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ESG Practices and Air Emissions Reduction in the Oil and Gas Industry: Empirical Evidence from Kazakhstan

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Abstract

This study examines the impact of Environmental, Social, and Governance (ESG) strategies on reducing air pollution in the West Kazakhstan region, a major hub for Kazakhstan's oil and gas industry. A spatial analysis of atmospheric emissions reveals an uneven distribution of emission sources, predominantly concentrated in the northern industrialized part of the region, where the Karachaganak oil and gas condensate field is located. The ESG model of Karachaganak Petroleum Operating b.v. (KPO), implemented as an integrated management system based on Global Reporting Initiative (GRI) standards, is compared with the ESG strategies of leading oil and gas companies in Kazakhstan and globally, aligning with current international research trends. The analysis underscores the interdependence of technological and social aspects in the transition to a low-carbon economy, confirming the importance of integrating the environmental, social, and governance components of ESG into a unified strategic planning framework for sustainable development. Using econometric modeling, the study establishes a relationship between ESG indicators and the reduction in atmospheric pollution and provides a forecast for emission reductions by 2030. The key measures proposed to improve regional air quality are linked to long-term decarbonization strategies within the context of the sustainable development of the entire region. The proposed algorithm for implementing ESG principles helps to identify the concentration of functions and associated risks at different management levels within Highly Polluting Enterprises (HPEs) and optimizes business processes by focusing efforts on air pollution mitigation. The findings are applicable to other countries, as oil and gas producers worldwide face a number of common air pollution challenges.

Keywords: air pollution; ESG strategy; sustainable development; energy efficiency; best available techniques; corporate social responsibility

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1. Introduction

Fossil fuel pollution represents a fundamental challenge for the modern economy, with detrimental impacts on the climate, environment, and human health [1]. Intensive oil and gas production is a primary source of carbon dioxide and other greenhouse gas (GHG) emissions, which are major drivers of climate change. The world's 60 largest oil and gas companies were responsible for over 40% of global cumulative industrial emissions from 1988 to 2015 [2], a trend that continued as global fossil fuel emissions reached a record high in 2023 [3].

The scientific concept of sustainable development is now operationalized through more specific ESG standards, which encompass environmental, social, and governance dimensions. Integrating ESG criteria into decision-making, alongside traditional economic metrics, has emerged as a promising mechanism for advancing the green economy and enabling low-carbon development [4].

As governments worldwide establish net-zero emissions targets, energy companies face increasing pressure to incorporate ESG principles into their business models. Effectively reducing atmospheric emissions within an ESG framework requires an integrated approach and continuous monitoring to achieve set goals and generate a positive environmental impact.

The substantial impact of the oil and gas sector on atmospheric pollution necessitates a shift in strategic management approaches, extending beyond individual companies to encompass the entire industry. Integrating the environmental aspects of the sector's development into a national socio-economic strategy is a critical tool for addressing ecological challenges and achieving broader socio-economic objectives [5]. Research on strategic management increasingly emphasizes the implementation of sustainable management principles, as traditional strategic management alone is insufficient to meet contemporary demands.

Consequently, these findings underscore the importance of incorporating social and technological dimensions into corporate carbon reduction strategies. They further validate the strategic value of investing in renewable energy and fostering a gender-sensitive corporate environment as integral components of a comprehensive ESG approach.

This study aims to analyze pathways for reducing air pollution in the West Kazakhstan region by applying novel environmental assessment approaches grounded in ESG principles. To achieve this aim, the following objectives are established:

- To assess the impact of ESG adoption on air pollution reduction in the West Kazakhstan region, a key oil-and-gas-producing area in Kazakhstan.
- To perform a spatial analysis of atmospheric emissions in the region to evaluate the environmental impact of the KPO company, which develops the Karachaganak oil and gas condensate field.
- To analyze the effectiveness of ESG strategy implementation at KPO, benchmarking its performance against leading national and international oil and gas companies within a sustainable development framework.
- To develop an ESG algorithm for evaluating recurring functions and identifying operations with concentrated ESG risks. This algorithm will integrate the environmental, social, and governance components of ESG into a unified strategic planning system for sustainable development.
- To perform a correlation-regression analysis examining the relationship between atmospheric emission levels and the E, S, and G factors of the ESG model for the selected oil and gas companies, and to provide a predictive assessment of ESG's influence on emission reduction.

The research questions and problem statement led to the formulation of the following hypothesis:

H1: *The implementation of ESG principles in corporate operations contributes to a reduction in regional air pollution.*

This study posits that integrating ESG principles into the corporate governance of oil and gas companies facilitates the reduction in GHG and pollutant emissions. The effectiveness of these strategies is hypothesized to depend on the level of institutional maturity, the robustness of ESG reporting mechanisms, and specific geographic factors.

In Kazakhstan, the national low-carbon development strategy and the country's commitments under the Paris Agreement have heightened the focus on regulating greenhouse gas emissions [6]. Given that KPO is a significant source of national GHG emissions, this research examines how the company's ESG strategy can inform effective management decisions to reduce air pollution and advance decarbonization goals, thereby contributing to the sustainable development of the region.

The novelty of this study lies in the integrated application of econometric modeling and spatial analysis within a comprehensive framework. This approach examines the reduction in air pollution through an ESG strategy in the context of sustainable development for the entire region. While most research assesses the impact of ESG principles either on corporate financial performance—such as profit and market value—through social and governance indicators, or on environmental metrics solely through environmental indicators, this study adopts a distinct perspective. Its methodological significance stems from assessing the sensitivity of atmospheric emissions to the influence of indicators from all three ESG components simultaneously.

Furthermore, the experience of KPO holds practical relevance for other countries, as oil and gas companies worldwide face similar air pollution challenges. This is particularly applicable in regions with significant hydrocarbon reserves, such as Central Asia [7].

2. Materials and Methods

2.1. Object of the Study

This study focuses on companies classified within the HPE category, which are characterized by their industrial operations and significant environmental impact. The analysis specifically centers on KPO, one of the principal sources of air pollution in the West Kazakhstan region.

2.2. Research Methodology

This research employs an interdisciplinary methodology, integrating cartographic and statistical modeling with a comparative analysis of socio-economic, energy, and environmental indicators. It also includes a systematic review of atmospheric impact reduction policies in global and Kazakhstani contexts.

A comprehensive analysis was conducted on representative data from the Scopus database, covering air pollution issues and ESG trends from 2012 to 2024. Consistent with the study's objectives, particular emphasis is placed on the environmental (E) component of the ESG triad.

Building on an examination of current practices in HPE-type companies, an algorithm was developed for an ESG strategy aimed at reducing air pollution through the implementation of Environmental Impact Assessment (EIA) principles.

Data were collected and selected based on comparability, relevance, and materiality criteria. To ensure systematic and objective analysis, the study benchmarks KPO's perfor-

mance against leading global oil and gas companies—Shell, Eni S.p.A., BP, and the Kazakh company KMG—examining their sustainable development goals, key trends, and ESG implementation challenges. The selection of these companies is justified by their participation, along with Chevron, in the KPO production sharing agreement (with BP included as an additional comparator). Chevron was excluded from detailed analysis due to largely unstandardized or unavailable ESG data, particularly for social (S) and governance (G) indicators. The collected data, covering the period 2019–2023, were systematized into panel data for analyzing ESG parameters.

Based on the theory of Lawrence D. Miles [8], "Algorithm of ESG Strategy for Reducing Air Pollution" maps were developed for each ESG component. These maps utilize color coding to facilitate the inventory and optimization of key functions during the implementation of an ESG strategy in oil and gas companies.

The relationships between ESG indicators and air pollution reduction were identified using econometric modeling in R. An element-by-element approach was applied to isolate the key factors driving emission reductions. Initial integration of all factors into a single model revealed the dominant influence of environmental (E) factors. Consequently, following the precedent of similar studies, social (S) and governance (G) factors were integrated for analysis, while environmental factors were evaluated independently. This methodological distinction yielded critical insights that form the basis for the presented practical recommendations.

This research builds upon the authors' prior work [9], which analyzed the impact of KPO on regional development and the formation of a circular economy between 2012 and 2022. The current study continues this line of inquiry by focusing on the implementation of ESG strategies and enhancements in energy efficiency.

2.3. Data Sources

This study utilizes three primary datasets. The key indicators are derived from internationally recognized frameworks, including GRI, ISO 14001:2015, ISO 50001:2018, ISO 26000, ISO 45001:2018, and standards from the International Association of Oil and Gas Producers (IOGP) [10–15]. These frameworks were selected for their global recognition, cross-industry applicability, user-friendly templates, and ongoing updates [16]. The first datasets comprise the following indicators for the companies under study:

1. Environmental indicators.
2. Economic and energy indicators.
3. Social (S) and governance (G) performance indicators.

Data were collected from annual environmental bulletins of Kazakhstan for 2019–2023 [17,18]. The analysis of ESG factors relied on sustainability reports from KPO, Shell, Eni S.p.A., BP, and KMG for the same period [19–24], supplemented by GRI reports and Sustainability Reporting Guidelines [10,25].

Spatial analysis of air pollution was conducted using ArcMap 10.8. with data sourced from the Emissions Database for Global Atmospheric Research (EDGAR) [26]. The data processing involved spatial interpolation via spherical kriging, selected for its efficacy in smoothing regional data. A spherical and isotropic variogram model was applied to ensure a uniform and accurate representation of pollution distribution across the region. Map construction employed kriging interpolation, with the specific method—Ordinary Kriging or Universal Kriging—chosen based on data characteristics and spatial distribution.

The second dataset comprises economic and energy indicators for the aforementioned companies from 2019 to 2023, sourced from fact sheets, sustainability reports, and the Emissions Database for Global Atmospheric Research (EDGAR) [26]. Key metrics included the average annual emission growth rate, specific energy intensity (GJ/t), specific CO_2

emissions (t/1000 t of extracted raw materials), and the share of renewable energy sources (%) in the energy balance, which characterizes production carbon intensity.

The third dataset encompasses social (S) and governance (G) indicators that reflect corporate performance. This information was extracted from the sustainability reports of KPO, Shell, Eni S.p.A., BP, and KMG for the period 2019–2023 (KPO, 2019–2023; SHELL, 2019–2023; ENI, 2019–2023; BP, 2019–2023; KazMunayGas, 2019–2023) [20–24].

The study faced several limitations in parameter selection:

- Varying reporting timelines: The sustainability reports of the analyzed companies covered different periods. To ensure comparability, the earliest common year for all five companies—2019—was selected as the baseline.
- Evolving reporting standards: Although the Sustainable Development Goals (SDGs) were adopted in 2015, the companies implemented GRI standards in different years. Furthermore, standardized requirements for the circular economy within ESG frameworks remain under development.
- Lack of standardized disclosure: Sustainability reports lack strict formatting requirements, allowing companies significant discretion in data presentation. Established practice shows that environmental (E) criteria are relatively standardized for indicators such as greenhouse gas emissions, net carbon intensity, energy consumption, and waste management. In contrast, no consensus exists regarding social (S) and governance (G) indicators, which complicates their analysis, comparative assessment, and interpretation.

Modeling difficulties External factors, such as fluctuations in oil and gas prices, are highly uncertain and can be caused by a variety of interrelated factors, including global economic conditions, political events and natural disasters. This requires a separate, independent study, as the purpose of this study was to establish the extent to which ESG commitment (companies' efforts to demonstrate their environmental, social and governance responsibilities) contributes to the reduction in air pollutant emissions.

2.4. Literature Review

ESG principles are increasingly recognized as a catalyst for technological innovation aimed at mitigating environmental pollution and addressing the drivers of climate change. While a substantial body of research has been dedicated to this field, the present study seeks to contextualize its relevance by systematically reviewing and classifying the existing literature into distinct thematic areas. This classification helps to identify prevailing research trends, gaps, and central debates (Table 1).

The preceding analysis identifies critical gaps in the literature on corporate ESG strategy implementation.

Table 1. Systematization of the results of the literature review in the direction of "The impact of ESG on reducing air pollution".

Direction	Works (Authors)	Conclusions	Field of Knowledge/Application
The relevance of ESG application	[3,4,27–37]	ESG is seen as a tool for implementing the concept of sustainable development, a driving force for technological development that can help reduce environmental pollution and eliminate factors influencing climate change.	Economic research
			Justification of the relevance of the research topic
Assessment of global, regional, and national greenhouse gas emissions	[2,38–47]	Growing global carbon emissions from fossil fuels are becoming one of the fundamental problems of the modern economy and require a comprehensive ESG approach that includes political regulators, technological, organizational, economic and social aspects.	Environmental research
			Identification of factors, independent variables
Studying the best global practices of ESG transformation	[48–55]	The study of the best global practices in ESG transformation and sustainable development around the world has shown that ESG strategies are supported at the legislative level	Interdisciplinary research
			Rationale for recommendations

Table 1. *Cont.*

Direction	Works (Authors)	Conclusions	Field of Knowledge/Application
Implementing ESG principles into the strategy of oil and gas companies	[56–60]	By integrating ESG principles, oil and gas companies can significantly improve their energy efficiency, which in turn helps reduce air pollution.	Economic research
			Identification of factors, independent variables
Development of green technologies, sustainable and responsible investment	[61–81]	The applicability of ESG strategies is discussed from a macroeconomic perspective of regulatory policy. Due to the dominance of the climate and environmental components of ESG, insufficient attention is paid to the disclosure of environmental S.G. components.	Economic research
			Justification of the relevance of the research topic Identification of factors, independent variables

First, departing from prior research, this study employs non-financial performance indicators to conduct a pioneering comparative analysis of ESG strategy effectiveness in reducing air pollution. By benchmarking leading global and Kazakhstan's oil and gas companies within a sustainable development framework, it integrates environmental, social, and governance indicators—constituting its primary novelty. While ESG has gained prominence in corporate sustainability discourse, scholarly focus has remained predominantly on its impact on economic metrics such as productivity, financial costs, risk, and foreign direct investment [54,55,62,64]. Although studies confirm significant indirect benefits from improved profitability and operational efficiency [68], the direct environmental impact of ESG in specific regional contexts remains underexplored.

The relevance of this approach is underscored by the limited research on ESG strategies for improving air quality in Kazakhstan. This study thus complements international scholarship by evaluating ESG efficacy in a context of high energy intensity and hydrocarbon dependency.

Second, a notable scarcity of data exists on how natural resource companies successfully integrate all three ESG components into a unified strategic planning system for sustainable development. The literature frequently addresses ESG from a macroeconomic and regulatory perspective [58,59], yet companies often lack the operational tools for practical implementation.

Third, this paper introduces a novel methodology for assessing ESG initiatives in Kazakhstan's oil and gas sector through the integration of econometric modeling and spatial analysis. Furthermore, by examining current practices in High Polluting Enterprises (HPE), it develops an algorithm for an ESG air pollution reduction strategy incorporating Environmental Impact Assessment (EIA) principles.

Fourth, investigating the contribution of ESG indicators to emission reduction holds profound practical and strategic importance. Based on a correlation-regression analysis of the relationship between atmospheric emissions and the E, S, G factors for the selected companies, this article provides an emissions forecast up to 2030. The results confirm the positive role of ESG indicators in reducing emissions, demonstrating that by actively fulfilling their environmental, social, and governance responsibilities, companies can enhance their sustainability and significantly contribute to regional and national carbon reduction goals.

So, most studies assessing the impact of ESG principles are considered either in the context of the impact of social and management indicators on the financial and economic performance of companies (profit, market value of the company) [5,54–56,66], or in the context of the influence of environmental indicators on an environmentally dependent variable [1–4,36,37,44,45,57,58,62,63]. The originality and significance of the research methodology is that the sensitivity of emissions into the atmosphere was assessed through the influence of indicators of all three ESG components.

KPO was selected as a case study to analyze the applicability of ESG principles in reducing air pollution. The company, located in the West Kazakhstan Region, was among the first in Kazakhstan to formulate a comprehensive environmental policy vision as an initial step in implementing an ESG system and adopting a "green economy" concept.

The West Kazakhstan Region is of particular interest due to its favorable geographical location and substantial resource potential, accounting for 97% of the republic's gas condensate production and 37% of its gas production. KPO, established at the world's largest Karachaganak oil and gas condensate field [9], serves as both a supplier and consumer of fuel and energy resources. A distinctive feature of the field is the high hydrogen sulfide content in its natural gas (4–4.3%), which is classified as a Class I hazard [82].

KPO's mission centers on developing gas condensate fields through principles that balance environmental respect with economic profitability while fostering socio-economic growth [20]. The company has demonstrated a longstanding commitment to sustainability reporting, becoming the first in Kazakhstan in 2009 to issue an independently verified sustainability report meeting international requirements, and adopting GRI guidelines by 2014. This commitment has been recognized in the PwC Kazakhstan rating, where KPO's reporting is ranked among the best non-financial companies for ESG disclosure [83]. Following assessments of reports for 2022 and 2023 based on completeness, quality, and availability of ESG information, the company secured a position among the top five leaders in Kazakhstan with a B+ rating [83,84]. Notably, GRI standards are actively utilized by leading global oil and gas companies, including Eni S.p.A, Shell, and BP, to enhance the transparency and quality of their sustainability reporting.

3. Results

The study is based on the task of constructing an algorithm for an ESG strategy to reduce air pollution, which includes a number of sequential steps (Figure 1).

The ESG strategy for reducing air pollution is grounded in Environmental Impact Assessment (EIA) principles and a comprehensive analysis of representative literature on air pollution issues and ESG trends from 2012 to 2025. The algorithm was developed considering recommendations for implementing the ESG agenda from various professional associations and international organizations. It constitutes a structured system of functional actions in the areas of environmental, social, and governance responsibility for High Polluting Enterprises (HPE).

3.1. Implementation of the Environmental (E) Component of the ESG Strategy

The proposed algorithm for an ESG strategy to reduce air pollution involves a sequence of steps (Figure 1). At the initial stage of assessing and monitoring the ESG ecosystem, it is prudent to begin with an analysis of the Environmental (E) component by identifying sources of environmental impact, the affected receptors, and the composition and volume of emitted pollutants.

Environmental Impact Assessment of KPO Operations

Hydrocarbon production at KPO affects nearly all components of the biosphere, with the most significant impact on the atmosphere and soil, which subsequently affects flora, fauna, and human populations. Primary sources of environmental impact at KPO include:

- Flares for gas and condensate combustion during well development and testing.
- Open tanks and storage facilities.
- Warehouses and storage areas for reagents.
- Boiler house operations.
- Drilling and cement solutions.

- Solid drilling waste and drilling wastewater.
- Heavy-duty vehicle fleet.

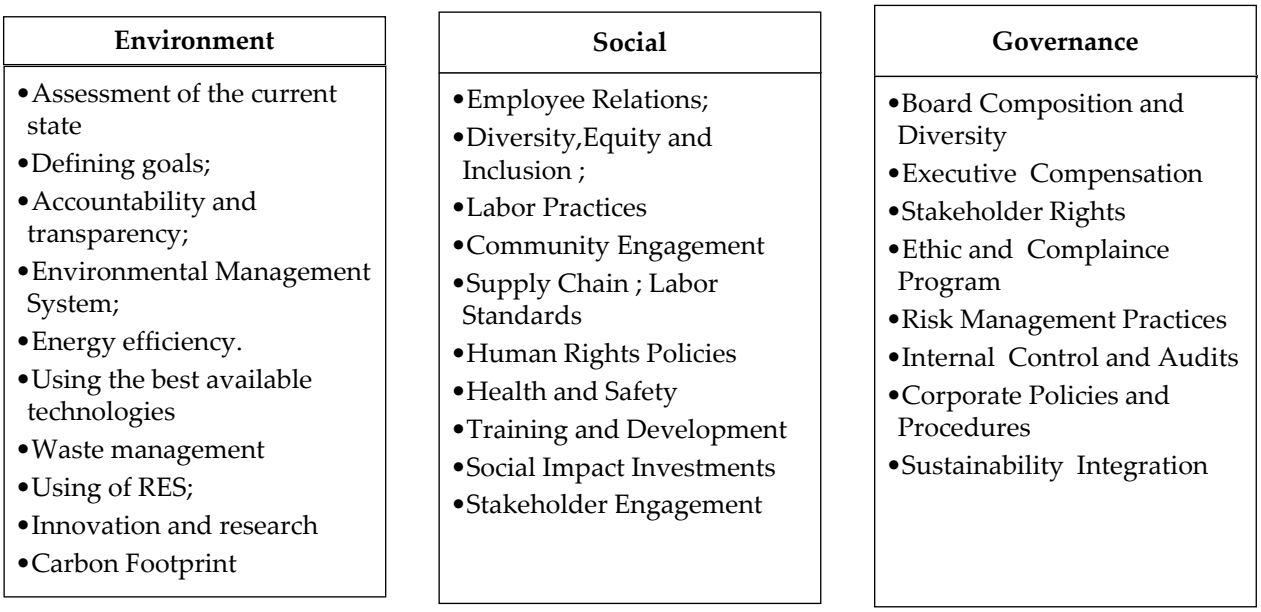


Figure 1. Algorithm of ESG strategy for reducing air pollution. Sources: Compiled by the authors based on [80,85,86].

Air pollutants are generated throughout the entire production cycle—extraction, treatment, storage, and transportation of gas and condensate. Twenty-two types of pollutants spanning hazard classes 1–4 are emitted into the atmosphere.

The chemical composition of the atmospheric air at the field is characterized by greenhouse gas emissions (nitrogen oxides, carbon dioxide, and methane), non-greenhouse pollutants (sulfur dioxide), and specific pollutants such as hydrogen sulfide, volatile organic compounds (VOCs), and particulate matter (PM) originating from oil and gas facilities. Leaks in process equipment are a significant source of specific emissions, including hydrogen sulfide and mercaptans.

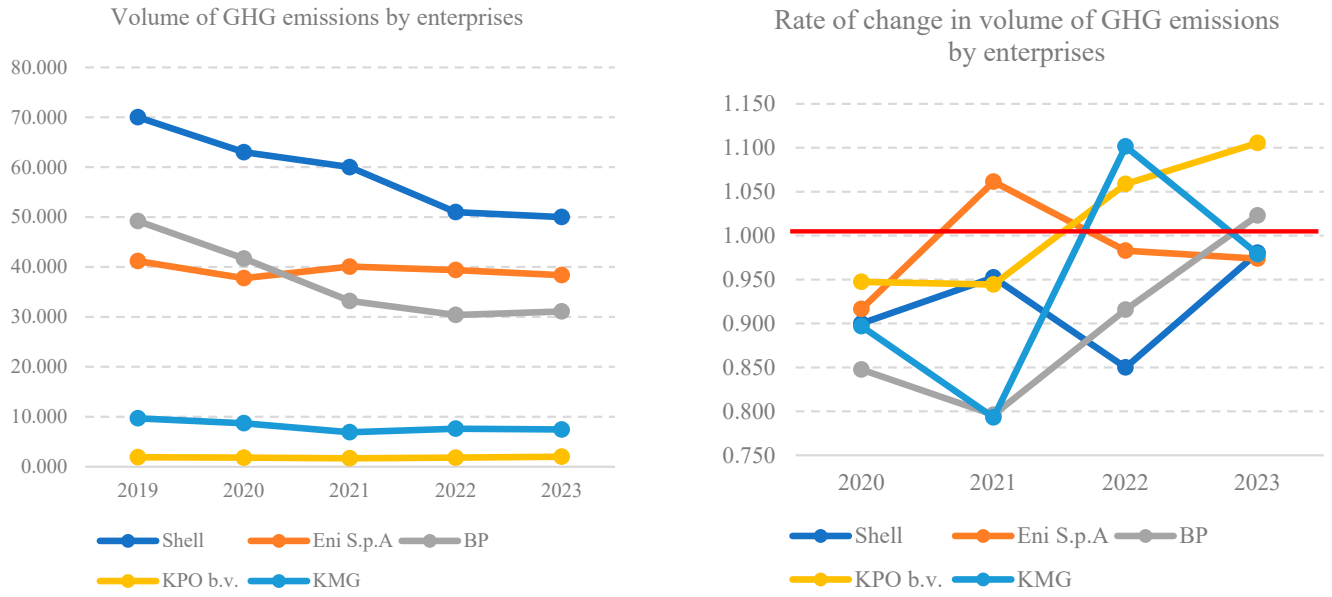
Sources of hydrocarbon emissions encompass pumping stations, petroleum condensate storage tanks, diesel fuel storage tanks, and equipment leaks. The majority of emissions are generated by gas combustion in flares (37%), waste incinerators (21%), gas turbine units (20%), with boilers, process furnaces, and compressors contributing 12%, and fugitive sources accounting for 10%. The primary combustion products are sulfur dioxide, carbon monoxide, and nitrogen oxides.

Based on the analysis of KPO's sustainable development reports for 2019–2023, key ESG metrics were selected in accordance with GRI standards and are presented in a comparative analysis with leading global and Kazakhstani oil and gas companies (Figure 2).

KPO's GHG emissions (in tons CO_2 equivalent) are significantly lower than those of the other companies analyzed (Figure 2a). Furthermore, a comparative analysis of specific greenhouse gas emission dynamics against International Association of Oil & Gas Producers (IOGP) benchmarks reveals that KPO's actual specific emissions are 15% lower than European averages and 44% below IOGP figures.

However, a comparison of absolute GHG emissions (Figure 2a) with their annual growth rates (Figure 2b) yields more nuanced insights. While standard practice expects a steady year-on-year decline in emissions, the data reveals a more complex picture. Figure 2a indicates that only Eni S.p.A. exhibited a temporary increase in emissions between 2020 and 2021, while other companies generally followed a linear decreasing trend. In

contrast, the analysis of annual growth rates in Figure 2b shows a cyclical pattern across all companies throughout the study period, deviating from the linear decline observed in absolute terms. Among the companies, only Shell demonstrated a consistent downward trend (with all growth rate values below 1.0), while others displayed periodic increases. Eni S.p.A. has achieved a sustained reduction over the past three years. KPO, despite its low absolute emissions, shows steady growth in the emission rate. This assessment of emission dynamics sustainability reveals that the overall downward trend is often accompanied by periodic deviations, likely attributable to seasonality, fluctuations in production activity, or external economic factors.



(**a**) (**b**)

Figure 2. Volume of GHG emissions by enterprises, million tons in CO_2 equivalent (**a**). Rate of change in volume of GHG emissions by enterprises, count (**b**). Source: compiled by the authors based on [19–24]. The red line in Figure 2 indicates the Rate of change in the volume of GHG emissions by enterprises equal to 1. Trends located below the red line indicate a reduction in emissions, while if the graphs are located above the red line, this indicates an increase in the level of GHG emissions.

Previous studies concluded that the impact on water, soil, and vegetation quality in the Karachaganak field area was negligible [87]. Air pollution studies conducted at the field analyzed four components: hydrogen sulfide, sulfur dioxide, nitrogen dioxide, and carbon monoxide. These studies indicated that while emissions lead to air pollution at the border of the sanitary protection zone, no significant deterioration of ambient air quality was reported [88,89]. Health risk assessments for the nearby population suggested that under normal operating conditions, concentrations of these priority pollutants do not pose a health hazard, though strict emission regulation was emphasized as necessary [90–92].

It is important to note that these studies were conducted more than 7–14 years ago and lacked a detailed geographical analysis of the regional impact. Our previous research identified two distinct zonal sectors in the West Kazakhstan region: an industrial north, responsible for the majority of atmospheric emissions, and an agricultural south [9]. To address this gap, we deemed it essential to conduct a contemporary geospatial assessment of emissions in the region.

The spatial maps presented in this study (Figure 3) serve to identify areas with the highest environmental burden, determine spatial pollution patterns, and assess the impact of industrial facilities, particularly KPO. Given that 2022 was identified as a period of

increasing GHG emissions for KPO in Figure 2b, the spatial analysis was conducted using data from this specific period to capture the associated environmental footprint.

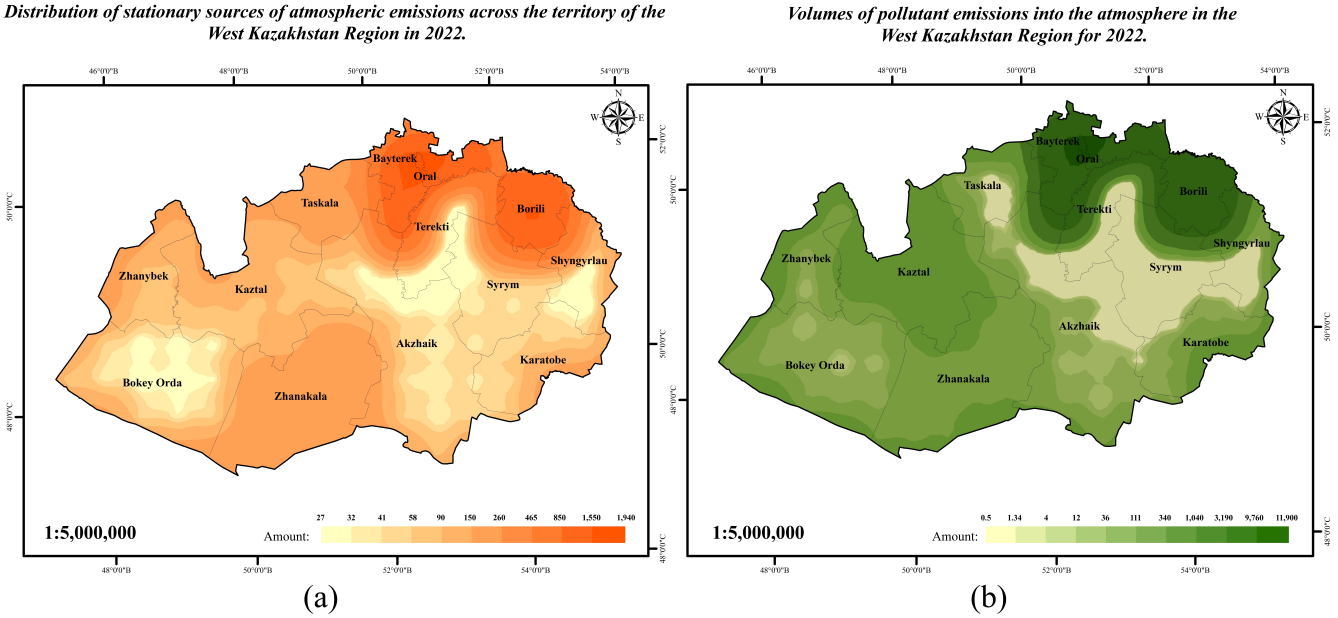


Figure 3. Interpolated spatial distribution maps. (**a**) Spatial distribution of air emission sources in West Kazakhstan Oblast, 2022, (count). (**b**) Spatial distribution of air emissions in West Kazakhstan Oblast, 2022, (tones). Sources: Compiled by the authors based on [17,18]. Built in the program based on ArcMap 10.8 software.

Thus, the spatial analysis of atmospheric pollutant emission sources (Figure 3a) and emission volumes (Figure 3b) for 2022 revealed an uneven distribution, with sources heavily concentrated in the northern industrial zone of the West Kazakhstan region. Key areas include Borly (the location of KPO), the city of Oral, and Baiterek. In the Borly area, gaseous and liquid marker emissions constitute the majority (86% of the region's total), while particulate matter (PM) accounts for the remaining 14%. The primary pollution sources in these zones are oil and gas extraction facilities, power generation plants, and main pipeline compressor stations. The interpolation results effectively visualize these pollution hotspots, and the maps (Figure 3) clearly illustrate the spatial disparity between emission sources and concentration levels. To confirm the presence of spatial patterns observed in the interpolated emission maps (Figure 3), a formal spatial autocorrelation analysis was conducted. The study was conducted using global and local indicators of spatial dependence. The study was conducted using global and local indicators of spatial dependence.

1. Global spatial autocorrelation (Moran's I)

To assess the overall degree of spatial dependence between emission values, the global Moran's I index (Cliff & Ord, 1981) [93] was used.

$$I = \frac{n}{\sum_{ij} w_{ij}} * \frac{\sum_{ij} w_{ij}(X_i - \overline{X})(X_J - \overline{X})}{\sum_i (X_i - \overline{X})^2}$$

where

n is the number of districts (13);
x_i is the value of outliers in district i;
w_{ij} is the spatial contiguity matrix (queen contiguity);
$\overline{x}$ is the average value of the indicator.

Calculation results:
Moran's I = 0.207;
Expected value: E(I) = −0.0833;
Variance: Var(I) = 0.00609;
Z-statistic = 3.73;
p-value = 0.0002.

A positive and statistically significant Moran's I value indicates the presence of a clearly expressed positive spatial autocorrelation. This means that areas with elevated emission levels tend to be adjacent to areas with similarly high values, while low emission levels also form spatial groups. Consequently, the spatial distribution of emissions in the West Kazakhstan region is not random, but forms stable spatial clusters, which confirms the conclusions obtained from the visual analysis of interpolation maps (Figure 3).

The Getis–Ord Gi* local indicator (Getis & Ord, 1992) [94] was used to identify specific hot and cold zones in the region.

To identify specific "hot" and "cold" zones in the region, the local indicator Getis–Ord Gi* (Getis & Ord, 1992 [94]) was used. In the above-mentioned areas of Borli, Uralsk, Baiterek, Z Gi* in "hot" zones are in the range of high values of 2.11–2.89, and in other non-industrial areas, Z Gi* are in the "cold spot" of low emissions, with Z Gi* in the range of −1.96–2.77.

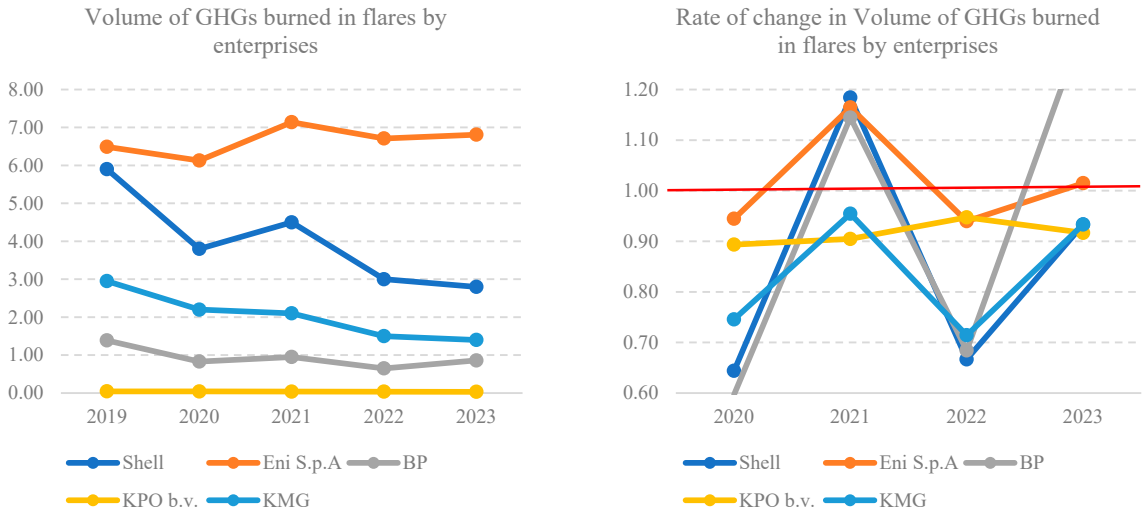
The Gi* method revealed two stable high-emission clusters forming around the Baiterek and Borli districts and the city of Uralsk, which corresponds to the location of industrial and oil and gas facilities. In contrast, the southern peripheral regions form distinct low-emission zones, reflecting the spatial inequality of environmental loads within the region.

The results of global and local analysis of spatial autocorrelation confirm that the distribution of atmospheric pollutant emissions across the districts of the West Kazakhstan region has a pronounced spatial character and forms statistically significant clusters. This confirms that the interpolated maps (Figure 3) reflect real spatial patterns and not random fluctuations. Taking spatial dependence into account is an important condition for correct environmental assessment and development of regional environmental policy.

KPO has implemented an integrated management system that incorporates control and monitoring mechanisms for all environmental parameters, aligned with the Global Reporting Initiative (GRI). This system forms the foundation for defining energy policy and establishing goals, objectives, and measures for energy conservation and efficiency improvement. It is noteworthy that KPO has published its Sustainability Development Report (SDR) since 2008, with reports from 2017 onward prepared in accordance with contemporary GRI standards.

An analysis of the company's sustainability reports from 2019 to 2023 identified ESG strategies where environmental commitments are focused on the following GRI 3-3 objectives: pollution prevention, GHG emission reduction, biodiversity and ecosystem conservation, protection of natural resources, and the continuous improvement of environmental performance (Figure 4). The inclusion of emission data and reduction progress in KPO's ESG reporting fosters public transparency regarding the company's contributions to the objectives of the Paris Agreement.

A comparison of the indicators in Figure 4a,b reveals that, in contrast to overall emissions, KPO demonstrates the most effective performance in reducing the volume of gases flared among the studied companies. The data for the period shows a generally stable downward trend (average value of 0.9). For the other companies, discrepancies between linear and cyclical trends are again observed.



(**a**) (**b**)

Figure 4. (**a**) Volume of GHGs burned in flares by enterprises, mil.t CO_2 equivalent. (**b**) Rate of change in volume of GHGs burned in flares by enterprises. Sources: Compiled by the authors based on [19–24]. The red line indicates the Rate of change in the volume of GHG emissions by enterprises equal to 1. Trends located below the red line indicate a reduction in emissions, while if the graphs are located above the red line, this indicates an increase in the level of GHG emissions.

While absolute emission volumes (Figure 4a) show a steady and consistent decline, indicating successful implementation of environmental mitigation plans, the stability of this trend (Figure 4b) reveals fluctuations. Periods of rapid decline alternate with short-term plateaus, suggesting that the overall positive trajectory is influenced by factors such as seasonal patterns, the phased introduction of new technologies, and global economic conditions. Consequently, a robust long-term climate strategy must aim not only for cumulative emission reductions but also for greater stability and predictability in the rate of change.

The heightened focus on the climate and environmental components of ESG has, however, led to an increase in "greenwashing"—the dissemination of misleadingly positive reports about a company's environmental impact. The flexible selection of ESG criteria can result in the overstatement or understatement of reported metrics, with studies showing that various ESG ratings are consistent in only six out of ten cases [71]. In response, major asset managers (e.g., BlackRock) and key industry players (e.g., Bloomberg) are advocating for mandatory ESG disclosures [16]. Consequently, the European Union is actively developing regulatory frameworks, including new rules to enhance the transparency and reliability of ESG ratings. These stringent regulations compel companies to disclose emissions and implement reduction measures, creating direct incentives for businesses to improve their environmental performance and reduce their carbon footprint [73].

According to external audits, the environmental monitoring system for air quality developed and implemented by KPO complies with international standards ISO 14001:2015, GRI, and the national legislation of the Republic of Kazakhstan [10,11,82].

KPO manages its direct GHG emissions within the framework of the national emissions trading system, adhering to the limits set in its environmental permits. This is achieved through systematic sampling and analysis by an accredited laboratory, supported by 18 stationary automatic monitoring stations. These stations operate continuously around the perimeter of the facility, within sanitary protection zones, and along the export pipeline, and are equipped with an alert system for when pollutant concentrations exceed permissible levels. This integrated approach has enabled the company to achieve a systematic

reduction in atmospheric emissions. KPO's technological targets include ensuring that the residual hydrogen sulfide content in fuel gas does not exceed 0.02 g/m^3 and mercaptans do not exceed 0.036 g/m^3. During the treatment of stable condensate, the company guarantees a hydrogen sulfide content of no more than 20 ppm and a mercaptan content of no more than 40 ppm in commercial crude oil.

During the study period, KPO achieved a 44.9% reduction in gross atmospheric emissions, with the most significant decreases observed for sulfur dioxide (59.3%), nitrogen dioxide (38.1%), and volatile organic compounds (40.3%). Specific pollutant emissions decreased by 51.3%. This reduction, and the corresponding decrease in ground-level pollutant concentrations, is attributed to a comprehensive set of technological and organizational measures implemented through an energy conservation-focused ESG strategy.

Applying Lawrence D. Miles' theory [8] as a framework for developing a color-coded ESG algorithm has helped identify recurring functions and pinpoint operations with concentrated ESG risks. The analysis of KPO's environmental and energy management systems shows that the achieved emission reductions can be attributed to the implementation of a structured algorithm (Table 2).

Thus, in the domain of accountability and transparency, KPO's reporting is verified by audit firms for data reliability, and its environmental and energy management systems undergo regular audits. Since 2014, with the adoption of GRI standards, ESG strategies have been progressively integrated. Under the areas of "Environmental Management System, Waste Management, and Energy Efficiency," KPO has deployed continuous monitoring systems for air, surface water, and groundwater. Strategies for water resource management, wastewater reuse, material recycling in production, and waste disposal have been established.

Pollutant concentrations in emissions are monitored in real-time. A Leak Detection and Repair (LDAR) system is utilized to identify and mitigate methane leaks, and international standards ISO 14001:2015 and ISO 50001:2018 are implemented [11,12]. The adoption of ISO 50001:2018 [12], in particular, has facilitated the optimization of energy consumption and enhanced energy efficiency in hydrocarbon production and processing.

As part of its "Innovation and Research: Using the Best Available Technologies" program, atmospheric emissions have been reduced through high-pressure (550 bar) gas reinjection technology. Since 2024, KPO has participated in the UN-led Oil and Gas Methane Partnership 2.0 (OGMP 2.0) under its Carbon Footprint initiative.

3.2. Implementation of the Social (S) and Governance (G) Components of the ESG Strategy

Karachaganak, as the region's largest enterprise, plays a pivotal role in its social, economic, and cultural development. An analysis of the company's socially responsible business strategy reveals a comprehensive set of measures focused on improving working and living conditions, healthcare, collaboration with trade unions, enhancing industrial safety, providing social guarantees, supporting education and internships, fostering university partnerships, maintaining dialogue with local communities, and developing social and infrastructure projects for the region.

Concurrently, an analysis of institutional and legislative differences between Kazakhstan and oil-producing nations with more advanced institutional frameworks (e.g., Norway, the USA, Canada) indicates that the latter manage natural resource revenues more effectively, achieving superior results in economic growth and social development [81]. For instance, unlike Norway, Kazakhstan's National Fund has not attained a similarly advanced level of sovereign wealth fund management, which has contributed to its depletion, low long-term investment efficiency, and limited signs of sustainable development [95].

Table 2. Algorithm for implementing the Environment component of KPO's ESG strategy to reduce air pollution.

Step of Algorithm	Essence/Meaning	Interaction	Frequency of Implementation	Management Level, Responsible Person	Management Risks
Assessment of the current state	Assessing achievements and gaps in reducing air pollution and implementing sustainable practices	Defining goals Using the best available technologies (BAT) Carbon Footprint Waste management	Annually, according to the terms of preparation of the SDR	KPO Environmental Department; Responsible person—Senior Management—Managing Director for Strategy/Deputy General Director	Failure to comply with international and national standards and regulations can lead to fines, legal consequences, and damage to a company's reputation. Failure to take current trends into account will lead to additional costs.
Defining goals	Defining the SDGs of both the company itself and its role in the sustainable development of the region and ways to achieve them	Environmental Management System Waste management Using of RES Using the best available technologies (BAT)	according to GRI—annual review and updating of objectives (KPO, Eni)	Middle and senior management (heads of departments responsible for implementing the relevant ESG principle). For KPO, the team responsible for developing the "Green Strategy" and ESG goals is approved by the KPO Board of Directors.	The unattainability of the set goals from the standpoint of resource inadequacy (time, financial, technological, human) can reduce the effectiveness of the measures being implemented
Accountability and transparency	Creation of mechanisms and tools to ensure transparency of ESG implementation processes	Assessment of the current state Using the best available technologies (BAT) Waste management Carbon Footprint	Annually, according to the ERM compilation deadlines. Ongoing coverage of ESG events/incidents	KPO Environmental Department, which is responsible for the implementation of sustainable development principles, the responsible person is senior management—Managing Director for Strategy/Deputy General Director	Risks of insufficient resources and investment, insufficient transparency and reporting, and risks of greenwashing
Environmental Management System	Planning environmental activities and monitoring their implementation	Accountability and transparency Energy efficiency Using the best available technologies (BAT) Waste management Using of RES	Implementation and review of environmental management systems on an annual basis (KPO, Eni)	Special committees and working groups implement an integrated management system that covers occupational health, safety, and environmental protection. The responsible person is the Director of Health, Safety, Environment, and Integrity.	Risks associated with non-compliance with national and international environmental standards, insufficient transparency and reporting
Energy efficiency	Rational use of energy resources, reduction in energy costs	Defining goals Environmental Management System Using of RES Assessment of the current state	In accordance with GRI 302, the frequency of implementation of energy efficiency measures within the framework of the ESG strategy of KPO includes both annual and long-term plans, for example, from 2022 to 2026.	KPO implements an energy management system in accordance with ISO 50001:2018. Special committees and working groups are in place. The responsible person is senior management—Managing Director for Strategy/Deputy General Director.	Environmental, technological and reputational risks

Table 2. *Cont.*

Step of Algorithm	Essence/Meaning	Interaction	Frequency of Implementation	Management Level, Responsible Person	Management Risks
Using the best available technologies (BAT)	Implementation of projects to introduce the best technologies for both reducing environmental pollution and business management	Environmental Management System Using of RES Innovation and research Energy efficiency	BAT implementation should be ongoing, with an annual review	The Committee is responsible for the implementation of sustainable development principles and environmental management, including the introduction of BAT. The responsible person is senior management—Managing Director for Strategy/Deputy General Director	Technological risks, lack of resources and investment, non-compliance with regulatory requirements
Waste management	Implementation of measures for the collection, accumulation, transportation, processing, disposal or rendering harmless of waste, supervision of these processes	Environmental Management System Using the best available technologies (BAT) Energy efficiency Carbon Footprint	constantly	KPO Environmental Department, which is responsible for the implementation of programs to reduce waste generation and minimize their negative impact on the environment. Responsible person—senior management—Managing Director for Strategy/Deputy General Director	Non-compliance with regulations, lack of transparency and reporting; changing public opinion and pressure from environmental organizations
Using of RES	Reduction in pollutant emissions; Compliance with environmental standards, Economic efficiency	Waste management Using the best available technologies (BAT) Using of RES	Every year, according to GRI	The committee is responsible for sustainable development and environmental management. The person responsible is senior management—Managing Director for Strategy/Deputy CEO.	Non-compliance with regulatory requirements, technological risks, lack of resources and investment
Innovation and research	EIA; Development of new technologies; economic efficiency	Energy efficiency Accountability and transparency Using the best available technologies (BAT) Using of RES Waste management	Annual reports on achieved results and future plans, which comply with GRI requirements for transparency and reporting	Project team responsible for innovation and research aimed at reducing air pollution; Person in charge—Senior Management—Managing Director for Strategy/Deputy CEO	Lack of resources and investment; insufficient personnel qualifications; non-compliance with regulatory requirements
Carbon Footprint	Reducing the negative impact on the environment, assessing the level of pollution	Innovation and research Environmental Management System Using the best available technologies (BAT) Energy efficiency	constantly	KPO Environmental Department, which is responsible for the implementation of programs to reduce waste generation and minimize their negative impact on the environment. Responsible person—senior management—Managing Director for Strategy/Deputy General Director	Non-compliance with regulations, lack of transparency and reporting; changing public opinion and pressure from environmental organizations

A review of global best practices in ESG transformation demonstrates that in the EU, ESG strategies are legislatively supported through initiatives like the European Green Deal, which aims for carbon neutrality by 2050 [48]. Governments of OECD member and partner countries have developed and are implementing numerous specific measures to stimulate the green economy [62].

An assessment of measures supporting KPO's social responsibility implementation and their impact on sustainable development underscored the need to systematize these actions using the proposed algorithm (Figure 1). This analysis resulted in the development of a structured action algorithm (Table 3).

As part of its commitment to balancing corporate and employee interests through a healthy work environment, KPO has increased the proportion of local hires over the past three years under its "Employee Relations, Diversity, Equity, and Inclusion, Labor Practices, Supply Chain, and Labor Standards" program. Local citizens now constitute 98% of the total workforce and 86% of management personnel.

To advance Sustainable Development Goal (SDG) 16.b, KPO has implemented the "KPO 365" Corporate Strategy, which focuses on preventing major incidents and mitigating risks to personnel, the environment, assets, and corporate reputation. The company's social responsibility policies, procedures, and standards align with International Financial Reporting Standards (IFRS).

Within the "Human Rights Policies, Health and Safety, Training and Development" framework, KPO has amended internal documents to ensure compliance with labor legislation, Kazakhstan's Environmental Code, and ISO 26000 [96] guidelines. A Safety Management Center, involving all employees, was established to implement process safety fundamentals, enhance industrial safety protocols, and conduct regular training. The introduction of health, safety, and environmental protection cards facilitated the identification of 125 potentially hazardous incidents. In 2023, the lost-time injury rate for KPO and contractor employees was 0.05. The company allocated over $240 million for local workforce development between 1999 and 2023, including the introduction of the Udemy e-learning platform in 2023. Security systems undergo regular audits, with new technologies continuously integrated for risk monitoring and management [83].

The "Community Engagement, Stakeholder Engagement, Social Impact Investments" program maintains dialogue through advisory council meetings with residents, forums, conferences, public hearings, surveys, and audits. A direct communication channel with the company has been established, and KPO's social project portfolio is coordinated with regional authorities.

Social investment has increased from $10 million in 2012 to $30 million in 2023. Eighteen social infrastructure projects worth $43.2 million have been completed, including the construction of 13 schools, two sports complexes, a visitor center, and road repairs in the West Kazakhstan region.

KPO actively engages Kazakhstani suppliers and manufacturers in its development process. The local content indicator for procurement of goods, works, and services reached 63.24% ($756.1 million) in 2023. During 2022–2023, 30 contracts totaling $107 million were awarded to domestic companies for locally produced goods.

Since 1998, the company has financed over 250 social and infrastructure facilities. These social responsibility initiatives contribute directly and indirectly to reducing air pollution by fostering sustainable community development and enhancing operational accountability.

Table 3. Algorithm for implementing the "Social" component of KPO's ESG strategy to reduce air pollution Management risks.

Step of Algorithm	Essence/Meaning	Interaction	Frequency of Implementation	Management Level, Responsible Person	Management Risks
Employee Relations	Creating a sustainable and responsible company	Supply Chain; Labor Standards Labor Practices Human Rights Policies Supply Chain; Labor Standards	Constantly, annually within the framework of the SDR	The contractor's committee, which develops the company's sustainable development strategy, is responsible for senior management—the Managing Director of Human Resources.	Violation of workers' rights, lack of transparency leading to social conflicts
Diversity, Equity and Inclusion	Creating equal opportunities, social responsibility	Employee Relations Labor Practices Supply Chain; Labor Standards Stakeholder Engagement Human Rights Policies	Constantly, annually within the framework of the SDR	A contractor committee that develops measures for the company's development, including aspects of diversity and inclusion; the person in charge is senior management—the Managing Director of Human Resources.	Lack of employee engagement, reputational, financial, and legal risks
Labor Practices	Working conditions and workers' rights, Social responsibility	Employee Relations Supply Chain; Labor Standards Health and Safety Training and Development Human Rights Policies	Constantly, annually within the framework of the SDR	Occupational Health and Safety and Environment Working Groups, responsible person—HR Director, senior management—HR Managing Director	Violation of labor rights, unsafe working conditions leading to social conflicts
Community Engagement	Community engagement strengthens social ties and contributes to a better quality of life in the region	Labor Practices Social Impact Investments Human Rights Policies	Constantly, annually within the framework of the SDR	Stakeholder Engagement Committee, responsible person—senior management—Managing Director for Strategy	Ineffective communication and violation of regulatory requirements can lead to social conflicts and reputational risks
Supply Chain; Labor Standards	Sustainable supply chain practices help minimize negative environmental impacts	Human Rights Policies Community Engagement Social Impact Investments	Constantly, annually within the framework of the SDR	A special subcommittee responsible for the implementation of ESG strategies, including supply chain management and compliance with labor standards; the person in charge is senior management—the Director of Sustainability	Lack of personnel qualifications, economic, reputational, social risks
Human Rights Policies	Compliance with legal regulations, creating a sustainable and responsible business model	Human Rights Policies Community Engagement Social Impact Investments Labor Practices Employee Relations Diversity, Equity and Inclusion	Constantly, annually within the framework of the SDR	Sustainable Development Subcommittee (Senior Management: Director of Sustainable Development)	Violations of workers' rights and a lack of transparency can lead to reputational damage.
Health and Safety	Preventing accidents and ensuring safe working conditions	Employee Relations Training and Development Labor Practices	Constantly, annually within the framework of the SDR	Occupational Health and Safety and Environment Working Groups, responsible person—HR Director, senior management—HR Managing Director	Risks of industrial injuries, insufficient personnel training, non-compliance with standards, emergency situations, reputational
Training and Development	Improving the skills of employees and implementing broad sustainable development goals	Employee Relations Human Rights Policies Labor Practices	Constantly, annually within the framework of the SDR	The Sustainable Development Committee is responsible for the development and implementation of strategies, including employee training, and the person in charge is senior management—the HR Director.	Insufficient staff qualifications, low employee engagement, and lack of clear goals and metrics can lead to reputational risks.

Table 3. *Cont.*

Step of Algorithm	Essence/Meaning	Interaction	Frequency of Implementation	Management Level, Responsible Person	Management Risks
Social Impact Investments	Creating a sustainable and socially responsible business	Diversity, Equity and Inclusion Community Engagement Human Rights Policies Social Impact Investments	Constantly, annually within the framework of the SDR	The Social Affairs Committee is responsible for the development and implementation of social programs aimed at improving the living conditions of local communities and employees. The person responsible is senior management—Managing Director for Strategy/Deputy CEO.	Risks of failure to meet stakeholder expectations, lack of transparency, changes in legislation, financial and reputational risks
Stakeholder Engagement	Contributes to improving relations with key groups, helps the company effectively achieve its goals	Social Impact Investments Community Engagement Supply Chain; Labor Standards	Constantly, annually within the framework of the SDR	Committee responsible for interaction with interested organizations; responsible person—senior management—Managing Director for Strategy	Incomplete understanding of stakeholder needs, insufficient transparency, and lack of resources can lead to conflicts of interest and reputational risks.

An analysis of processes, case studies, and documentation related to KPO's corporate governance implementation and its impact on sustainable development highlighted the value of structuring these efforts using the proposed algorithm (Figure 1). This analysis resulted in the development of a corresponding action algorithm (Table 4).

Under the "Board Composition and Diversity, Executive Compensation" guidelines, KPO implements ESG best practices, including ensuring board independence and conducting regular performance assessments. The company adheres to principles of equal opportunity and non-discrimination, with all compensation, hiring, evaluation, and promotion decisions based on objective criteria such as merit, qualifications, and performance.

The "Stakeholder Rights, Ethics and Compliance Program" operates within the framework of applicable legislation and internal corporate procedures. By transparently disclosing emissions data and reduction progress in its ESG reporting, KPO enables stakeholders and interested parties to assess the strategy's effectiveness and its environmental impact.

Furthermore, adherence to business ethics, compliance with GRI standards, and the digital transformation of production and safety operations collectively contribute to reducing the company's environmental footprint. In accordance with "Risk Management Practices, Internal Control, and Audits," a systematic approach and continuous assessment are employed to develop optimal business strategies and manage organizational change.

KPO is continuously enhancing its methods for assessing environmental risks and incidents, including those related to oil spills and hazardous substances. The implementation of GRI standards facilitates a more structured approach to risk management. The "Goal Zero" principle underscores the company's commitment to personnel and environmental safety.

The company has launched an enhanced methane emissions monitoring program for 2024–2029, making transparent reporting a key priority. Internal audits are regularly conducted in high-risk operational areas. The ESG report is approved by the Company's Board of Directors and, during its preparation, is coordinated with members of the Sustainability Subcommittee representing the partner companies. Prudent resource management within a stable budgetary framework, aligned with strategic management approaches and sustainability targets, has become a cornerstone of corporate governance. An electronic procurement and work permit system was launched in 2024.

In line with "Corporate Policies and Procedures, Sustainability Integration," KPO is developing and implementing the "KPO-365 Business Strategy." This strategy integrates sustainable development principles into business operations, investment planning, and decision-making processes, supported by a comprehensive digitalization strategy and production forecasting using advanced analytical tools [20].

Table 4. Algorithm for implementing the "Governance" component of KPO's ESG strategy to reduce air pollution.

Step of Algorithm	Essence/Meaning	Interaction	Frequency of Implementation	Management Level, Responsible Person	Management Risks
Board Composition and Diversity	contributes to the improvement of corporate governance, increasing the sustainability and reputation of the company, compliance with modern requirements and expectations of stakeholders.	Stakeholder Rights Ethic and Compliance Program Corporate Policies and Procedures	annually or as part of strategic planning	The Board of Directors of the company, responsible person—senior management—Director of Sustainable Development	Lack of diversity in the boardroom, conflicts of interest, lack of transparency, and poor risk management can lead to ignoring different perspectives, which will negatively impact the company's strategy.
Executive Compensation	contributes to the improvement of corporate governance and the overall development of the company	Stakeholder Rights Sustainability Integration Ethic and Compliance Program	annually or as part of strategic planning	The Remuneration Committee is responsible for developing and implementing policies that link executive compensation to the achievement of ESG objectives; responsible person—senior management—Chief Sustainability Officer	Insufficient effectiveness of strategic and operational management may lead to non-compliance with established ESG goals and objectives, conflicts of interest, and reputational risks
Stakeholder Rights	Involvement of all stakeholders, including investors, employees, customers and local communities, in the process of developing and implementing an ESG strategy	Board Composition and Diversity Executive Compensation Ethic and Compliance Program	constantly	The Board of Directors ensures interaction with stakeholders, including investors, employees and local communities; the person responsible is the senior management of the company.	Lack of transparency can lead to mistrust from stakeholders, conflicts of interest, reputational and regulatory risks.
Ethic and Compliance Program	developing a corporate culture based on honesty and responsibility, ensuring the integration of ethical standards into business processes and contributing to the achievement of the company's environmental goals.	Board Composition and Diversity Stakeholder Rights Executive Compensation	annually or as part of strategic planning	The Board of Directors is responsible for the strategic direction and oversight of the Ethics and Compliance Program; the responsible person is the Chief Ethics and Compliance Officer.	Lack of clear and transparent reporting on compliance with regulations and standards can lead to a lack of trust from stakeholders, including investors and the public.
Risk Management Practices	Systematic identification and analysis of risks associated with environmental, social, and governance aspects.	Board Composition and Diversity Corporate Policies and Procedures Integral control and audit	annually or as part of strategic planning	The Board of Directors and specialized committees responsible for strategic direction and oversight of ESG initiatives	Environmental, social, corporate, regulatory risks

Table 4. *Cont.*

Step of Algorithm	Essence/Meaning	Interaction	Frequency of Implementation	Management Level, Responsible Person	Management Risks
Integral control and audit	the company's compliance with environmental regulations and standards, which is important for reducing air pollution and minimizing the negative impact on the environment	Risk Management Practices Corporate Policies and Procedures	annually within the framework of the SDR	The Sustainable Development Committee includes representatives from various departments to ensure a cross-functional approach to management; the responsible person is middle management (ESG managers), senior management (the Director of Internal Audit).	A lack of open data on a company's activities can make it difficult to prove its sustainability to investors and regulators, which can lead to greenwashing, loss of trust, and reputational risks
Corporate Policies and Procedures	form the basis for managing a company's ESG aspects, creating clear goals and standards that guide the company's actions in the area of sustainable development and air pollution reduction	Board Composition and Diversity Risk Management Practices Integral control and audit	Constantly	The Company's Board of Directors is responsible for strategic direction and oversight of ESG initiatives, including the development and implementation of corporate policies and procedures. Responsible person: Senior Management—Chief Sustainability Officer	Insufficient integration of ESG into business processes can lead to a discrepancy between the stated goals and the actual actions of the company, reputational and regulatory risks
Sustainability Integration	Integrating sustainability into a company's business strategy allows for environmental, social, and governance considerations to be taken into account when making decisions.	Board Composition and Diversity Corporate Policies and Procedures	annually within the framework of the SDR	The Board of Directors of the company, responsible person—senior management—Director of Sustainable Development	Reputational, financial, regulatory, operational risks

4. Modeling

In accordance with the adopted research methodology, the subsequent stage involved econometric modeling to explain variations in GHG emissions and to assess the impact of environmental, social, and governance factors on air pollution levels through a staged approach.

This process yielded three separate models for a single dependent variable—the volume of GHG emissions by enterprises. All generated indicators were consolidated into panel data series for the companies under study. Given the previously noted limitation of non-uniform ESG reporting requirements for the social (S) and governance (G) components, the number of independent variables collected for these dimensions was smaller than for the environmental (E) component (Table A1).

In the next step, the factors identified through regression analysis were integrated into a single aggregate regression model to assess the collective impact of oil and gas companies' ESG strategies on emission reductions. The results of the econometric modeling necessitated the evaluation of ESG factor influence using two distinct models: a comprehensive ESG model and a combined S + G model.

4.1. Modeling of GHG Emissions Based on Environmental Factors in the Oil and Gas Industry

A total of 16 factors (X1–16) were collected for the five companies covering the period from 2019 to 2023. This timeframe was selected because comprehensive sustainability reporting has been consistently compiled and published by companies for a relatively short duration, particularly considering the Sustainable Development Goals (SDGs) were adopted in 2015. It should be noted, however, that some companies have published reports in various forms significantly earlier. For example, Shell has formally reported on sustainability-related performance for over 25 years, aiming to maintain transparency regarding activities relevant to investors, governments, and civil society [21]. Nevertheless, disparities in the calculation and measurement methodologies for certain indicators made it feasible to generate systematic and comparable data only from 2019 onward.

During the model construction, explicit linear relationships (aliases) were identified:

X13 and X14 in KMG: close values—minimal difference → high multicollinearity → alias).
X1 and X2: In some companies, they move in parallel (correlation ≈ 1).
X6 and X7: At Shell, BP, and EniS.p.A, the indicators often move in sync (the same trend).
X9 and X10: The variables are "scaled," but proportional to each other.
X11 and X12: Often nearly proportional (all years rise/fall together).

Based on this, in order to obtain a reliable model, the following predictors were excluded from the equation: X2, X6, X10, X12, X14—they were the ones that caused the alias error when calculating vif ().

Rationale for this choice:

X2 is a strong duplicate of X1 → makes the X matrix undefined.
X6 and X7—in small samples, it is better to leave only one (X7 is more informative).
X10 is almost always linearly dependent on X9 (all observations are nearly proportional).
X12 is very close to X11 (a scale factor, duplicates).
X14 ≈ X13 (in some rows, the difference is 0 → complete collinearity).

After removing them, alias() will return an empty result, and vif() will be calculated without error.

The following results were obtained as a result of the transformations (Table 5):

Table 5. Results of the analysis of the linear dependence of predictors.

Independent Variable	Coefficient	Std.Error	z-Value	*p*-Value	Significance
Intercept	10.941	5.84	1.874	0.061	
X1 Volume of GHGs burned in flares	0.86	0.471	1.827	0.068	
X3 GHG intensities	−2.115	4.043	−0.523	0.601	ns
X4 Methane emissions	0.055	0.028	2.009	0.045	*
X5 Methane intensity	−9.115	4.744	−1.922	0.055	
X7 Compliance with Environmental Regulations	0.03	0.04	0.747	0.455	ns
X8 Nitrogen oxides (NOx)	0.0367	0.0101	3.64	<0.001	***
X9 Total energy consumption	−2.174	1.968	−1.105	0.269	ns
X11 Energy efficiency	−0.0039	0.00178	−2.188	0.029	*
X13 Total Waste Disposal	0.00253	0.00099	2.562	0.010	*
X15 Water Usage	−0.183	1.16	−0.158	0.874	ns
X16 Oil Spills and Environmental Incidents	0.0696	0.0175	3.974	<0.001	***

Note: * $p < 0.05$; *** $p < 0.001$; ns—not significant, and further the maximum levels of values are indicated (*—significant, ***—extremely significant, ns—not significant).

Of all the indicators, X8, X11, X13, and X16 turned out to be significant, and when testing for fixed and random effects, the Hausman test [97] determined that the model with random effects is more acceptable (Tables 6 and 7).

$$\hat{y} = 5.3807 + 0.05288 \cdot X_8 - 0.00637 \cdot X_{11} + 0.00261 \cdot X_{13} + 0.10166 \cdot X_{16} \quad (1)$$

Table 6. Results of the significance test of independent variables on environmental responsibility.

Independent Variable	Coefficient	Std.Error	z-Value	*p*-Value	Significance
Intercept	5.381	3.552	1.515	0.130	ns
X8—Nitrogen oxides (NOx)	0.0529	0.00222	23.804	$<2 \times 10^{-16}$	***
X11—Energy efficiency	−0.00637	0.00153	−4.164	<0.001	***
X13—Total Waste Disposal	0.00261	0.00084	3.125	0.0018	**
X16—Oil Spills and Environmental Incidents, volume	0.10166	0.01319	7.705	1.31×10^{-14}	***

Note: ** $p < 0.01$; *** $p < 0.001$; ns—not significant, and further the maximum levels of values are indicated (**—very significant, ***—extremely significant, ns—not significant).

Table 7. Results of the Hausman endogeneity test for environmental responsibility.

Model	R^2	Adj_R^2	Hausman Test
Reduced Model	0.99284	0.98678	0.99

The obtained results of regression modeling allow us to determine statistically significant factors influencing the volume of the GHGs. Coefficients expressed in terms of the original scales of the variables provide information about the direction and magnitude of the effect, but do not allow one to assess how sensitive aggregate emissions are to relative changes in each factor. Therefore, the next stage of the analysis was the calculation of elasticity coefficients, which allow us to interpret the influence of X-variables in percentage terms. This approach enables the transition from purely statistical conclusions to economically significant results, revealing the true scale of the impact of operational emissions, production load, waste volume, and accidents on GHG dynamics.

Elasticities are calculated using the formula

$$E_i = \beta_i \cdot \frac{\overline{X}_i}{\overline{Y}},$$

where $\overline{X}_i$ and $\overline{Y}$—average values of GHG factors and emissions for 2019–2023. Calculations have shown the following: a 1% increase Energy efficiency leads to a decrease in total GHG emissions by 1.73%; a 1% increase in NO_x emissions increases GHG by 0.008%; a 1% increase in waste volume increases GHG by 0.008%; a 1% increase in accidents leads to an increase in GHG by only 0.00009%.

The resulting regression model allows us to identify the influence of key factors X8, X11, X13, and X16 on the performance indicator and understand their uniqueness. To forecast future performance indicators, Holt's exponential smoothing model and the ARIMA model [98] will be used, as they allow for the trend and seasonality of time series.

In the next step, we apply RW + drift, the addition of which allows us to reflect the average annual decline. ARIMA models over short time periods can be sensitive to recent changes, so for conservative predictions, a random walk model with trend accounting is preferable.

Negative results should be considered a side effect of econometric analysis; to avoid their influence, the parameter "level = 0" is set and special attention is paid to the range of possible values rather than to a specific point.

Thus, using RW + drift with "level = 0" generates a conservative, replicable baseline for gradual reduction in cumulative emissions by 2030, which should be regularly updated as new data becomes available (Figure 5). The RW + drift model is based on recent data, taking into account that a new year may slightly shift the average rate of decline (Figure A1).

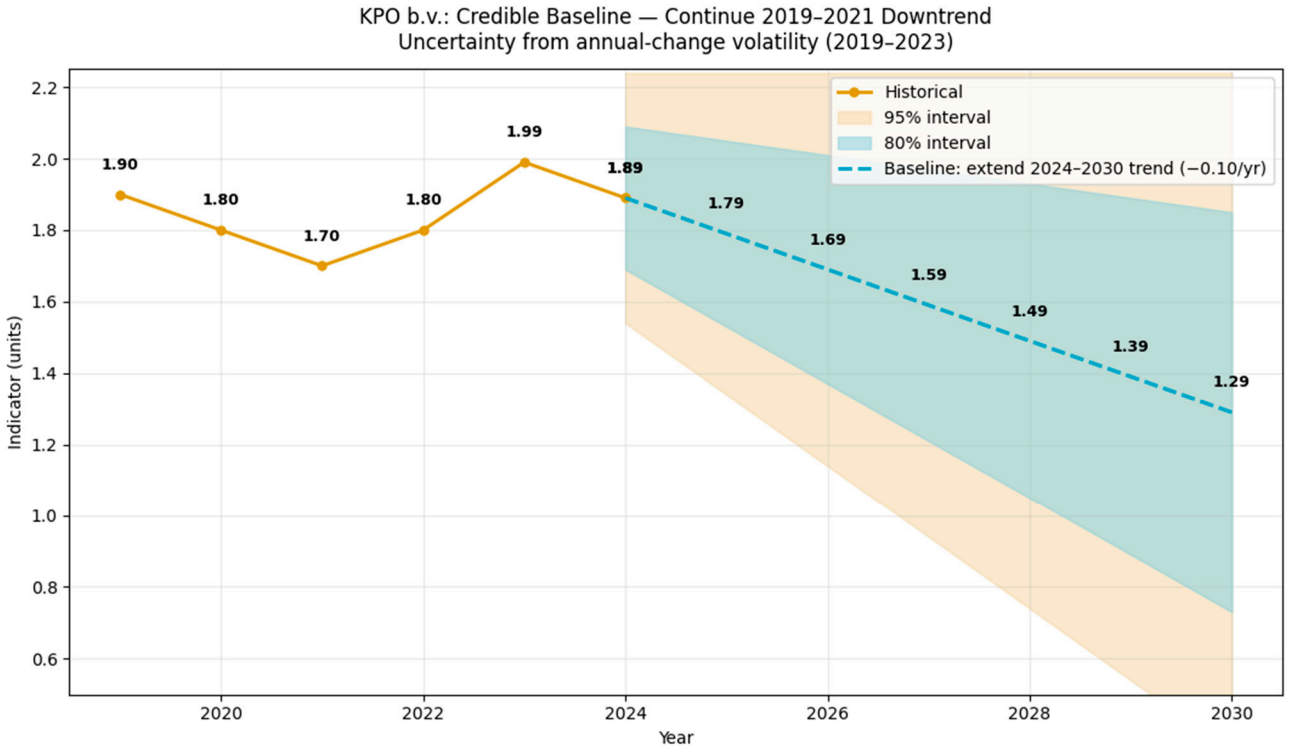


Figure 5. Forecasting RW + drift of GHG emissions at KPO (mil.t CO_2 equivalent) taking into account the impact of factors demonstrating the company's environmental responsibility. Note: constructed using R Studio 3.5.0.

As part of the study, an ARIMA (1,1,0) model was constructed for the time series of KPO's greenhouse gas emissions for 2019–2023. The Ljung–Box test [98] yielded a *p*-value of 0.5462, which significantly exceeds the critical significance level of 0.05.

This allows us to conclude that the model residuals do not contain statistically significant autocorrelation, and the model itself adequately describes the dynamics of the

original time series and can be used for forecasting. Analysis of the resulting forecast values for GHG emissions shows that, all other things being equal, the implementation of the KPO environmental strategy to reduce environmental pollution will lead to a reduction in emissions.

A review of forecasts for Shell, Eni S.p.A., BP, and KMG revealed the following. For Eni S.p.A., maintaining its ESG principles implementation approaches will result in a 13% reduction in pollutant emissions by 2030 (compared to 2023). Similarly, at Shell, we achieved a 70% reduction in emissions, and at BP, we are seeing a complete elimination of emissions and the achievement of complete decarbonization of oil and gas production technologies. For the Kazakh company KMG, the forecast model shows a 22% reduction in emissions. All these findings indicate that environmental management in oil and gas companies demonstrates varying levels of effectiveness, suggesting the value of studying the experiences of leading companies.

4.2. Modeling of GHG Emissions Based on Factors Demonstrating the Social Responsibility of Companies in the Oil and Gas Industry

A total of 11 (Xs1–11) factors were collected for five companies for the period from 2019 to 2023, demonstrating corporate social responsibility (Table A1). The results of the panel regression analysis are presented, including the coefficients for the independent factors, their corresponding errors, significance criteria, and probability (*p*-values). (Table 8):

Table 8. Results of the analysis of the linear dependence of predictors on the social responsibility of companies.

Independent Variable	Coefficient	Std.Error	z-Value	*p*-Value	Significance
Intercept	102.75	31.881	3.223	0.00127	**
Xs1 Occupational Safety count of accidents	10.166	9.989	1.018	0.309	ns
Xs2 Fatal accident rate	−0.362	1.357	−0.267	0.789	ns
Xs3 Training and Development	0.0325	0.021	1.549	0.121	ns
Xs4 Total Social Investments	−0.0379	0.0326	−1.162	0.245	ns
Xs5 Environmental investment	0.00948	0.00955	0.993	0.321	ns
Xs6 Investments in Biodiversity Conservation	0.484	0.41	1.181	0.238	ns
Xs7 Low carbon development	−0.00325	0.00162	−2.007	0.0448	*
Xs8 Diversity and Inclusion (women in the company)	−2.385	0.747	−3.194	0.00141	**
Xs9 Human Rights	−0.00168	0.00537	−0.312	0.755	ns
Xs10 Employee Satisfaction	−0.0965	0.1474	−0.655	0.513	ns
Xs11 Number of employees	-1.8×10^{-5}	0.000136	−0.134	0.894	ns

Note: * $p < 0.05$; ** $p < 0.01$; ns—not significant, and further the maximum levels of values are indicated (*—significant, **—very significant, ns—not significant).

According to the results of the analysis of the correlation matrix (Figure 6), the most pronounced positive relationship was recorded with the variables Xs4 (r = 0.81), Xs7 (r = 0.81) and Xs9 (r = 0.86), indicating a close relationship between emissions and these indicators.

A moderately positive correlation can be observed for Xs6 (r = 0.66), Xs8 (r = 0.60), and Xs11 (r = 0.56). In turn, variables Xs2, Xs3, Xs5, and Xs10 showed an insignificant or negative correlation with emission volumes, indicating a minor influence of these factors. It was also established that there are strong relationships between the independent variables themselves, such as Xs4–Xs7 (r = 0.81) and Xs8–Xs9 (r = 0.80), which can create a problem of multicollinearity when constructing regression models. After checking for multicollinearity, Xs7 (Low carbon development, Renewable Energy Investments) and Xs8 (Diversity and Inclusion (women in the company), %) were found to be significant

in the model. Furthermore, the Hausman test confirmed the use of the random-effects model (Tables 9 and 10).

$$Y = 94.3244368 - 0.0034038 \cdot Xs7 - 2.1699157 \cdot Xs8$$

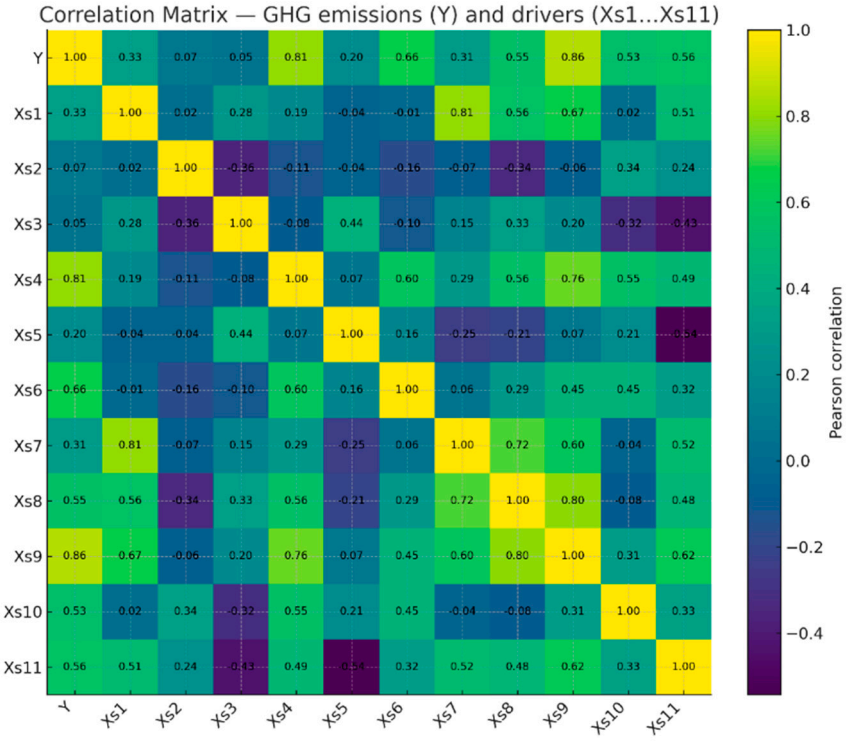


Figure 6. Pearson correlation matrix of pairwise coefficients between GHG emissions and social responsibility indicators of oil and gas companies. Note: constructed using R Studio 3.5.0.

Table 9. Results of the significance test of independent variables on social responsibility.

Independent Variable	Coefficient	Std.Error	z-Value	*p*-Value	Significance
Intercept	94.324	23.356	4.039	5.38×10^{-5}	***
Xs7—Low carbon development, renewable energy Investments	−0.0034	0.000834	−4.08	4.5×10^{-5}	***
Xs8—Diversity and Inclusion (women in the company)	−2.17	0.544	−3.99	6.62×10^{-5}	***

Note: *** $p < 0.001$, and further the maximum levels of values are indicated (*** $p < 0.001$).

Table 10. Results of the Hausman endogeneity test for social responsibility.

Model	R^2	Adj_R^2	Hausman Test
Reduced Model	0.80043	0.63156	0.98

To assess the practical significance of social and environmental development factors, an assessment of elasticity coefficients was carried out.

The results show that a 1% increase in low-carbon development investment (X7) leads to a 0.088% reduction in GHG emissions. This indicates the gradual and long-term impact of infrastructure investment on environmental outcomes. The most significant effect is demonstrated by the social indicator X8—the share of women in the company. The elasticity is −2.16, meaning that a 1% increase in the share of women reduces greenhouse gas emissions by 2.16% on average. This finding is consistent with research showing that inclusiveness and gender balance in management improve process safety, reduce the likelihood of accidents, and enhance the quality of operational control.

The results of the autocorrelation test are presented in Figure 7.

Surface visualization (Y = 94.3244368 − 0.0034038•Xs7 − 2.1699157•Xs8) Y = f(Xs7, Xs8) shows that the slope of the plane clearly indicates a negative influence of both factors. The red dots (real data) fit well on the theoretical surface, confirming the adequacy of the model.

Turquoise projections onto the Xs7–Xs8 plane allow us to see the distribution of factors without taking Y into account. Thus, a regression analysis of the impact of the ESG strategy of oil and gas companies in the context of their social responsibility on the reduction in GHG emissions showed that investments in renewable energy sources as a criterion for low-carbon development (Xs7) and the share of women in the company (Xs8) are significant.

Negative coefficient values for both variables indicate an inverse relationship: increased investment in renewable energy and increased representation of women in the workforce lead to a decrease in GHG emissions. The coefficient Xs7 = −0.0034 demonstrates that each additional investment in renewable energy sources is accompanied by an average reduction in GHG emissions by 0.0034 conventional units, which is a manifestation of the transition to production with a smaller carbon footprint.

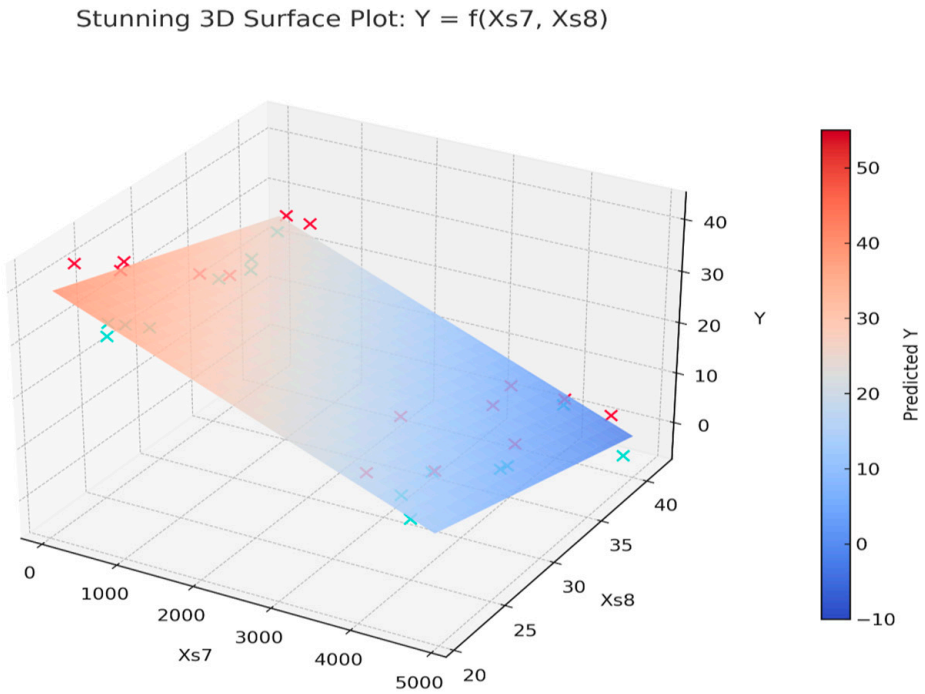


Figure 7. Results of autocorrelation testing of social responsibility indicators for oil and gas companies. Note: constructed using R Studio 3.5.0.

This is in line with the principles of sustainable development, where the introduction of innovative and environmentally friendly technologies helps to reduce the intensity of carbon use. The coefficient Xs8 = −2.1699 indicates that a one percent increase in the share of women leads to a reduction in emissions of approximately 2.17 units, which can be seen as a beneficial effect of gender diversity on environmental management performance.

4.3. Modeling GHG Emissions Based on Factors Demonstrating the Management Responsibility of Companies in the Oil and Gas Industry

As a result of the study, data were generated from ten indicators (X1–10G) characterizing the implementation of corporate governance principles of five enterprises in the period from 2019 to 2023 (Table A1). The results of the analysis conducted using the panel

regression method include data on the coefficients of influence of independent variables, as well as estimates of their errors, statistical indicators of reliability and *p*-values (Table 11).

Table 11. Results of the analysis of the linear dependence of predictors on the management responsibility of companies.

Independent Variable	Coefficient	Std.Error	z-Value	*p*-Value	Significance
Intercept	6.2276	21.4709	0.29	0.7718	ns
X1G Board Structure (Proportion of women	−0.0258	0.1362	−0.1894	0.8498	ns
X2G Transparency and Anti-Corruption Policy	−0.00395	0.01654	−0.2385	0.8115	ns
X3G—Corporate Ethics	0.15765	0.04931	3.197	0.00139	***
X4G Share of Economic diversification in Local development investments	0.19086	0.11264	1.6944	0.09019	
X5G Total amount of goods, works and services of local content	−0.01277	0.009746	−1.3105	0.19003	ns
X6G—Taxes	−0.58114	0.17463	−3.3278	0.000875	***
X7G Human Resource Management	0.41296	0.25318	1.6311	0.10287	
X8G Supplier engagement	0.00798	0.00983	0.8117	0.41694	ns
X9G Stakeholder Management System	0.00264	0.00782	0.3377	0.73557	ns
X10G Sustainability Strategy SDGs	0.15657	0.11821	1.3245	0.185	ns

Note: *** $p < 0.001$; ns—not significant, and further the maximum levels of values are indicated (***—extremely significant, ns—not significant).

The indicators X3G (number of violations of corporate ethics) and X6G (amount of taxes paid) were determined as the indicators (Tables 12 and 13).

Table 12. Results of the significance test of independent variables on management responsibility.

Independent Variable	Coefficient	Std.Error	z-Value	*p*-Value	Significance
Intercept	30.1626	15.2251	1.9811	0.04758	*
X3G—Corporate Ethics	0.14749	0.03262	4.5212	6.15×10^{-6}	***
X6G—Taxes	−0.52982	0.16327	−3.2451	0.00117	**

Note: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; and further the maximum levels of values are indicated (*—significant, **—very significant, ***—extremely significant).

Table 13. Results of the Hausman endogeneity test for managerial responsibility.

Model	R^2	Adj_R^2	Hausman Test
Reduced Model	0.76822	0.60266	0.99

The presence of coefficients of different signs allows us to identify two opposing influencing factors. First, the positive value of the X3G variable (0.1475) demonstrates that an increase in the number of business ethics violations leads to an increase in GHG emissions.

The presence of coefficients of different signs allows us to identify two opposing influencing factors. First, the positive value of the X3G variable (0.1475) demonstrates that an increase in the number of business ethics violations leads to an increase in greenhouse gas emissions.

This fact points to a link between corporate governance effectiveness and environmental performance. An increase in ethical violations indicates deficiencies in the internal control system, a lack of concern for the environment, and unclear corporate policies.

Thus, the study's results support the hypothesis that an organization's honest behavior is an indicator of its commitment to environmentally friendly development. On the other hand, the negative coefficient for X6G (−0.5298) indicates that increasing the amount of taxes paid leads to a reduction in GHG emissions.

The analysis of elasticity coefficients shows that corporate governance indicators have a significant impact on the environmental performance of companies. A 1% increase in corporate ethics violations leads to a 0.24% increase in GHG emissions, highlighting the

importance of a culture of corporate compliance in minimizing environmental risks. In contrast, a 1% increase in tax payments reduces emissions by 0.28% on average, reflecting the impact of institutional and regulatory incentives on corporate environmental responsibility.

This can be seen as a sign of financial discipline and corporate social responsibility: companies that meet their tax obligations on time tend to be more mindful of environmental issues and implement carbon footprint reduction technologies. Furthermore, full tax payment may indicate a high level of transparency and stability in company management, which is linked to environmental compliance.

The conducted principal component analysis (PCA) revealed that the corporate governance variables X1G–X10G collectively account for approximately 56.32% of the total variance—a robust result for a multidimensional set of factors. Among them, the X3G and X6G variables contribute most substantially to this explained variance.

The analysis demonstrates that corporate governance practices (the G aspect of ESG) directly impact companies' environmental performance.

Failure to comply with business ethics principles leads to an increase in environmental threats, while honest financial management (including tax issues) helps to reduce these risks. The proposed model indicates that ethical and open governance are important not only from a moral point of view, but also serve as economic and environmental factors for sustainable progress, strengthening the connection between the elements of Environmental and Governance in the context of ESG.

4.4. Modeling GHG Emissions Based on Factors Demonstrating the Integrated Impact of ESG Responsibility of Oil and Gas Companies

At the initial stage of the integration process, indicators identified as significant based on the component-by-component impact assessment were included in the model. A panel regression analysis revealed the overwhelming influence of the Environment group of factors, which largely offset the impact of Social and Governance (Table 14).

Table 14. Full Model. Results of the analysis of the linear dependence of predictors according to the integrated ESG model.

Independent Variable	Coefficient	Std.Error	z-Value	*p*-Value	Significance
Intercept	12.743	9.609	1.326	0.185	ns
X8—Nitrogen oxides (NOx)	0.0461	0.00549	8.397	<0.001	***
X11—Energy Efficiency	−0.0079	0.00172	−4.583	<0.001	***
X13—Total waste disposal	0.00272	0.00086	3.155	0.0016	**
X16—Oil spills	0.10795	0.02153	5.013	<0.001	***
Xs7—Renewable energy inv.	−0.00027	0.00035	−0.781	0.435	ns
Xs8—Women in company (%)	−0.11803	0.22847	−0.517	0.605	ns
X3G—Corporate ethics	0.00978	0.01049	0.932	0.351	ns
X6G—Taxes	−0.05641	0.0435	−1.297	0.195	ns

Note: ** $p < 0.01$; *** $p < 0.001$; ns—not significant, and further the maximum levels of values are indicated (**—very significant, ***—extremely significant, ns—not significant).

In addition to the traditional ordinary least squares (OLS) method, new regression analysis approaches were used to ensure the stability of the created model and identify the most determining factors: partial least squares (PLS) and LASSO regression.

The use of these tools helps to increase the reliability of conclusions by reducing the influence of multicollinearity between variables, and also helps to identify those parameters that have the greatest impact on the indicator under study.

According to the results of PLS and LASSO testing, only four main factors continue to have a significant impact on the amount of GHGs emitted.

This allows us to conclude that the analysis of the relationship between eight sustainability indicators—four environmental, two social and two governance-related—and GHG emissions, carried out within a single model, showed a significant impact mainly of environmental aspects.

To study in detail the nature of this influence, an independent model was developed, focusing exclusively on social and managerial factors.

This methodology is consistent with common principles of empirical analysis and is used in particular in the work of [99] to assess the stability of the obtained data (robustness check). Thus, according to experts, comparing the results obtained using full and simplified versions of the model helps determine the stability of the impact of individual parameters and avoid a situation where strong predictors obscure the effect of other variables.

This approach is common in studies addressing multicollinearity and factor dominance. In complex models [100,101] that incorporate ESG factors, environmental parameters often have the most significant and direct impact on emissions, which can obscure or mask the contribution of social and governance indicators. In fundamental works on the application of the LASSO method, this approach is explained through the application of the principle of model parsimony [102]. In his works, the selection of individual influencing parameters corresponds to sequential regression and regularization approaches, which strive to create the most concise and understandable structure.

According to methods for assessing mediation effects, within the framework of the ESG integration concept, governance and social aspects can influence environmental performance indirectly, but rather through organizational systems or internal company policies. The S+G model makes it possible to precisely measure this indirect effect [103]. Thus, the creation of an isolated model that includes social and governance variables allows us to assess the independent contribution of these factors to reducing greenhouse gas emissions. At the same time, it provides a detailed explanation of the ways in which they are impacted through management and social instruments. The construction of an S + G model allows for the mitigation of the overwhelming influence of environmental factors during the modeling process.

At the same time, this approach improves understanding of the model and provides greater clarity to scientific conclusions (Tables 15 and 16).

$$\hat{Y} = 75.2838 - 0.00195 \cdot Xs7 - 1.5542 \cdot Xs8 + 0.0822 \cdot X3G$$

Table 15. Results of the analysis of the linear dependence of predictors on the social and managerial responsibility of companies.

Variable	Coefficient	Std.Error	z-Value	*p*-Value	Significance
Intercept	75.284	23.772	3.167	0.00154	**
Xs7—Renewable energy inv.	−0.00195	0.00096	−2.033	0.0421	*
Xs8—Women in company (%)	−1.5542	0.574	−2.7075	0.00678	**
X3G—Corporate ethics	0.08223	0.03425	2.401	0.0164	*
X6G—Taxes	−0.24492	0.16967	−1.444	0.149	ns

Note: * $p < 0.05$; ** $p < 0.01$; ns—not significant, and further the maximum levels of values are indicated (*—significant, **—very significant, ns—not significant).

Table 16. Results of the Hausman endogeneity test for socio-managerial responsibility.

Model	R^2	Adj_R^2	Hausman Test
Reduced Model	0.71669	0.67622	0.99

The model shows that investments in low-carbon development (Xs7) have a negative impact on emissions, which is consistent with the expected effect of the transition to clean

technologies A higher proportion of women in a company (Xs8) is also associated with lower emissions, confirming the link between D&I and sustainable corporate behavior; an increase in the number of corporate code violations (X3G) increases emissions, reflecting a weakening of the control and compliance system.

At the next stage, the model was tested for heteroscedasticity of residuals and autocorrelation.

bptest(model_re)

studentized Breusch–Pagan test

data: model_re

BP = 3.5702, df = 3, *p*-value = 0.3118. The *p*-value confirmed the null hypothesis that there is no heteroscedasticity, and the constancy of variance is confirmed.

pbgtest(model_re)

Breusch–Godfrey/Wooldridge test for serial correlation in panel models

chisq = 4.9697, df = 5, *p*-value = 0.4196. In the autocorrelation test, the p-value also confirmed the hypothesis of no autocorrelations, which indicates that the model does not suffer from residual autocorrelation, meaning that its estimates are efficient and unbiased.

The reliability of the estimates of an econometric model requires checking its robustness to changes in the specification, sample structure, and method for calculating standard errors Since heteroscedasticity, intra-group correlation, and dynamic endogeneity issues often arise in corporate ESG research (Wintoki et al., 2012; Kim et al., 2025 [104,105]), the standard OLS estimation may be sensitive to the panel data format and small number of observations.

In this regard, to increase the reliability of the results, a series of robustness tests were carried out, including: a test for sensitivity to heteroscedasticity; firm-clustered standard errors—resistance to autocorrelation within companies.

The Breusch–Pagan test for heteroscedasticity did not reject the null hypothesis of equal error variance (BP = 3.5702; p = 0.3118), which confirms the absence of heteroscedasticity and the correctness of the assumption of constant variance. The Breusch–Godfrey/Wooldridge test for autocorrelation in panel models also revealed no significant effect of serial correlation (χ^2 = 4.9697; p = 0.4196). This means that the model does not suffer from residual autocorrelation, and therefore the resulting coefficient estimates remain efficient and unbiased.

Thus, the conducted diagnostic check shows that the model errors satisfy the key assumptions of panel regression, and the results themselves are robust to violations of the residual structure. The results of the endogeneity tests are included in Appendix B The diagnostics carried out show that there is no endogeneity for most of the variables of the E model. For the X8 and X16 indicators, a weak form of reverse causality is observed, which does not affect the interpretation of the results, since they are not used as instrumental or causal variables.

Despite the identified two-way relationship between the proportion of women (Xs8) and the outcome variable, such endogeneity is dynamic (feedback effect) rather than structural. The indicator Xs8 is an institutional characteristic of the company, formed by long-term social policy and not correlated with the individual effects α_i. Since the Hausman test confirms the validity of the random effects model, the inclusion of Xs8 does not violate the assumptions of RE and does not bias the coefficients. Thus, Xs8 is an acceptable regressor in the corporate sustainability model. The observed bidirectional causality between corporate ethics violations (X3G), tax payments (X6G), and the outcome variable does not indicate structural endogeneity. This dynamic relationship has been widely documented in leading corporate governance research (Wintoki et al., 2012 [104]). Governance indicators reflect stable institutional characteristics of the company, which

are formed by internal policies and do not correlate with individual effects α_i, which is confirmed by the Hausman test ($p \approx 0.98$). Therefore, the inclusion of X3G and X6G in the random effects model is methodologically correct, and the two-way causality reflects the real dynamics of management policies and the tax burden.

The ANOVA results confirmed that the environmental index significantly improves the quality of the model (F = 140.2; $p < 0.001$), while the social and governance indices do not show a statistically significant contribution after taking into account fixed effects. Taken together, the conducted tests indicate that the main empirical findings are robust to the choice of model specification and sample variations, which underscores the robustness of the identified leading role of environmental practices in reducing corporate GHGs (Table 17).

To quantify the marginal contribution of each ESG component to explaining the variance of the model, Shapley decomposition was performed (Figure 8).

These findings strongly support the dominant role of environmental factors in shaping the dynamics of corporate greenhouse gas emissions, while social and governance practices have a limited impact. This served as the basis for the development of an isolated S + G model aimed at identifying managerial and social channels of influence that are usually hidden against the background of the dominant environmental block.

The next step involved forecasting greenhouse gas emissions, taking into account socio-governance factors. To ensure methodological rigor and consistency in the study, the ARIMAX model was used, accounting for both the internal dynamics of the time series and the impact of controllable ESG factors. Unlike basic autoregressive models, ARIMAX integrates exogenous variables reflecting investments in low-carbon development, gender diversity, and corporate ethics, making the model more managerially realistic (Figures 9 and A2).

Table 17. The ANOVA results.

	sum_sq	df	F	PR(>F)
C(Company)	50.92451	4	8.605556	0.001271
C(Year)	6.701253	4	1.132422	0.383858
E_index	207.4344	1	140.2145	2.45×10^{-8}
S_index	0.91099	1	0.61578	0.446684
G_index	1.673532	1	1.131218	0.306874
Residual	19.2323	13		

The forecast presented in Figure 9 (model of the dependence of GHG emissions into the atmosphere on social and management factors of KPO activities) shows that according to the geometric interpretation of the linear trend of emission reduction, the trend slope angle is −10 over a 7-year period ($\tan(\alpha) = \Delta Y / \Delta X$; $\alpha = \arctan(-0.01714) = -0.9820$). From an econometric perspective, this amounts to 7% over a seven-year period, or an estimated 1% per year. Meanwhile, the forecast compiled for the KPO model of GHG emissions dependent on environmental management factors (Figure 5) shows a slope of almost 60 (−5.710), or a sixfold greater effect. From an econometric perspective, the reduction rate is 35% over a seven-year period, or 5% per year—five times higher. A geometric interpretation of the linear trend in emissions reduction is more accurate for management decision-making. This comparison once again confirmed the powerful impact of environmental management on reducing greenhouse gas emissions. However, it also demonstrated that measures to demonstrate ESG commitment within the social and governance component also have an impact.

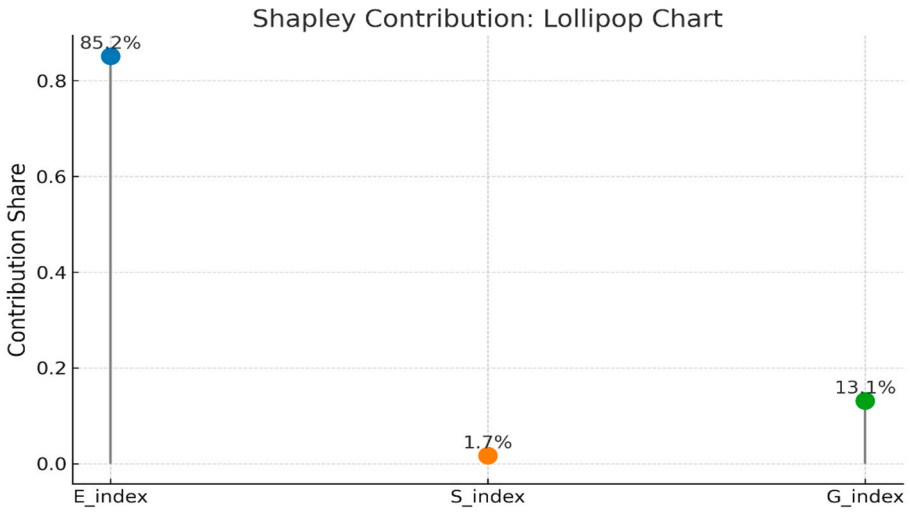


Figure 8. Shapley decomposition of ESG indices in explaining GHG emissions. The results show that the environmental index accounts for about 85% of the total explanatory power, while the social and governance indices contribute only 1.7% and 13.1%, respectively.

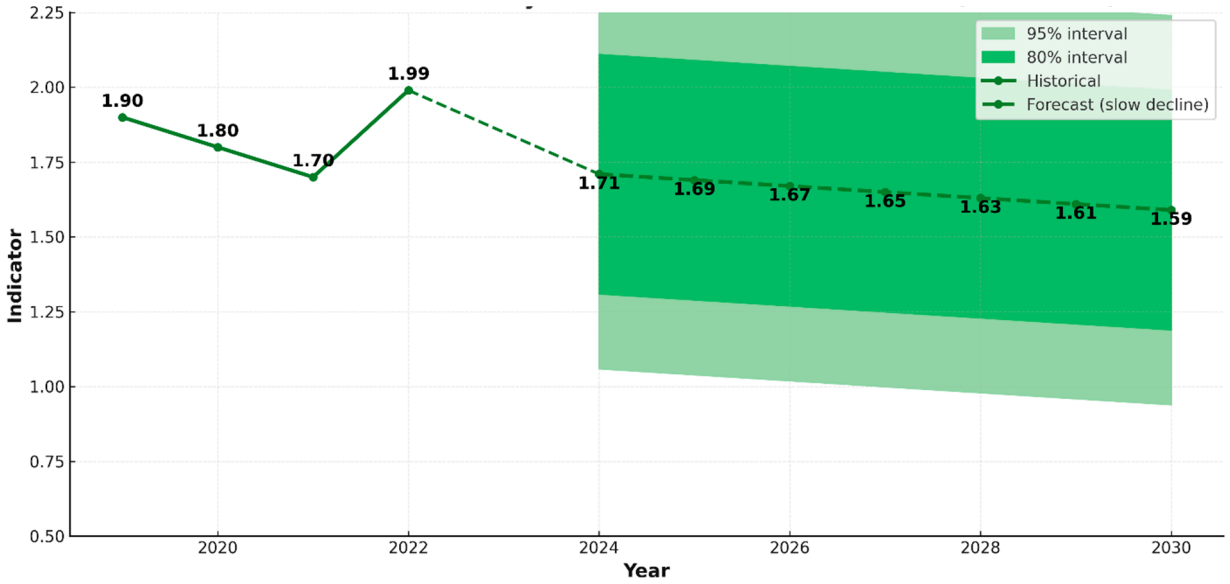


Figure 9. Results of forecasting GHG emissions (mil.t CO_2 equivalent) into the atmosphere based on the integrated S + G model for KPO. Note: compiled using R Studio 3.5.0.

Forecasts for other companies, compiled using the S + G model, are presented in Figure A2. Thus, the forecasted reduction in GHG emissions into the atmosphere from social and management factors of the activities of BP, Shell, and Eni S.p.A. is more effective than that of KPO Moreover, while Eni S.p.A.'s forecast for component E showed a 13% reduction, the integrated S + G model showed only an 8% reduction. Conversely, KMG's implementation of ESG principles in the social and governance responsibility components shows a greater impact on reducing atmospheric emissions—55% versus 22% for component E. The results are consistent with the findings of the IOGP Energy Efficiency Expert Group, which found that leading global companies such as BP, ExxonMobil and Shell are actively implementing various strategies to improve energy efficiency by investing in new technologies and innovations [15,106]. Clearly, KPO faces limitations in funding and access to modern foreign technologies, which may limit flexibility in applying international practices and technologies used in Western companies.

The overall conclusion indicates that the hypothesis put forward in the study has thus been tested and confirmed: the use of ESG principles in companies' activities contributes to the reduction in air pollution.

5. Suggestions for Improving the ESG Strategy for Reducing Atmospheric Emissions

The econometric analysis identified key ESG factors in the performance of oil and gas companies that contribute to addressing the important issue of maintaining air quality in the context of global climate commitments.

An empirical analysis of environmental, social, and governance (ESG) performance indicators yielded findings relevant to management recommendations. According to the analysis of the Environmental component, the relationship between energy consumption (X_8), the number of environmental deviations (X_{16}), and greenhouse gas emissions is direct, while water use (X_{11}) has an inverse effect: more efficient water use is associated with reduced emissions.

Hazardous waste disposal (X_{13}) shows a small but positive effect, consistent with the growth of industrial production and the need for efficient waste management. Such findings are confirmed by international studies: for example, ref. [107] found that reducing water losses and introducing energy-saving technologies significantly reduce GHG emissions in water supply and sanitation systems. The work [108] highlights the high energy costs of wastewater treatment processes, particularly aeration, and points to a direct link between reduced energy consumption and reduced emissions. Based on the model data and similar international studies, the following management recommendations can be formulated:

Implement programs to improve energy efficiency at enterprises, paying particular attention to areas with the highest consumption (e.g., resource provision, production, waste disposal). An important area is improving the rational use of water resources and improving wastewater treatment methods as part of sustainable development policies, which simultaneously reduce emissions and save resources. Now KPO is taking steps to improve energy efficiency, most notably through an innovative high-pressure gas re-injection system, which not only increases production volumes but also minimizes environmental impacts by achieving 99.94% associated gas utilization. To effectively manage waste at KPO in accordance with GRI standards, it is proposed to integrate AI-based waste monitoring systems with other corporate management systems, such as Enterprise Resource Planning (ERP) and supply chain management systems [109]. This will provide a more comprehensive understanding of the environmental impact of operations and improve reporting according to GRI standards. Furthermore, the use of Artificial Intelligence (AI) to analyze waste data will enable waste volume forecasting and the development of waste minimization strategies.

Continue improving the atmospheric air monitoring systems as part of the region's ESG strategy. As noted above, the system for industrial environmental monitoring of industrial emissions at KPO facilities is ongoing. Furthermore, it should be noted that the region has currently established a regional geoportal developed within the framework of the national scientific program, which serves as a key platform for integrating real-time environmental data into decision-making processes [110]. In addition, within the framework of the scientific program for Western Kazakhstan, a methodology for comparing Sentinel-5P/TROPOMI data and ground-based measurements was developed [111]. The patterns of formation of atmospheric air pollution at various levels in the region were studied based on an analysis of the features of the formation of the atmospheric mixing layer in the region under consideration, as well as scenarios for changes in atmospheric air quality. In the context of Compliance with Environmental Regulations, conducting

further systematic research at the KPO will help identify patterns in the distribution of pollutants in the atmospheric boundary layer and create a modern pollutant database using GIS technologies, allowing for the prediction of atmospheric air quality, taking into account the socio-economic development of the region. The results obtained can serve as a basis for subsequent modeling based on best international practices for the future.

To establish the objective impact of the deposit on biotic communities and agrocenoses, it is necessary to conduct comprehensive in-depth monitoring studies using GIS technologies. Current climate change trends require more frequent biodiversity monitoring in areas where oil and gas operations operate. Unlike the approach used at KPO, where satellite imagery is conducted once every ten years, it is recommended to conduct such surveys more frequently. Although the company has developed regulatory actions for sensitive coastal ecosystems and created a database of flora and fauna species, analysis has shown that the data has not yet been systematized, and the results are unclear. At the same time, there is a study whose results showed a high level of impact on living organisms [112]. Modern remote sensing technologies, including hyperspectral imaging and machine learning algorithms, allow for more accurate and effective analysis of ecosystem and biodiversity status, further necessitating more frequent surveys.

The data obtained for the assessment of the Social component is in harmonious agreement with global scientific research devoted to issues of social responsibility and sustainable development.

Considering that there is still no practical use of renewable energy sources at KPO and no significant investments in renewable energy sources are planned, it is proposed to increase funding for RES. The negative value of the coefficient for the variable X_7 indicates a genuine impact of the move towards a low-carbon economy, which is noticeable even with a small increase in the volume of "green" investments in total capital investments.

As numerous studies show [34,36,113–115], increasing funding for renewable energy sources stimulates the restructuring of production processes, the introduction of resource-saving technologies and the reduction in greenhouse gas emissions by companies. Thus, PwC, among the key trends influencing global oil and gas production, emphasizes the importance of switching to renewable energy sources to reduce atmospheric emissions. Therefore, companies must balance traditional operations with increasing investment in low-carbon technologies. In the context of increasing investment in renewable energy sources, biogas production from agricultural raw materials in the West Kazakhstan region (the total volume of agricultural waste in the West Kazakhstan region was 162,200 tons per year) at KPO appears entirely feasible, given the availability of suitable resources and the growing interest in renewable energy sources. This will provide significant potential to generate economic benefits by complementing existing energy sources and reducing the region's dependence on electricity imports from Russia and improve the environmental situation.

In terms of the Governance component, it is recommended to increase the representation of women among the organization's employees, since the impact of the social aspect—the representation of women among KPO employees—demonstrates a significant and inverse correlation. An analysis of the application of ESG principles [116,117], according to scientific data [118–120], shows that women's participation in corporate governance and decision-making increases attention to environmental issues, stimulates the creation of an ethical management style and optimizes resource consumption. This indicates that gender diversity can be considered not only as an important social factor, but also as a significant element influencing environmental stability.

Furthermore, the inverse relationship between the size of tax payments and the level of pollution obtained in the study demonstrates that financial honesty and transparency

are key indicators of business environmental awareness. The negative value of the coefficient for the tax payments indicator (−0.5298) indicates that further improvement of corporate governance and openness of the information provided is necessary. This finding is consistent with a number of studies that show that financial integrity and transparency have a positive impact on emissions reduction, while non-compliance with business ethics standards is associated with increased environmental threats and deterioration in the performance of internal control systems. This trend is supported by studies [121–126] (indicating that ineffective corporate governance and limited information transparency exacerbate carbon footprints and negatively impact organizational image. Emissions and corporate ethics are interrelated in the context of ESG analysis, where compliance with ethical standards and emission reduction are key factors for achieving sustainable development and enhancing a company's reputation. This is consistent with the principles of good governance, according to which compliance with tax legislation is a sign of maturity of management practices, accountability and a high level of trust in institutions.

Research shows that companies with high levels of emissions often experience downgrades to their ESG scores. This is because pollutant emissions can be perceived as a breach of social and environmental responsibility, negatively impacting the company's reputation and sustainability scores [127]. Research by the OECD (2023) and the World Economic Forum (2023) [122] highlights the link between tax transparency and sustainable business development, as organizations operating within the legal framework are more likely to invest in emission reduction technologies and publish ESG reports.

Companies that engage in ethical violations typically have little interest in implementing environmental responsibility measures and sustainable development strategies. Violations of corporate ethics, such as insufficient transparency in emissions reporting or disregard for environmental regulations, can lead to legal consequences and fines. This can also impact the company's perception among investors and consumers, which in turn affects its ESG ratings.

6. Discussion

In summary, this research primarily contributes by articulating how ESG performance impacts emissions reduction and decarbonization in the oil and gas industry. ESG will undoubtedly be a focus for many energy companies' future strategies. Further research should expand the scope to include various production types and geographic locations. Studying diverse production sectors will provide a holistic understanding of how ESG performance impacts emissions reduction across different operational contexts.

The study presents a systematic analysis of the effectiveness of ESG strategies for reducing emissions and their relationship to the socioeconomic aspects of the region, enabling the proposal of effective solutions tailored to local realities. The hypothesis that implementing ESG principles in company operations contributes to reducing regional air pollution has been confirmed. Using KPO as a case study, this paper analyzes for the first time the impact of ESG initiatives in Kazakhstan's oil and gas industry within the context of spatial pollution distribution, comparing these indicators with international trends. This choice is justified by KPO being one of the largest emitters in the country and among the first in Kazakhstan to implement ESG principles.

Our study features a comparative analysis of the company's air emissions with regional data from KazHydromet, enabling assessment of the company's actual results against its regional impact. A key scientific contribution is the comparative evaluation of KPO's emissions reduction efforts with those of leading global and Kazakhstani oil and gas companies, alongside recommendations for reducing emissions based on economic and geospatial conditions.

The study highlights the interdependence of technological and social aspects in transitioning to a low-carbon economy, confirming the importance of integrating environmental and social elements of ESG into a unified strategic sustainability planning system. This approach helps mitigate both reputational damage and negative environmental impacts.

Analysis of the obtained results indicates that to reduce their carbon footprint, companies should: increase funding for RES and energy efficiency technologies; improve ESG management by implementing equitable corporate practices and supporting women's leadership in environmental projects; and incorporate social and environmental criteria into company and regional development plans to achieve emissions reductions and ensure long-term progress.

Unlike leading global oil and gas companies, KPO currently has no practical RES implementation and has announced no immediate plans for significant renewable energy investment. For example, companies like Shell, Eni S.p.A and BP are actively investing in renewable technologies [128,129]. BP has announced intentions to reduce fossil fuel dependence and increase renewable energy investment, resulting in improved environmental performance, operational efficiency, and financial results [67]. The authors [130] emphasize that European governments can enhance green technology innovation through increased investment. China is also actively developing green finance, with green loans reaching approximately $3.94 trillion as of 2023 [77].

Financing constraints may impede implementation of proposed measures. However, governments can play a key role in stimulating ESG adoption through various mechanisms, including taxes, subsidies, and public procurement. Tax incentives for companies actively implementing ESG practices and subsidies can significantly assist ESG initiatives. Additional financial resources include grants from international institutions like the EBRD, which actively supports sustainable development projects [131,132].

Comparative analysis revealed that for training employees in emission-reduction technologies, KPO could adopt Shell's approach of collaborating with Udacity for digital AI training, which helps optimize processes and reduce carbon footprint [133].

Women's representation on KPO's board does not exceed 33–40%. Analysis of successful gender equality practices at international companies and this study's results demonstrate that gender diversity in management improves carbon disclosure. Women in leadership positions tend to be more open to environmentally friendly practices and more sensitive to sustainability issues [119]. Other studies indicate that having at least three women on boards significantly enhances environmental decision-making and reduces CO_2 emissions, attributed to women's higher moral sensitivity and greater support for environmental initiatives [120].

The Governance component findings are valuable for improving sustainability management strategies in both corporate and government contexts. The identified correlation between ethical standard non-compliance and increased emissions underscores the importance of strengthening compliance measures, establishing internal control functions, and developing corporate social responsibility policies. When assessing ESG indicators and developing government incentive programs, tax compliance should be considered as evidence of responsible business conduct. The study confirms that effective corporate governance directly impacts environmental awareness, necessitating a shift from formal ESG declarations to comprehensive management tools promoting responsibility and transparency.

To improve corporate governance and attract investment, introducing mandatory standardized ESG reporting according to GRI in Kazakhstan will enable companies to better assess and report their environmental, social, and governance impacts. This will contribute to more sustainable business development and enhanced international competi-

tiveness [134,135]. As noted, the absence of unified perspectives on S and G components creates analytical and comparative assessment challenges.

Several approaches to unifying S and G reporting exist, based on current ESG trends and recommendations. One approach involves developing unified standards using international frameworks like GRI and SASB, which already offer disclosure frameworks [136]. Another approach integrates ESG into corporate strategies while leveraging technologies like AI and data analytics [137].

Further research on pollutant emissions and their environmental impact in the region could explore several key areas. In-depth monitoring studies are needed to establish the objective impact of KPO operations on biotic communities and agrocenoses. Comprehensive regional environmental assessment requires not only ground-based methods but also modern geospatial and aerospace technologies enabling dynamic assessment, modeling, and forecasting based on global best practices. In-depth analysis of spatiotemporal CO_2, PM2.5, and SO_2 emission dynamics using high-precision modeling methods that account for spatiotemporal changes and economic factors is essential. Developing models evaluating pollution reduction mechanism effectiveness, such as carbon taxation and renewable energy incentives, is equally important.

The study encountered limitations related to varying time periods in company sustainability reports, resulting in 2019–2023 being the most acceptable uniform period for all five companies. Furthermore, GRI standards were implemented in different years for each company, and integrated reporting requirements within ESG frameworks remain under development. It should be noted that sustainability reports lack rigid structural regulations, allowing companies freedom in data presentation formats.

The models could not account for variables such as production volume changes, oil and gas price fluctuations, government regulations (e.g., emission quotas), and technological changes (e.g., new equipment purchases), as these data were not fully available across all companies. Current ESG business practice generally shows that E criteria requirements are standardized, while no unified perspective exists for S and G indicators, undoubtedly creating difficulties in their analysis, comparative assessment, and interpretation.

The limitations in the availability of ESG data defined a key characteristic of this study's methodology. In line with other research, our study has demonstrated the applicability of the ARIMA model for analysis using short data samples. According to the Box–Jenkins methodology [138], the limited length of the time series is not an obstacle to the application of ARIMA models. The book emphasizes that the method is particularly useful for short non-seasonal series when structural patterns cannot be identified. When identifying ARIMA, it is not the number of observations that is important, but rather the fulfillment of key conditions: stationarity after differentiation and the absence of autocorrelation in the residuals. Also, the Box-Jenkins book explicitly states that the time series methodology is focused on short-term forecasting: "forecasting is primarily concerned with accurately predicting short-term future values of a series." In the present study, the Ljung–Box test ($p = 0.5462$) confirmed that the model residuals are white noise, which meets the Box–Jenkins ARIMA adequacy criteria and proves the validity and applicability of the methods used in the study.

7. Conclusions

1. This article presents a relevant study on implementing ESG strategies to reduce emissions in an industrial region of Kazakhstan. The study focuses on the Karachaganak oil and gas condensate field, selected because spatial analysis identified it as a primary source of atmospheric pollution in the region. To ensure systematic and objective analysis, KPO's indicators, along with its plans for achieving sustainable develop-

ment goals, key trends, and ESG implementation challenges, were benchmarked against leading global oil and gas companies—Shell, Eni S.p.A., and BP—and the Kazakh company KMG. This comparative approach aligns with current trends in international research.

2. This paper proposes a novel methodology for assessing ESG initiatives in Kazakhstan's oil and gas industry. Its contribution lies in developing a comprehensive approach to ESG emission analysis that incorporates the spatial distribution of emission sources. The study holds practical significance by examining the oil and gas sector—a cornerstone of the national economy—and evaluating the impact of ESG initiatives on air pollution reduction. Implementing a tailored ESG strategy in the region represents a promising pathway for effective emission reduction, decarbonization, sustainable natural resource management, and the transition to a green economy. The paper provides specific recommendations for oil and gas companies to reduce atmospheric emissions.
3. Econometric modeling was employed to identify relationships between ESG indicators and air pollution reduction. A piecewise approach was used to isolate key factors influencing emission reductions. Integrating all factors into a single model revealed the dominant influence of environmental factors. Consequently, following methodologies in similar studies, social and governance factors were integrated into a combined model, while environmental factors were assessed independently. Correlation and regression analysis demonstrated a strong relationship between emission volumes and specific E-factors (Total Energy Consumption, Water Usage, Hazardous Waste Disposal, Compliance with Environmental Regulations), S-factors (Investments in Renewable Energy, Gender Representation), and G-factors (Corporate Ethics as measured by Code of Conduct violations, Tax Compliance).
4. Compared to KPO, the other companies studied have a longer history of ESG implementation, which is reflected in the modeling results. In the integrated S+G model for these companies, these factors contribute significantly more to emission reductions than those at KPO b.v. This indicates that ESG principles hold substantial potential to help countries meet their commitments under the Paris Agreement. Furthermore, in contexts where environmental factors—despite their dominant role—face limitations (technological, financial, or geographical), robust social and governance criteria can significantly contribute to achieving decarbonization targets.
5. A significant finding of our study is the constraint posed by the limited ESG information base. Although oil and gas companies generally demonstrate high transparency and can be considered highly accountable, their sustainability reports vary considerably in content and reported indicators. Established practice in Sustainability Development Reporting (SDR) for oil and gas and other High-Polluting Enterprises (HPE) shows that Environmental (E) criteria are standardized, with data comparable across reporting periods, units of measurement, and calculation methodologies (e.g., greenhouse gas emissions, net carbon intensity, energy intensity, waste disposal). In contrast, no unified framework exists for Social (S) and Governance (G) indicators, creating substantial difficulties in their analysis, comparative assessment, and interpretation.
6. The experience of KPO can be extrapolated to other countries, as oil and gas companies globally face similar challenges related to air pollution. The study's findings provide compelling evidence to support further research into implementing ESG strategies for air pollution reduction, not only in Kazakhstan but also in other oil-and-gas-producing regions worldwide.

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Appendix A

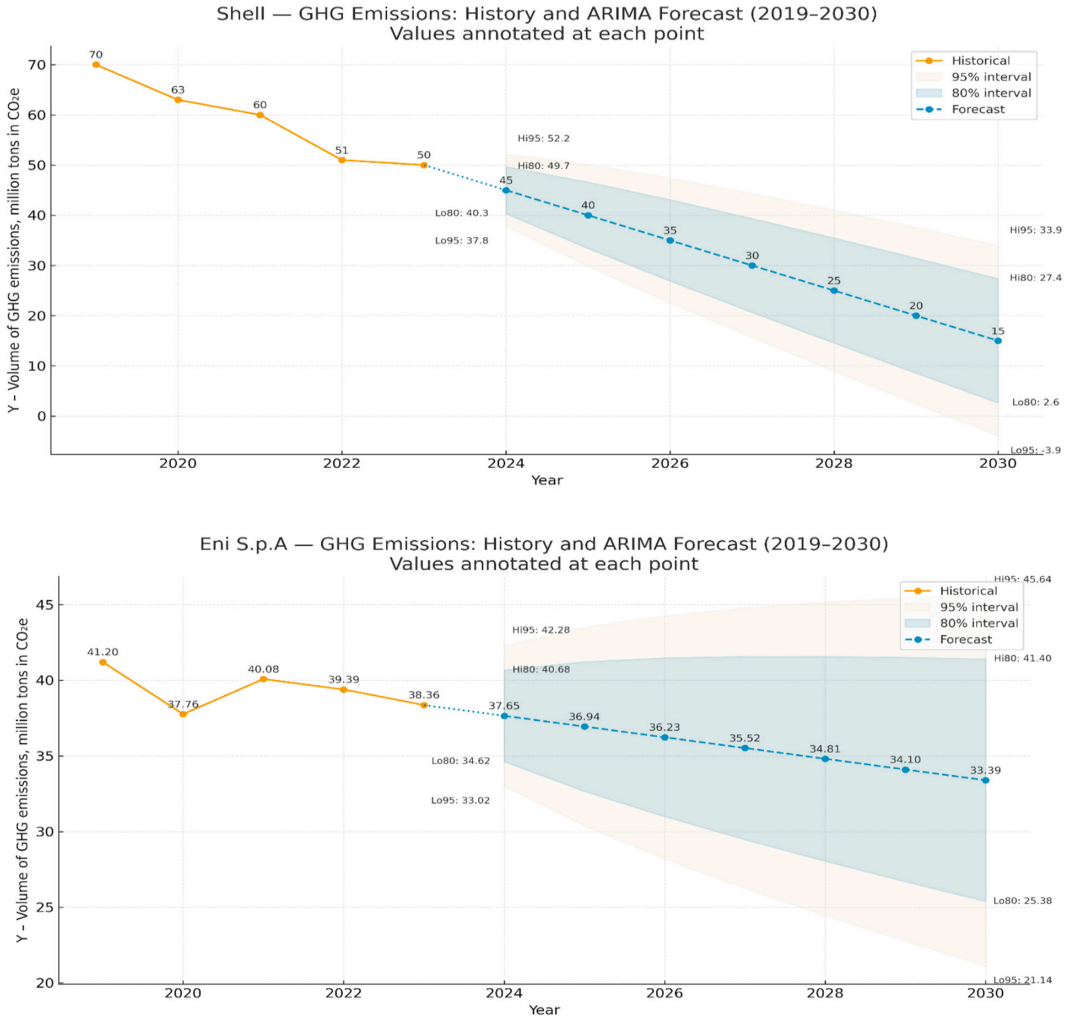


Figure A1. *Cont.*

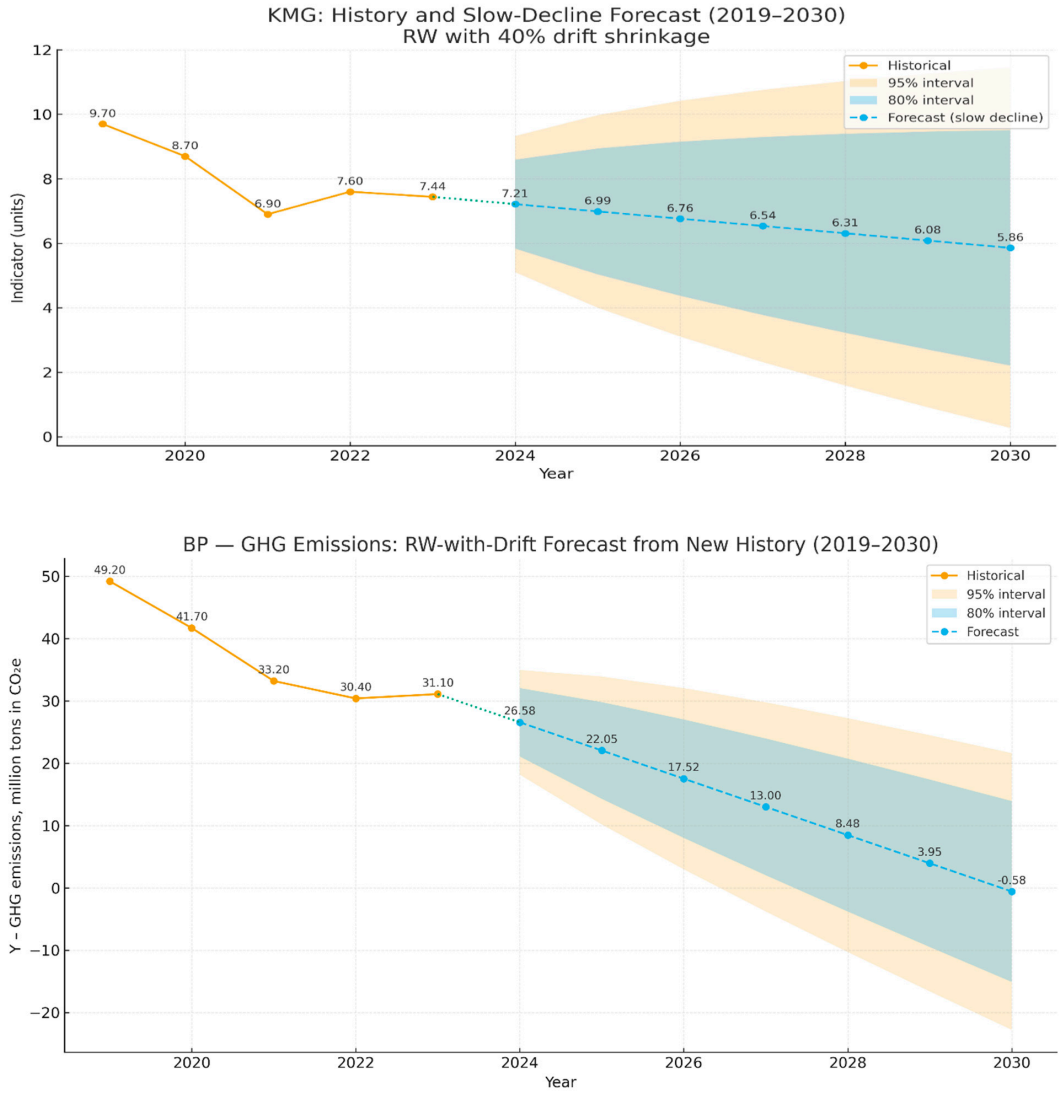


Figure A1. RW + Drift Forecasting of GHG Emissions (mil.t CO_2 Equivalent) Taking into Account the Impact of Factors Demonstrating the Environmental Responsibility of Oil and Gas Companies. Note: Constructed using R. Studio 3.5.0. Doted line shows trends for the next period till 2030.

Table A1. Environmental, Social and Corporate Responsibility Indicators Derived from Sustainability Reports and Annual Reports of Oil and Gas Companies.

No.	Environmental X1–16	Social Xs1–11	Governance X1–10G
1	Volume of GHGs burned in flares, mil.t CO_2 equivalent, refers to the total amount of GHGs that are emitted as a result of burning gas in flare systems, measured in million metric tons of carbon dioxide equivalent (mil.t CO_2e).	Occupational Safety count of accidents (LRIT) per 1 million hours refers to a specific metric used to measure workplace safety, specifically the Lost Time Injury Frequency Rate (LTIFR).	Board Structure (Proportion of women), %, refers to the percentage of board seats held by women compared to the total number of board seats.
2	Carbon Footprint Reduction = net carbon intensity, gCO_2e/MJ—the amount of GHGs (in grams of CO_2 equivalent) produced per megajoule of energy consumed or produced.	Fatal accident rate (FAR), Number per 100 million hours, expressed as the number of fatalities per 100 million hours worked	Transparency and Anti-Corruption Policy, count, refers to the number of reported incidents, violations, or compliance activities related to these policies. This can include instances of corruption, breaches of ethical conduct, or failures to adhere to transparency standards
3	GHG intensities, t CO_2e/t production, refers to the measurement of GHG emissions expressed in tonnes of carbon dioxide equivalent per tonne of production	Training and Development, H, refers to structured programs and initiatives aimed at enhancing employees' skills, knowledge, and performance in their current roles while preparing them for future opportunities	Corporate Ethics (Code of Conduct violations), count, refer to instances where employees or board members fail to adhere to the established ethical guidelines and policies set forth by an organization.

Table A1. *Cont.*

No.	Environmental X1–16	Social Xs1–11	Governance X1–10G
4	Methane emissions, thousands t—refers to the measurement of methane emissions quantified in thousands of tons	Total Social Investments, mil. USD, refer to the comprehensive sum of resources that organizations allocate towards social initiatives	Share of Economic diversification in Local development investments, %, refers to the percentage of total investments that are specifically directed towards initiatives aimed at diversifying the local economy within local development efforts.
5	Methane intensity, %, refers to the measurement of methane emissions expressed as a percentage of the total amount of natural gas produced or marketed	Environmental investments, mil USD, refer to the allocation of financial resources towards projects, companies, and initiatives that aim to achieve positive environmental outcomes.	Total amount of goods, works and services of local content, mil. USD, quantifies the financial value of all goods, services, and labor that are procured locally
6	Sulfur oxides (SOx), thousand t, refers to the measurement of sulfur oxides emissions quantified in thousands of metric tons.	Investments in Biodiversity Conservation, mil.USD, refer to the financial resources allocated towards activities and projects designed to protect, restore, and maintain the variety of life on Earth	Taxes, bil.USD—it indicates the total amount of tax revenue collected by a government, measured in billions of U.S. dollars
7	Compliance with Environmental Regulations, count, refers to the numerical measurement of how many instances or occurrences of compliance activities have been recorded within a specific timeframe.	Renewable Energy Investments (Low carbon development), mil.USD, refer to the financial resources allocated towards the development, installation, and maintenance of renewable energy technologies.	Human Resource Management (employee level of staff turnover),%, refers to the rate at which employees leave an organization over a specific period, which can include both voluntary departures (resignations) and involuntary separations (terminations)
8	Nitrogen oxides (NOx), thousand t., refers to the measurement of nitrogen oxides emissions quantified in thousands of metric tons.	Diversity and Inclusion (women in the company), %, refers to the proportion of female employees relative to the total workforce	Supplier engagement (suppliers with criticalities/areas for improvement), count, typically reflects the number of suppliers that are involved in the supplier engagement process.
9	Total energy consumption (millions of GJ) refers to the overall amount of energy consumed, measured in millions of gigajoules (GJ).	Human Rights reports to the Global Helpline, count, refers to the total number of reports or cases submitted to the Global Helpline over a specific period.	Stakeholder Management System, grievances, count, refers to the total number of complaints or issues recorded within the system.
10	Volume of production, thousand t, refers to the total quantity of goods produced, measured in thousands of metric tons (t).	Employee Satisfaction, %, represents the proportion of employees who express contentment with their jobs and work environment	Sustainability Strategy SDGs (the overall weight of the sustainability goals), %, refers to the relative importance or impact of each SDG within a sustainability strategy, expressed as a percentage
11	Energy efficiency, GJ/t—this metric is used to quantify the amount of energy consumed to produce one ton of a product	Number of employees, count, refers to the total number of individuals employed by a company at a given time	
12	Hazardous Waste disposal, thousand t., refers to the total amount of hazardous waste that is disposed of, measured in thousands of tons.		
13	Total Waste Disposal, thousand t., refers to the total amount of waste that is disposed of, measured in thousands of tons.		
14	Non-hazardous waste disposal, thousand t, refers to the total amount of non-hazardous waste that is disposed of, measured in thousands of tons.		
15	Water Usage, Million m^3, refers to the total volume of water consumed or utilized, measured in millions of cubic meters (m^3).		
16	Oil Spills and Environmental Incidents, volume, thousand t./count, indicates the total amount of oil spilled, measured in thousands of tons or the number of oil spill incidents recorded within a specific timeframe		

Appendix B. Testing Variables for Endogeneity

1. A rigorous endogeneity test was conducted for each of the ESG variables included in the three estimated models. Two reverse causality tests were performed:

ESG(t − 1) → Y(t)—testing the impact of ESG lags on current values of the performance indicator Y.

Y(t − 1) → ESG(t)—testing the impact of Y lags on current ESG values.

Both tests were performed using company-level panel lags, and the tests were conducted separately for each ESG block.

The results show the following:

For variables X11 (Energy efficiency) and X13 (waste disposal), the hypothesis of reverse causality is rejected in both directions ($p > 0.48$), confirming the absence of endogeneity—these factors are exogenous and can be correctly used in the model.

Variables X8 (NOx emissions) and X16 (incidents and oil spills) exhibit bidirectional causality ($p < 0.001$), suggesting a possible weak form of endogeneity. This article now includes a discussion of this finding and explains the reason: these ESG indicators interact dynamically with the company's current environmental performance.

The obtained test results do not affect the main interpretation of the results, since significant endogenous indicators are not used as causal inferences, but are of a descriptive nature.

Endogeneity and Reverse Causality Testing

Since some ESG detection indicators can be combined with the Y outcome, endogeneity diagnostics were conducted using reverse causality tests in the spirit of the Granger test. The methodology included two single-factor regressions for each ESG indicator:

$$Y_{it} = \alpha + \beta \cdot ESG_{i,t-1} + \varepsilon_{it} \quad \text{(A1)}$$

It is tested whether the ESG lag explains the change in Y.

$$ESG_{it} = \gamma + \delta \cdot Y_{i,t-1} + \eta_{it} \quad \text{(A2)}$$

It is checked whether the past value of Y influences ESG.

All regressions use company-level panel lags, which eliminates data overlap and improves the accuracy of comparisons.

The diagnostics conducted show that endogeneity is absent for most model variables. For the X8 and X16 indicators, a weak form of reverse causality is observed, which does not affect the interpretation of the results, as they are not used as instrumental or causal variables.

Table A2. Testing reverse causality and endogeneity diagnostics of the E indicator.

E Indicator	Direction	Coefficient	*p*-Value	Endogeneity
X8 (NOx) Nox emissions	X8(t − 1) → Y(t)	0.0709	<0.001 ***	Yes
	Y(t − 1) → X8(t)	14.003	<0.001 ***	Yes
X11 (Energy efficiency)	X11(t − 1) → Y(t)	0.0059	0.482	No
	Y(t − 1) → X11(t)	3.692	0.482	No
X13 (Total Waste Disposal)	X13(t − 1) → Y(t)	0.004	0.707	No
	Y(t − 1) → X13(t)	1.553	0.707	No
X16 (Oil Spills and Environmental Incidents)	X16(t − 1) → Y(t)	0.5016	<0.001 ***	Yes
	Y(t − 1) → X16(t)	1.2938	<0.001 ***	Yes

Note: *** $p < 0.001$; and further the maximum levels of values are indicated (***—extremely significant).

The table is based on a Granger causality test applied to panel data (5 companies × 5 years). For each ESG indicator, a pair of single-variable models were estimated:

$$Y(t) = \alpha + \beta \cdot X(t - 1) + \varepsilon$$

$$X(t) = \alpha + \beta \cdot Y(t - 1) + \varepsilon$$

Hypothesis H_0 is tested: "past values of a variable do not contain information to predict another variable."

Rejection of H_0 at $p < 0.05$ is interpreted as dynamic endogeneity.

Variables without endogeneity:

X11 (Energy efficiency): $p = 0.48$ in both directions.

X13 (Total waste disposal): $p = 0.71$ in both directions.

These indicators can be considered exogenous and are correctly included in the regression models.

Variables with possible endogeneity:

X8 (NOx emissions): $p < 0.001$ in both directions.

X16 (oil spills and incidents): $p < 0.001$ in both directions.

Bidirectional causality is observed. This is typical for a company's environmental performance: deterioration in environmental performance affects the level of incidents and emissions, which in turn affect current environmental performance.

Table A3. Testing the dynamic endogeneity of social indicators (S) using the Granger causality method.

S Indicators	Direction	Coefficient	*p*-Value	Endogeneity
Xs7—Low carbon development	$Xs7(t-1) \rightarrow Y(t)$	0.0055	0.133	No
	$Y(t-1) \rightarrow Xs7(t)$	17.3	0.133	No_T
Xs8 Diversity and Inclusion (women in the company) (D&I	$Xs8(t-1) \rightarrow Y(t)$	1.6679	0.0041 **	Yes (one-sided)
	$Y(t-1) \rightarrow Xs8(t)$	0.1837	0.0041 **	Yes (one-sided)

Note: ** $p < 0.01$, and further the maximum levels of values are indicated (**—very significant).

The table is based on a Granger causality test applied to panel data (5 companies × 5 years). For each ESG indicator, a pair of single-variable models were estimated.

$$Y(t) = \alpha + \beta \cdot X(t - 1) + \varepsilon$$

$$X(t) = \alpha + \beta \cdot Y(t - 1) + \varepsilon$$

Hypothesis H_0 is tested: "past values of a variable do not contain information to predict another variable."

Rejection of H_0 at $p < 0.05$ is interpreted as dynamic endogeneity.

Results:

Xs7—$p > 0.1$ in both directions, exogenous indicator, correctly included in the model.

Xs8 (D&I)—has a significant relationship in both directions ($p < 0.01$).

Sign of endogeneity.

Despite the identified bidirectional relationship between the share of women (Xs8) and the outcome variable, this endogeneity is dynamic (feedback effect) rather than structural. Xs8 is an institutional characteristic of the company, shaped by long-term social policy and uncorrelated with individual effects α_i. Since the Hausman test confirms the validity of the random effects model, the inclusion of Xs8 does not violate the assumptions of RE and does not bias the coefficients. Thus, Xs8 is an acceptable regressor in the corporate sustainability model.

The table is based on a Granger causality test applied to panel data (5 companies × 5 years). For each ESG indicator, a pair of single-variable models were estimated:

$$Y(t) = \alpha + \beta \cdot X(t-1) + \varepsilon$$

$$X(t) = \alpha + \beta \cdot Y(t-1) + \varepsilon$$

Hypothesis H_0 is tested: "past values of a variable do not contain information to predict another variable."

Rejection of H_0 at $p < 0.05$ is interpreted as dynamic endogeneity.

Table A4. Testing the dynamic endogeneity of corporate governance indicators (G) using the Granger causality method.

G Indicators	Direction	Coefficient	*p*-Value	Endogeneity
X3G—Corporate Ethics	X3G(t − 1) → Y(t)	0.374	0.016 *	Yes
	Y(t − 1) → X3G(t)	0.609	0.016 *	Yes
X6G—Taxes	X6G(t − 1) → Y(t)	0.68	<0.001 ***	Yes
	Y(t − 1) → X6G(t)	0.771	<0.001 ***	Yes

Note: * $p < 0.05$; *** $p < 0.001$, and further the maximum levels of values are indicated (*—significant, ***—extremely significant).

The methodology is fully consistent with recommendations for accounting for reverse causality in corporate research (Wintoki et al., 2012 [104]).

The observed bidirectional causality between corporate ethics violations (X3G), tax payments (X6G), and the outcome variable does not indicate structural endogeneity. Such a dynamic relationship has been widely documented in leading corporate governance studies. (Wintoki et al., 2012 [104]). Governance indicators reflect stable institutional characteristics of the company, which are shaped by internal policies and are uncorrelated with individual effects α_i, as confirmed by the Hausman test ($p \approx 0.98$). Therefore, the inclusion of X3G and X6G in the random effects model is methodologically correct, and the bidirectional causality reflects the actual dynamics of governance policies and the tax burden.

2. The robustness of econometric model estimates requires testing its robustness to changes in specification, sample design, and standard error calculation method. Since heteroscedasticity, intra-group correlation, and dynamic endogeneity issues often arise in corporate ESG research (Wintoki et al., 2012; Kim et al., 2025 [104,105]), standard OLS estimation can be sensitive to the panel data format and small number of observations.

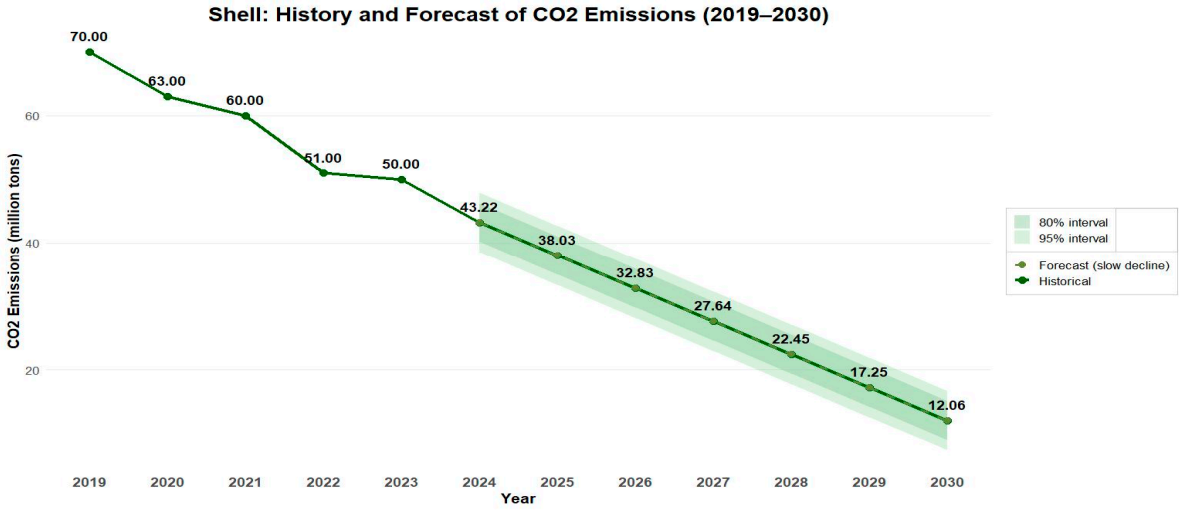
Therefore, to enhance the reliability of the results, a series of robustness tests were conducted, including:

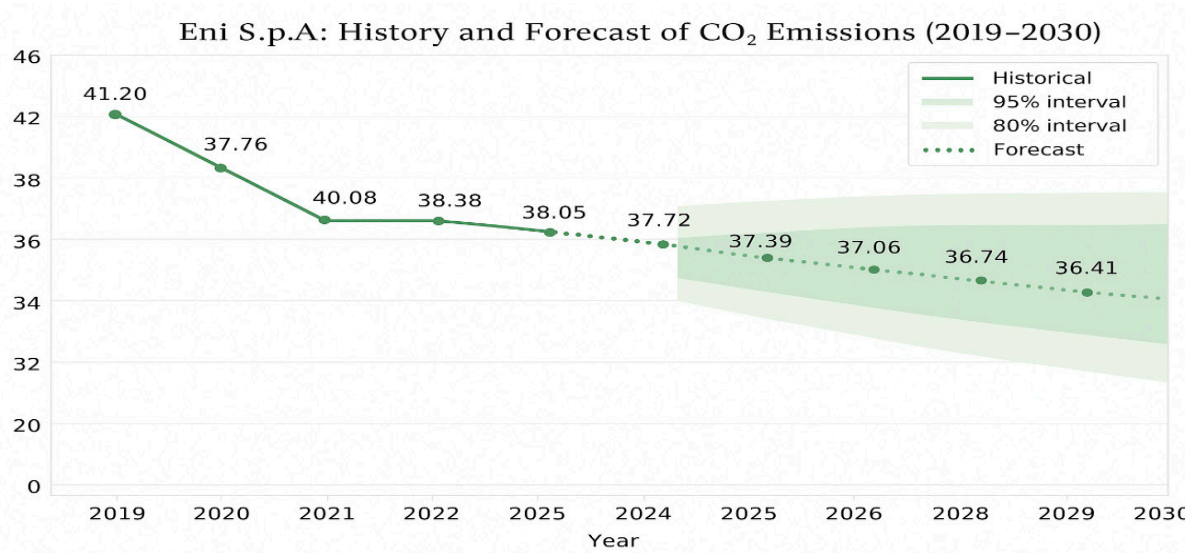
The Breusch–Pagan test for heteroscedasticity failed to reject the null hypothesis of equal error variances (BP = 3.5702; $p = 0.3118$), confirming the absence of heteroscedasticity and the validity of the constant variance assumption.

The Breusch–Godfrey/Wooldridge test for autocorrelation in panel models also revealed no significant effect of serial correlation ($\chi^2 = 4.9697$; $p = 0.4196$). This indicates that the model does not suffer from residual autocorrelation, and therefore the resulting coefficient estimates remain efficient and unbiased.

Thus, the diagnostic test demonstrates that the model errors satisfy the key assumptions of panel regression, and the results themselves are robust to violations of the residual structure.

Appendix C





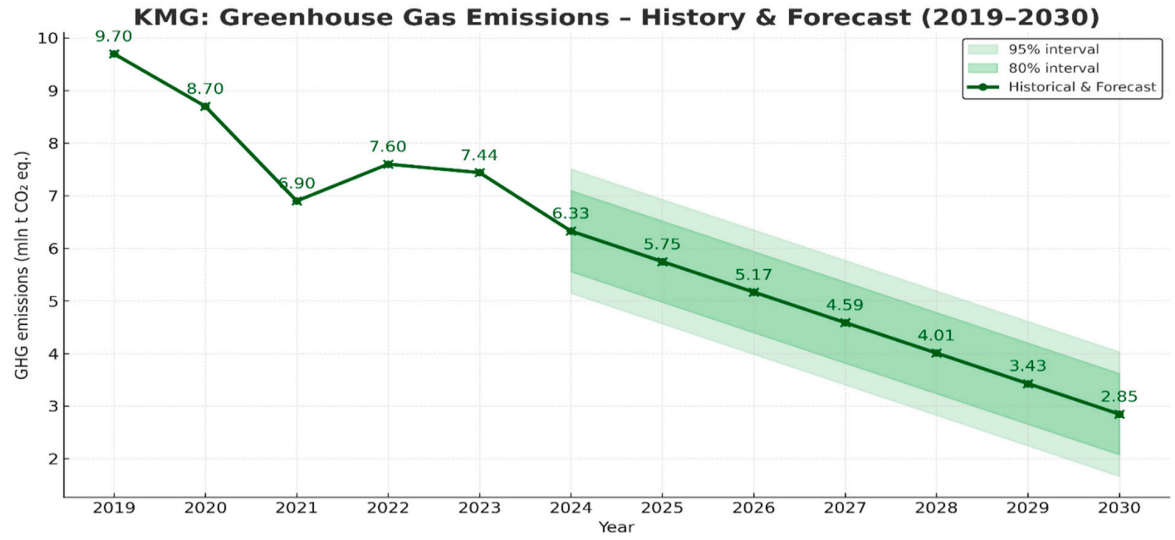


Figure A2. *Cont.*

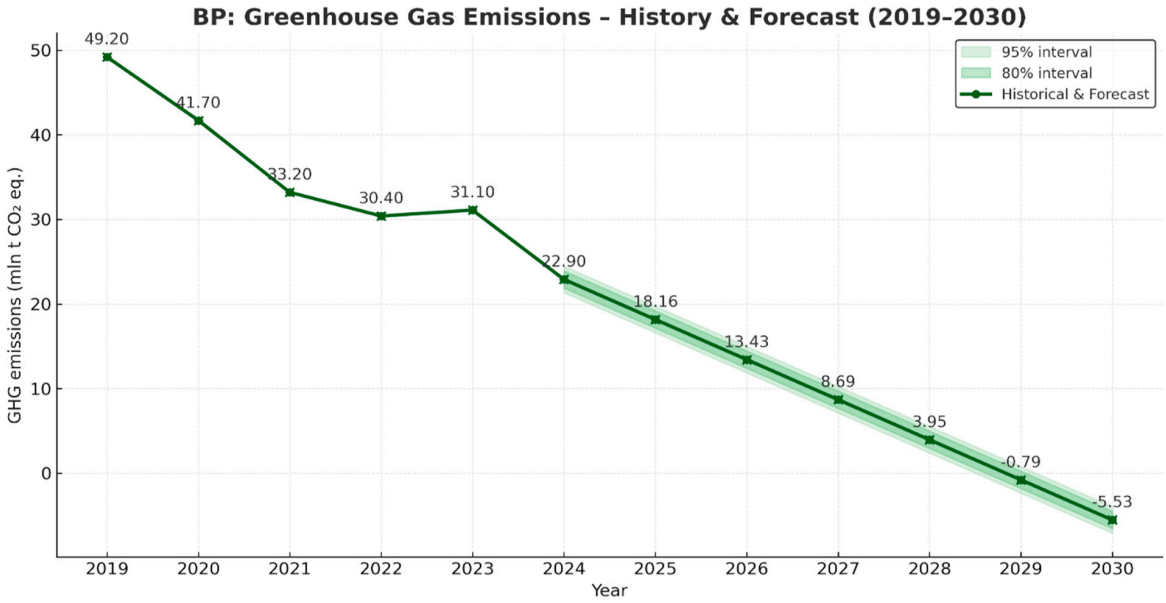


Figure A2. Results of Forecasting GHG emissions (mil.t CO_2 Equivalent) into the Atmosphere Based on the Integrated S + G Model for Shell, EniS.p.A, KMG, and BP. Note: compiled using R. Studio 3.5.0.

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