and bentonite – was identified, which arrive by rail transport, are unloaded into receiving bunkers, and ground on mill circuits. Research results confirmed that part of the carbon present in the raw materials undergoes oxidation during charge preparation and pellet firing, leading to carbon oxide emissions into the atmosphere through identified emission points – chimneys of firing machines, mill circuits, and rotary dryers. Additionally, supplementary emission sources were identified in the form of numerous combustion installations and boiler houses located in various structural divisions of the combine for space heating and hot water supply.

Based on the results of the conducted analysis of the main stages of the technological process, it was established that the sources of greenhouse gas emissions include: pellet drying zones, bentonite drying drum, mills, steam and hot water boilers, infrared heat radiators, gas heating furnaces, and drying drums. The study showed that each identified source has a corresponding emission point – a chimney through which greenhouse gas emissions are released into the atmosphere.

During the study, after identifying emission sources and points, the necessity of establishing material flows was determined – physical flows of substances or materials containing carbon that enter the enterprise, are used in technological processes, and leave the enterprise in the form of products or emissions. The analysis confirmed that material flow can be of input nature (raw materials, fuel) or output nature (finished products, waste, emissions).

Based on the study results, the following material flows were identified for greenhouse gas emissions monitoring purposes:

- Fuel gas;
- Limestone (input material flow);
- Coal (input material flow);
- Bentonite (input material flow);
- Iron concentrate (input material flow);
- Iron ore pellets (Output material flow);
- Coal;
- Sunflower husk as biofuel.

Based on the obtained results of emission sources and material flows identification, a schematic diagram of material flows was developed (Fig. 3). The diagram visually demonstrates the key system elements identified during the study: input material flows include iron ore concentrate, limestone, bentonite, fuel gas, and coal, which enter the pelletizing plant.

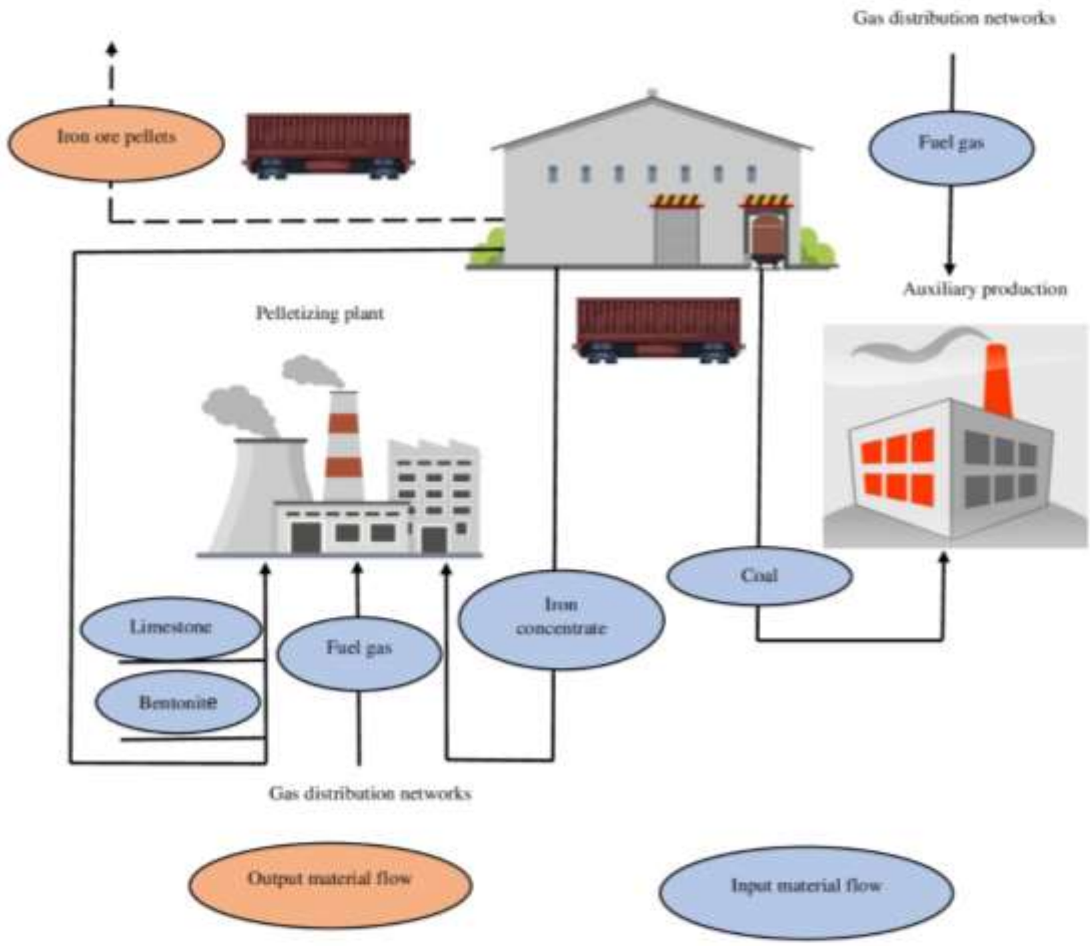

Fig. 3 – Material flows diagram (developed by the authors)

The scheme reflects the process of transforming input raw materials into output material flow – iron ore pellets, which are transported by rail.

The identification of material flows allows for accounting both direct emissions (from fuel combustion) and process emissions (from chemical transformations in raw materials). At mining and processing plants, carbon contained in limestone and other carbonate materials is released during thermal treatment in the form of CO_2. This approach ensures complete coverage of all significant emission sources. Subsequently, detailed analysis of material flows provides the basis for modeling technological processes and developing innovative solutions for greenhouse gas emissions reduction.

The mass balance method was used to calculate greenhouse gas emissions, since the enterprise lacks a certified laboratory that could perform continuous measurements, and its establishment would result in significant unjustified costs.

CO_2 emissions calculations were performed stepwise according to the selected methodology. In the first stage, data were collected on the consumption volumes of all identified material flows for the reporting period: fuel gas (77 000 thousand m^3), limestone (50 000 t), bentonite (85 348 t), iron concentrate (4 546 490 t), coal (130.15 t) and the volume of produced products - iron ore pellets (5 125 342 t). In the second stage, corresponding emission factors were determined for each material flow according to the official reference values of the Ministry of Environmental Protection and Natural Resources and the national greenhouse gas emissions inventory of Ukraine. For fuel gas, an emission factor of 55.7 t CO_2/TJ was used with a net calorific value of 34.5 GJ/1000 m^3 and an oxidation factor of 1, for coal, an emission factor of 94.5 t CO_2/TJ was used with a net calorific value of 22.0 GJ/1000 m^3 and an oxidation factor of 1. For carbon-containing materials, carbon content coefficients were applied: for limestone and bentonite - 0.121 t C/t, for iron concentrate - 0.00628393 t C/t, for iron ore pellets -

0.00084918 t C/t. In the third stage, emissions from natural gas combustion were calculated using formula (4), while emissions from process materials were calculated using mass balance formulas (1-3) taking into account the conversion factor of carbon molar mass to CO_2 (3.664). Total CO_2 emissions were determined as the sum of emissions from all identified sources.

The results of the conducted calculations are systematized in Table 1, which demonstrates the contribution of each material flow to the total greenhouse gas emissions of the enterprise.

Since the sunflower husk material flow is a biomass material flow, according to Resolution 960, if the material flow consists exclusively of biomass, the greenhouse gas emission factor from biomass use equals zero.

Table 2 presents the quantitative indicators of carbon dioxide emissions from various material flows of the mining and processing plant.

Analysis of the tabulated data reveals that coal constitutes the predominant contributor to total greenhouse gas emissions, with an emission

Table 1

Calculation of CO_2 emissions from material flows of the mining and processing plant using the mass balance methodology

Material flow	Consumption/Sales volume	Emission factor	NCV/EF	OF
Fuel gas	77000 thousand m³	55.7 t CO_2/TJ	34.5 GJ/1000 m³	1
Limestone	50000 t	0.121 t C/t	3.664	-
Bentonite	85348 t	0.121 t C/t	3.664	-
Iron concentrate	4546490 t	0.00628393 t C/t	3.664	-
Iron ore pellets	5125342 t	0.00084918 t C/t	3.664	-
Coal	130.15 t	94.5 t CO_2/TJ	22 GJ/1000 m³	1

Table 2

CO_2 emissions from material flows

№ з/п	Material flow	CO_2 emissions, t
1	Fuel gas	147967.05
2	Limestone	22167.20
3	Bentonite	1965.08
4	Iron concentrate	14145.93
5	Iron ore pellets	-6499.88
6	Coal	270 581.85
7	Sunflower husk	0
8	Total CO_2 emissions (excluding biomass)	450 327.23

volume of 270,581.85 t CO_2, representing approximately 60% of aggregate emissions. The elevated emission level is attributable to substantial carbon content and intensive utilization of solid fuel in metallurgical production energy cycles. Natural gas represents the second-largest emission source at 147,967.05 t CO_2, accounting for approximately 33% of total emissions. Notwithstanding lower specific emissions relative to coal, considerable natural gas consumption volumes establish it as the secondary critical source of greenhouse gases at the facility. Limestone generates 22,167.20 t CO_2, associated with thermal decarbonization processes of carbonate minerals during high-temperature processing. Iron ore concentrate utilization results in emissions of 14,145.93 t CO_2, reflecting the energy intensity of ore beneficiation processes and logistics operations. Bentonite, employed in molding operations, exhibits the minimal emission level among principal material flows at 1,965.08 t CO_2. Sunflower husks demonstrate zero emissions, consistent with biomass carbon neutrality principles and biogenic emission accounting methodology. Structural analysis of the enterprise emission profile demonstrates fossil fuel dominance in the overall carbon footprint, with coal and natural gas collectively accounting for over 93% of cumulative CO_2 emissions. This necessitates a comprehensive decarbonization approach to energy processes, encompassing equipment modernization for enhanced coal utilization energy efficiency and natural gas consumption optimization.

Effective functioning of the monitoring, reporting and verification system for greenhouse gas emissions at mining and processing plants requires a comprehensive approach to risk management, which can significantly affect the accuracy and reliability of reported data. Risk analysis is a critically important component of the internal quality control system, as it allows for the identification of potential threats to data integrity and the development of preventive measures for their minimization. Table 3 presents a risk matrix that shows impact levels (in t CO_2) and probability (in % probability that an incident will occur within one year), as well as the risk assessment result (probability multiplied by impact). Three risk levels are distinguished: low (green color), medium (yellow), and high (red).

The presented risk matrix represents a structured tool for assessing threats to the monitoring, reporting and verification system for greenhouse gas emissions, built on a two-dimensional approach considering the probability of risk events occurrence and their potential impact on the accuracy of reported data. The matrix has a classic 5×5 structure, which ensures an optimal balance between assessment detail and practical application in industrial enterprise conditions.

Table 3

Risk matrix

Probability	Impact	1 28.3	283.22	3 566.5	4 2 832.4	5 11329.6
1	0.005	0.1	1.4	2.8	14.2	56.6
2	0.01	0.3	2.8	5.7	28.3	113.3
3	0.1	2.8	28.3	56.6	283.2	1133.0
4	0.2	5.7	56.6	113.3	566.5	2265.9
5	0.5	14.2	141.6	283.2	1416.2	5664.8

The vertical axis of the matrix reflects the gradation of risk event occurrence probability from level 1 (0.5% probability per year) to level 5 (50% probability per year), which allows for differentiating events from extremely rare to those with high likelihood of realization during the operational period. The horizontal axis characterizes the potential impact of risk events on monitoring data quality, expressed in CO_2 equivalent tonnes, with a range from 28.3 t CO_2 (minimal impact) to 11,329.6 t CO_2 (critical impact), corresponding to different scenarios of monitoring system integrity violations.

The quantitative values in the matrix cells represent an integral risk assessment calculated as the product of probability and impact, which allows for obtaining a weighted measure of criticality for each threat category. This methodology ensures objective risk ranking and rational allocation of resources for preventive measures. The lowest risk values (0.1-14.2) characterize events with minimal impact on monitoring system functioning, while the highest values (1.133.0-5.664.8) correspond to critical threats capable of causing systemic violations of reporting reliability.

The risk matrix, which distinguishes three threat levels based on probability and impact criteria, allows for establishing priorities for resource allocation to control measures. Implementation of a systematic approach to risk management not only ensures compliance with regulatory requirements, but also creates a foundation for increasing stakeholder confidence in enterprise reporting, which is critically important in the context of participation in international carbon markets and attracting green investments.

Unreliable monitoring data can lead to serious legal and financial consequences for the enterprise. According to Ukrainian legislation on monitoring, reporting and verification of greenhouse gas emissions, operators are obligated to ensure accuracy and completeness of reported data. Failure to meet these requirements may result in administrative sanctions, fines and loss of operating licenses. In the context of implementing the European Union's Carbon Border Adjustment Mechanism (CBAM) from 2026, inaccurate emissions data may lead to additional financial obligations when exporting products to the EU. Risk systematization by technological processes allows for identifying several key threat categories. Measurement equipment risks include power supply failures, accounting instrument malfunctions and data transmission disruptions. Particularly critical are natural gas meter failure risks, as this material flow accounts for over 82% of the enterprise's total emissions. To minimize such risks, it is necessary to implement autonomous power sources, backup accounting instruments and data verification through supplier invoices. Automated data registration risks encompass technical failures of computer equipment, virus infections and information system security breaches. Effective control measures include implementing enhanced information security systems, regular database backups and archiving primary data sources. A significant category comprises errors in data transmission processes and emissions calculations, which are characterized by high potential impact levels. To minimize these risks, implementation of the two-person verification principle and conducting cross-checks with previous years' results is critically important. Laboratory analysis risks include loss of research results, non-representative samples and analysis inaccuracies. Control measures should include regular transfer of results to electronic files, assignment of multiple responsible persons and annual laboratory certification by independent organizations.

Although the studied enterprise has not experienced significant data quality incidents since the implementation of the MRV system, the probability levels in the matrix are substantiated by analysis of documented cases at comparable mining and processing enterprises in Ukraine and the international metallurgical industry. In particular, high probability levels (4-5) are attributed to risks of measurement equipment failure resulting from electrical supply instability, which triggered over 500 emergency shutdowns in Ukraine's energy system during 2022-2023, whereas medium levels (2-3) represent typical rates of manual data entry errors (5-15% according to international research) and industrial equipment failures (0.5-1.5% annually per reliability engineering standards).

The conducted study has a number of methodological limitations that should be considered when interpreting the results and their extrapolation to other industry enterprises.

First, the empirical analysis is based exclusively on data from one mining and processing plant, which may not fully reflect the specifics of technological processes and emission structure of other Ukrainian mining and processing plants due to differences in raw material base, technological equipment, energy characteristics and production scales.

Second, the study covers only one reporting period, which prevents analysis of emission dynamics, identification of seasonal fluctuations and long-term trends necessary for forecasting and planning decarbonization measures.

Third, although the developed methodology for identifying material flows is universal in nature, its practical application requires validation at enterprises with different technological schemes (for example, mining and processing plants with different types of firing machines, alternative types of fluxes, other energy carriers) to confirm its general applicability and calculation accuracy.

Furthermore, the study does not account for indirect emissions from electricity consumption (Scope 2), which may lead to underestimation of the total carbon footprint of enterprises. Further research should be directed toward expanding the empirical base through involvement of data from multiple mining and processing plants, conducting multi-year monitoring and including all emission categories in accordance with international reporting standards.

Conclusions

The conducted study enabled the development of a comprehensive scientifically grounded approach to greenhouse gas emissions monitoring at Ukrainian mining and processing plants, which considers the specifics of technological processes and European integration requirements. Analysis of greenhouse gas emission dynamics in Ukraine for the period 1990-2023 revealed a paradoxical situation where the 62.5% emission reduction compared to the baseline 1990 occurred primarily as a result of economic crises, structural changes in the economy and military conflicts, rather than through implementation of targeted environmental decarbonization policy. This creates a unique challenge for the country's post-war reconstruction, as it is necessary to ensure economic growth without proportional increase in greenhouse gas emissions and utilize opportunities for implementing modern low-carbon technologies.

Based on the study results using the example of one of Ukraine's leading mining and processing plants, it was established that total annual CO_2 emissions amount to 179 745.38 tonnes, with the emission structure characterized by natural gas dominance (82.3%), which emphasizes the industry's critical dependence on fossil fuel and the necessity of priority energy efficiency measures. The second most significant material flow - limestone (12.3%) - reflects process emissions from carbonate material decarbonization, while iron ore concentrate accounts for 7.9% of emissions through carbon-containing components in raw materials. It was established that finished product export (pellets) ensures carbon removal from the enterprise equivalent to 6 499.88 t CO_2, which constitutes 3.6% of total emissions and demonstrates the importance of accounting for output material flows for accurate determination of the enterprise's net emissions.

The feasibility of applying the mass balance methodology for calculating greenhouse gas emissions at mining and processing plants has been substantiated as an optimal approach that ensures comprehensive accounting of all significant emission sources, including process emissions from carbonate material decarbonization, demonstrates optimal balance between accuracy and economic efficiency, is based on existing production accounting data and ensures full compliance with European EU ETS standards. The developed 5×5 risk matrix allows for systematizing threats to monitoring data quality by probability and impact levels, providing a scientifically grounded approach to risk management through establishing clear criteria for threat classification and defining appropriate response strategies.

Practical recommendations of the study include phased implementation of a greenhouse gas emissions monitoring system based on the mass balance methodology with initial focus on the most significant material flows (natural gas and limestone), which account for over 94% of the enterprise's total emissions. It is necessary to ensure installation of certified measuring equipment for natural gas consumption accounting with backup control systems, implementation of automated data collection and processing systems with regular backup copying, development of internal quality control procedures with two-person verification principle and annual laboratory certification by independent organizations. It is recommended to establish a specialized greenhouse gas emissions monitoring unit with qualified personnel and implement a system of continuous professional development in accordance with European legislation updates. To prepare for CBAM implementation from 2026, it is necessary to ensure full compliance of monitoring systems with European standards, develop reporting verification procedures by accredited organizations and create a document management system that meets international reporting requirements.

Directions for further research should be focused on expanding the empirical base through conducting comprehensive analysis of emissions monitoring systems at all major mining and processing plants in Ukraine to validate the developed methodology and identify industry-specific features. Promising is the research on possibilities of integrating indirect emissions from electricity consumption (Scope 2) and emissions from logistics operations (Scope 3) to ensure complete life cycle assessment of enterprise carbon footprint. A promising direction is research on possibilities of applying digital technologies, including artificial intelligence and machine learning, for automating monitoring processes and forecasting greenhouse gas emissions, as well as developing integrated carbon footprint management systems that combine emissions monitoring with production process optimization and strategic enterprise decarbonization planning.

Conflict of Interest

The authors declare no conflict of interest regarding the publication of this manuscript. Furthermore, the authors have fully adhered to ethical norms, including avoiding plagiarism, data falsification, and duplicate publication.

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МОНІТОРИНГ ВИКИДІВ ПАРНИКОВИХ ГАЗІВ НА ГІРНИЧО-ЗБАГАЧУВАЛЬНИХ КОМБІНАТАХ УКРАЇНИ В УМОВАХ ЄВРОІНТЕГРАЦІЇ

Цілі. Розробити науково обґрунтований підхід до моніторингу викидів парникових газів на гірничодобувних та переробних підприємствах України в контексті європейської інтеграції та промислової декарбонізації, забезпечуючи дотримання стандартів Системи торгівлі викидами Європейського Союзу та вимог Механізму коригування вуглецевих кордонів.

Методи. Використовується методологія балансу маси та матриця ризиків шляхом оцінки ймовірності та впливу.

Результати. Для розрахунку викидів парникових газів на основі аналізу матеріальних потоків на одному з провідних гірничодобувних та переробних підприємств України проведено послідовний аналіз технологічного процесу для виявлення джерел викидів, включаючи зони сушіння та випалювання окатишів, сушильні барабани для бентоніту, млинні контури та котельні установки. Картування матеріальних потоків охоплювало вхідні потоки (природний газ, вугілля, вапняк, бентоніт, залізорудний концентрат, біомаса) та вихідні потоки (окатиші, викиди CO_2). Розроблено комплексну матрицю ризиків для оцінки загроз якості даних моніторингу на основі критеріїв ймовірності та впливу. Аналіз динаміки викидів парникових газів в Україні за останні десятиліття виявив значне скорочення порівняно з базовими рівнями, що є насамперед результатом економічних криз та збройних конфліктів, а не цілеспрямованої кліматичної політики. Для досліджуваного підприємства загальний річний обсяг викидів CO_2 був розрахований, при цьому домінуючу частку складає природний газ, за яким слідують декарбонізація вапняку, переробка залізорудного концентрату та бентоніт. Аналіз міжнародної практики показує, що провідні світові виробники досягають суттєво нижчих рівнів викидів на тонну окатишів завдяки ефективним системам моніторингу та стратегіям декарбонізації.

Висновки. Методологія балансу маси виявляється оптимальною для гірничодобувних та переробних підприємств, забезпечуючи комплексний облік усіх значних джерел викидів, включаючи технологічні викиди від декарбонізації карбонатних матеріалів. Розроблена матриця ризиків дозволяє систематично управляти загрозами шляхом оцінки ймовірності та впливу. Впровадження сертифікованих систем моніторингу є критично необхідним для українських гірничодобувних підприємств для підтримки конкурентоспроможності на міжнародних ринках та дотримання європейських кліматичних вимог.

КЛЮЧОВІ СЛОВА: *кліматичні зобов'язання, матеріальні потоки, декарбонізація, моніторинг, парниковий газ, промислова екологія*

Конфлікт інтересів

Автори заявляють, що конфлікту інтересів щодо публікації цього рукопису немає. Крім того, автори повністю дотримувались етичних норм, включаючи плагіат, фальсифікацію даних та подвійну публікацію.

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В роботі не використано ресурс штучного інтелекту.

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