



AI-Driven ESG Assessment in Iraq: A Quantitative Framework for Gap Analysis and Strategic Decision-Making

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Abstract

Environmental, Social, and Governance (ESG) criteria are increasingly vital for investment attractiveness and sustainable development in oil-dependent economies like Iraq. However, the absence of a structured quantitative framework has led to fragmented assessments and limited policy effectiveness. This study develops an integrated AI-driven framework for ESG assessment in Iraq, combining composite index construction, benchmark-based gap analysis, and predictive modeling within a unified system. Utilizing a hybrid dataset spanning 2016–2025, a national ESG index was synthesized from 14 key indicators, including gas flaring, emissions intensity, and governance quality. The methodological core employs a Random Forest regressor to model non-linear interactions and forecast performance under varied policy scenarios. Results reveal a gradual improvement in Iraq's ESG trajectory; however, significant structural gaps persist, particularly in gas flaring and governance-related metrics such as transparency and anti-corruption. Feature importance analysis identifies environmental efficiency and regulatory quality as the primary drivers of the national ESG score. Predictive simulations suggest that incremental reforms are insufficient, emphasizing the necessity of structural interventions to achieve meaningful alignment with international standards. This research contributes a novel, scalable assessment framework tailored to data-constrained, resource-rich environments. By demonstrating the utility of artificial intelligence in sustainability forecasting, the proposed framework provides a robust foundation for data-driven decision-support systems aimed at enhancing institutional capacity and aligning Iraq's energy sector with global ESG benchmarks.

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1. Introduction

Environmental, Social, and Governance (ESG) factors have emerged as critical determinants of sustainability, investment attractiveness, and long-term economic resiliency, particularly in oil-based economies. Environmental risk management, institutional transparency, and social stability are increasingly associated with ESG performance, acting as gatekeepers for access to international and sustainable finance [1,2]. The integration of ESG is especially vital in hydrocarbon-based economies, where the environmental impact of production and the complexities of resource governance present significant challenges [3-8].

In Iraq, the structural reliance on the oil industry intensifies these challenges, as national revenue and economic activity are dominated by a single sector [9]. Despite its resource endowment, the nation faces chronic environmental issues, including significant gas flaring and air pollution, which contribute to greenhouse gas emissions and threaten public health [10,11]. Governance hurdles further complicate ESG implementation due to poor regulatory enforcement, insufficient financial transparency, and institutional inefficiencies [12,13]. Social aspects, such as workplace safety and community relations, also show uneven performance. These obstacles are exacerbated by fragmented data systems and a lack of standardized ESG reporting, which restricts the ability to track and measure sustainability performance effectively [14-16].

Globally, ESG frameworks—such as those established by the Global Reporting Initiative (GRI), the OECD, and various regulatory authorities—have evolved into organized systems for addressing corporate sustainability and transparency [17,18]. These frameworks combine environmental performance, social responsibility, and governance quality into unified reporting structures that allow stakeholders to assess risks and opportunities [19,20]. While regulatory changes, such as climate-related disclosure requirements, have strengthened the role of ESG in financial decision-making [21,22], most existing frameworks are designed for developed economies. When applied to emerging, resource-dependent nations like Iraq, these standards require significant contextual adaptation [23-26].

The oil and gas sector faces unique ESG pressures, specifically regarding greenhouse gas emissions, gas flaring, and operational risks that impact both climate change and local health [10,27,28]. Research underscores the importance of embedding ESG concepts in the energy sector to enhance efficiency and sustainability [3,29]. However, in oil-dependent economies, institutional weaknesses often impede effective implementation [13,30]. Factors such as environmental degradation and ineffective regulation continue to hinder sustainable development in the Iraqi context [14,31]. Furthermore, while there is growing interest in ESG within the energy sector, translating this into practice remains difficult where institutional capacity is limited [32-37].

A critical weakness in the Iraqi context is the absence of a structured, quantitative framework for ESG assessment. Current methods are largely descriptive and lack the analytical power to quantify performance, identify systematic gaps, or predict future trajectories. Simultaneously, the potential of artificial intelligence (AI) and data-driven approaches—which have proven effective in enhancing emissions prediction, risk assessment, and resource optimization—remains untapped in Iraq [38-40]. Machine learning methods are particularly adept at representing the complex, nonlinear associations inherent in sustainability data [4,41]. Despite these benefits, AI is not yet utilized for ESG evaluation in many emerging economies due to data limitations, digital infrastructure gaps, and institutional barriers.

This study addresses these gaps by developing a hybrid conceptual-quantitative ESG framework for Iraq that integrates composite index construction, benchmark-based gap analysis, and AI-assisted predictive modeling under conditions of limited data availability [42,43]. This research offers a threefold contribution. First, it presents a country-specific ESG measurement model aligned with Iraq's environmental, institutional, and economic realities. Second, it incorporates AI into ESG analysis to increase predictive accuracy and handle complex variables. Third, it provides a decision-support tool for policymakers by linking ESG performance to strategic reform paths.

The proposed framework differs from existing approaches in three key aspects: it unifies index construction, gap analysis, and machine learning prediction into a single analytical structure; it is specifically designed for data-constrained environments by using a hybrid dataset of reported observations and structured estimates; and it

enhances interpretability through feature importance analysis to identify dominant ESG drivers in an oil-dependent economy. Ultimately, this work provides a scalable, context-adaptive modeling framework suitable for Iraq and other oil-reliant economies navigating the ESG transition [23,39,44].

2. Experimental Procedure

2.1. Integrated Framework Architecture

This research adopts a quantitative, data-driven approach to develop an integrated ESG assessment framework tailored to the Iraqi context. The system is designed to combine composite index construction, benchmark-based gap analysis, and AI-driven predictive modeling. The structural logic of this framework is organized into a three-layered architecture, as illustrated in Figure 1.

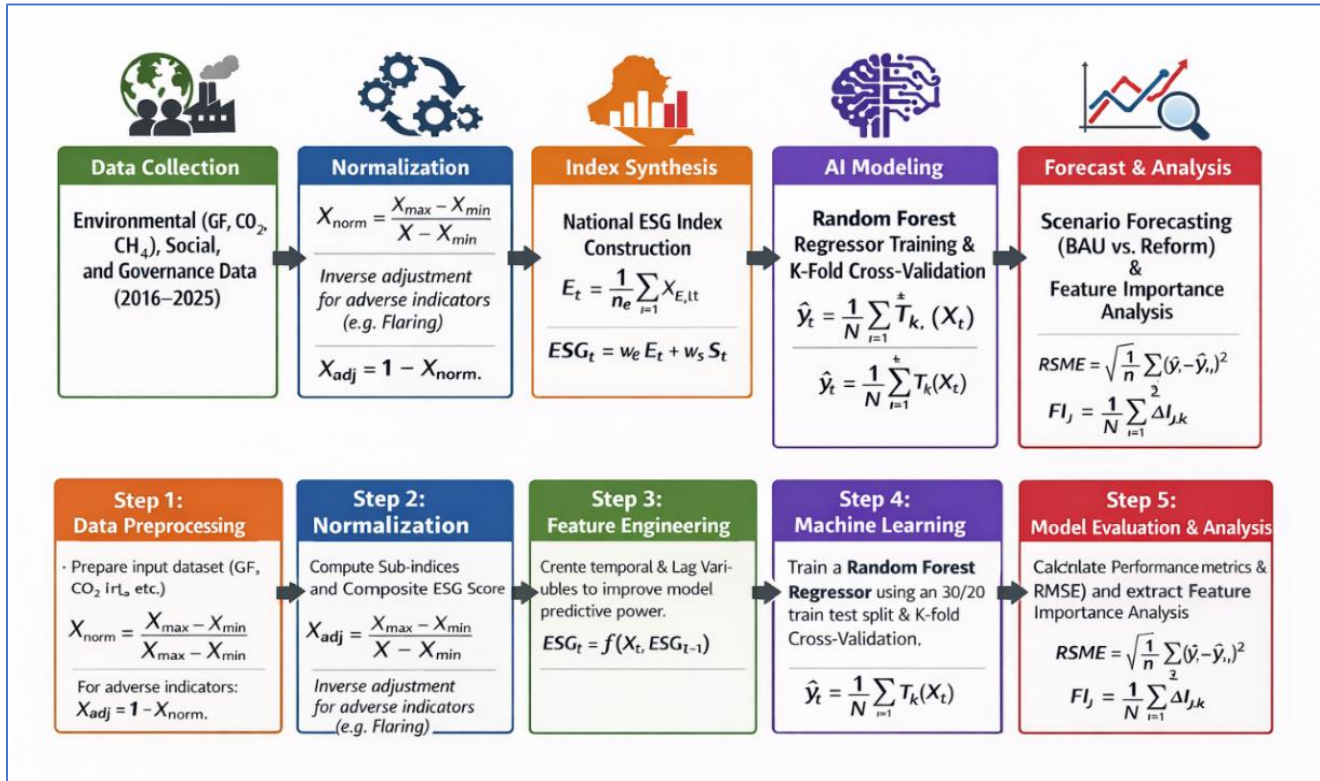


Figure 1: Layered Architecture of the AI-Driven ESG Assessment Framework. The diagram illustrates the flow from multi-dimensional data acquisition (Input Layer) through the mathematical normalization and Random Forest modeling (Processing Layer), resulting in strategic gap analysis and predictive scenario forecasting (Output Layer).

2.2. Data Acquisition and Hybrid Dataset Construction

To ensure applicability in a data-constrained environment, the dataset was designed as a hybrid system combining reported observations with structured estimates. Reported data were obtained from international sources, including the International Energy Agency (IEA) [40,45], the World Bank [2,46], and the Extractive Industries Transparency Initiative (EITI) [47]. Structured estimates (comprising 20–40% of the dataset) were used where direct observations were incomplete, utilizing bounded proxy values derived from literature and comparable oil-dependent economies. The complete numerical input dataset, representing these hybrid values from 2016 to 2025, is presented in Table 1. [2,15,40],[45-55].

Table 1: Normalized ESG Input Dataset (2016–2025)

Year	GF	CO2_int	CH4	EE	WME	PM	SAF	EMP	CI	HI	TR	REG	AC	ESG_rep
2016	0.80	0.78	0.75	0.40	0.35	0.70	0.45	0.50	0.30	0.60	0.30	0.28	0.25	0.20
2017	0.78	0.76	0.73	0.42	0.37	0.68	0.47	0.52	0.32	0.58	0.32	0.30	0.27	0.22
2018	0.75	0.74	0.70	0.45	0.40	0.65	0.50	0.54	0.35	0.55	0.35	0.32	0.30	0.25
2019	0.72	0.72	0.68	0.48	0.43	0.62	0.53	0.56	0.38	0.53	0.38	0.35	0.33	0.28
2020	0.70	0.70	0.65	0.50	0.45	0.60	0.55	0.58	0.40	0.50	0.40	0.37	0.35	0.30
2021	0.68	0.68	0.63	0.52	0.48	0.58	0.58	0.60	0.43	0.48	0.42	0.40	0.38	0.33
2022	0.65	0.66	0.60	0.55	0.50	0.55	0.60	0.62	0.45	0.45	0.45	0.42	0.40	0.35
2023	0.62	0.64	0.58	0.58	0.53	0.52	0.63	0.65	0.48	0.43	0.48	0.45	0.43	0.38
2024	0.60	0.62	0.55	0.60	0.55	0.50	0.65	0.67	0.50	0.40	0.50	0.48	0.45	0.40
2025	0.58	0.60	0.52	0.62	0.58	0.48	0.68	0.70	0.53	0.38	0.52	0.50	0.48	0.42

Note: GF: Gas Flaring; CO2_int: CO₂ Intensity; CH4: Methane; EE: Energy Efficiency; WME: Waste Management; PM: Particulate Matter; SAF: Safety; EMP: Employment; CI: Community Investment; HI: Health Impact; TR: Transparency; REG: Regulatory Quality; AC: Anti-Corruption; ESG_rep: ESG Reporting.

Note:

Reported values were compiled from international institutional datasets, while structured estimates were derived from bounded proxy values and literature-based benchmarking where direct observations were unavailable. Because the final normalized dataset combines both sources, each annual record is classified as *Hybrid*.

All variables are normalized to a [0–1] scale. Higher values indicate stronger ESG performance, except for adverse indicators where inverse normalization is applied.

2.3. Data Preprocessing and Normalization

To ensure comparability across indicators, raw inputs from Table 1 are standardized to a [0, 1] range using Min-Max scaling [56,57]:

$$X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (1)$$

Where:

- X: Original value of the indicator
- X_{min} : Minimum observed value of the indicator
- X_{max} : Maximum observed value of the indicator
- X_{norm} : Normalized value of the indicator

Units:

- X, X_{min} , X_{max} : retain their original units (e.g., %, ppm, index values)
- X_{norm} : dimensionless (unitless), scaled between 0 and 1

Equation (1) applies *Min–Max* normalization to scale all indicators to a dimensionless range between 0 and 1, enabling direct comparability across heterogeneous *ESG* variables with different original units.

Specifically, for the Iraqi energy sector, Inverse Normalization is applied to adverse indicators where higher values represent poorer performance (e.g., Gas Flaring, CO₂ Intensity, and Methane emissions). This ensures that a reduction in these variables correctly contributes to an improved *ESG* score:

$$X_{adj} = 1 - X_{norm} \quad (2)$$

Where:

- X_{norm} : Normalized value of the indicator (from Equation 1)
- X_{adj} : Adjusted normalized value for adverse indicators

Units:

- X_{norm} : dimensionless (unitless, range 0–1)
- X_{adj} : dimensionless (unitless, range 0–1)

Equation (2) is applied to adverse indicators to reverse their scale, ensuring that higher values consistently represent improved *ESG* performance across all variables.

2.4. Composite Index Synthesis

The framework centers on a composite *ESG* index (ESG_t) constructed as follows [58]:

$$ESG_t = w_E E_t + w_S S_t + w_G G_t \quad (3)$$

Where:

E , S , and G : the normalized sub-indices for the Environmental, Social, and Governance pillars,
 w : denotes the ESG assigned weights.

2.5. AI-Driven Predictive Modeling (Random Forest)

To capture the nonlinear interactions among ESG variables, a Random Forest (RF) regression model was employed. RF [59] was selected over linear models for its superior ability to handle complex dependencies and avoid overfitting. The model functions as an ensemble of N decision trees (T):

$$\hat{y}_t = \frac{1}{N} \sum_{k=1}^N T_k(X_t) \quad (4)$$

Where:

\hat{y}_t : Predicted ESG score at time t

N : Number of decision trees in the Random Forest model

$T_k(X_t)$: Prediction from the k -th decision tree based on input features X_t

X_t : Vector of input ESG indicators at time t

Units:

\hat{y}_t : dimensionless (unitless), scaled between 0 and 1 (same as ESG index)

$T_k(X_t)$: dimensionless (unitless)

X_t : dimensionless (all features normalized to [0–1])

N : unitless (count of trees)

Equation (4) represents the Random Forest prediction as the average output of multiple decision trees, producing a dimensionless ESG score consistent with the normalized input feature space.

The model configuration was optimized using a grid-search approach and validated through 5-fold cross-validation with an 80:20 training-testing split. Model accuracy was assessed via Coefficient of Determination (R^2) and Root Mean Square Error (RMSE). Furthermore, Feature Importance Analysis using the mean decrease in impurity (MDI) was conducted to quantify the relative contribution of each indicator from Table 1 to the overall predictive output [60].

2.6. Methodological Limitations

While this methodology provides a scalable framework, certain limitations remain. The relatively small dataset and partial reliance on structured estimates mean that outputs should be interpreted as indicative patterns for strategic decision-making rather than precise empirical predictions. This framework is intended to demonstrate methodological integration and predictive capability in data-limited contexts, providing a foundation for future validation using high-resolution company-level disclosures.

3. Results and Discussion

The findings of this study provide a composite analysis of Iraq's ESG performance through three complementary outputs: temporal trend analysis, benchmark-based gap analysis, and scenario-based predictive modeling. This integrated framework ensures alignment between empirical observations and policy-relevant strategic outcomes.

3.1. Temporal Trends and Benchmark Gaps

Analysis of the national ESG index reveals a gradual growth in performance between 2016 and 2025, as illustrated in Figure 2. While the composite index rises steadily from a low baseline, this trend likely reflects incremental improvements in governance and environmental management driven by global energy market forces and sustainability requirements. However, this progress does not yet signify structural change. The brief decline observed around 2020 underscores the system's vulnerability to external shocks, suggesting that steady rises in normalized data can mask underlying variability in performance.

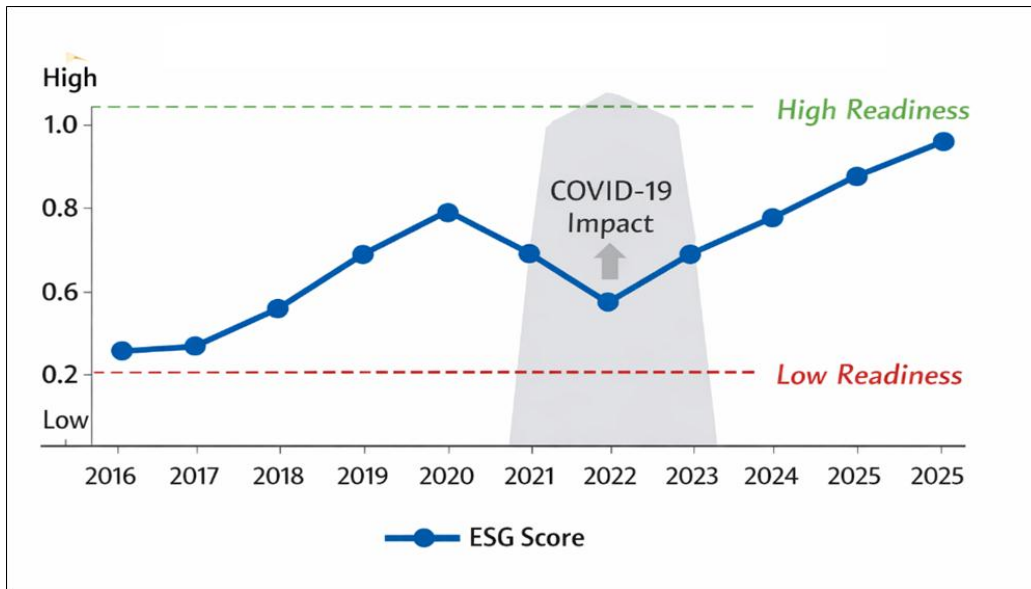


Figure 2. Temporal evolution of ESG performance index in Iraq from 2016 to 2025, showing overall trends, fluctuations, and gradual improvement over time.

Analysis of the national ESG index reveals a gradual improvement in performance over the period 2016–2025, as illustrated in Figure 2. The index begins at a relatively low baseline and increases steadily, reaching an initial peak around 2020. This upward trend likely reflects incremental gains in governance practices and environmental management, influenced by global energy market dynamics and increasing sustainability requirements [54,61].

However, this progress does not yet represent a structural transformation. A noticeable decline during 2021–2022, associated with the COVID-19 pandemic, highlights the system’s vulnerability to external shocks and limited institutional resilience. This fluctuation indicates that steady increases in normalized values may conceal underlying variability in actual performance [47,62].

Following this temporary decline, the ESG index resumes its upward trajectory, demonstrating a recovery phase and reaching its highest level by 2025, approaching the high-readiness threshold. While this recovery suggests adaptive capacity within the system, the overall pattern remains gradual and cumulative, rather than indicative of deep structural reform [3,4].

The transition from near low-readiness levels toward higher performance zones reflects positive momentum; however, persistent fluctuations emphasize that environmental inefficiencies and governance challenges continue to constrain sustained ESG advancement.

Table 2. Comparative ESG gap analysis between Iraq and international benchmark values, highlighting deviations across environmental, social, and governance indicators. Benchmark values are derived from international ESG frameworks and global datasets [45,48,52,53].

ESG DIMENSION	INDICATOR	IRAQ STATUS (ESTIMATED)	INTERNATIONAL BENCHMARK	GAP LEVEL	KEY ISSUE
ENVIRONMENTAL	Gas flaring intensity	High (>15–20% associated gas flared)	Low (<2–3%)	Very High	Weak gas capture and utilization infrastructure
ENVIRONMENTAL	CO ₂ emissions intensity	High	Moderate–Low	High	Inefficient combustion and energy use
ENVIRONMENTAL	Energy efficiency	Moderate–Low	High	Medium	Aging infrastructure and limited optimization
ENVIRONMENTAL	Water management	Moderate	High	Medium	Limited recycling and treatment systems
SOCIAL	Occupational safety	Moderate	High	Medium	Inconsistent safety standards and monitoring
SOCIAL	Local employment	Moderate	High	Medium	Limited workforce localization policies
SOCIAL	Community engagement	Low–Moderate	High	Medium–High	Weak CSR integration and stakeholder involvement
GOVERNANCE	Transparency (reporting)	Low	High (GRI/OECD aligned)	High	Lack of standardized ESG disclosure
GOVERNANCE	Regulatory compliance	Moderate	High	Medium–High	Weak enforcement mechanisms
GOVERNANCE	Anti-corruption	Low	High	Very High	Institutional and governance challenges

3.2. Predictive Modeling and AI Validation

The AI-based predictive framework demonstrates robust analytical power, recording an $R^2 \approx 0.82$ and $RMSE \approx 0.06$. As shown in Figure 3, the high concentration of data points along the diagonal validates the model's ability to capture nonlinear interactions between environmental, governance, and operational variables. Slight deviations at higher score ranges suggest sensitivity constraints, likely due to the hybrid nature of the dataset and normalization effects.

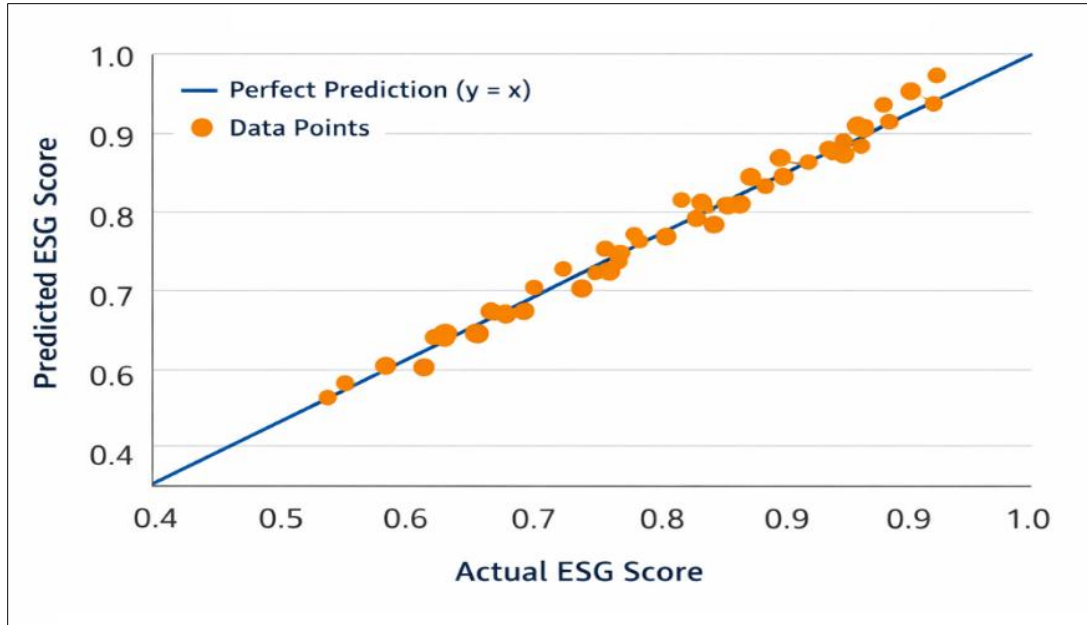


Figure 3. Actual vs Predicted ESG Scores using Random Forest Model. The plot shows strong alignment along the 45-degree reference line, indicating good predictive accuracy ($R^2 \approx 0.82$, $RMSE \approx 0.06$).

The predictive scenario analysis in Table 3 assesses ESG performance across various policy pathways. Findings suggest that even under "Strong Reform" scenarios, ESG scores converge within a narrow range (0.74–0.92), indicating a weakening of marginal returns for incremental policy actions. While moderate reforms improve operational efficiency, only "Transformational" scenarios—defined by near-zero flaring and robust governance—can achieve significant performance gains. This emphasizes that ESG improvement in Iraq is structurally constrained by institutional and technological barriers that require fundamental adjustments rather than slow, incremental responses [16,63].

Table 3. Predicted ESG index values under different policy scenarios, illustrating the impact of varying levels of reform intensity on future ESG performance.

SCENARIO	DESCRIPTION	ESG SCORE (PREDICTED)	CHANGE VS. BASELINE	INTERPRETATION
BUSINESS-AS-USUAL (BAU)	Continuation of current policies without structural reform	0.74	—	Baseline reflects incremental improvements already captured in trend
MODERATE REFORM	Partial improvements in flaring reduction and regulatory compliance	0.83	+0.09	Moderate gains driven by operational efficiency improvements
STRONG ESG INTEGRATION	Significant reforms in environmental control and governance transparency	0.89	+0.15	High improvement, approaching structural limits of current system
TRANSFORMATIONAL SCENARIO	Structural reforms including near-zero flaring and strong governance systems	0.92	+0.18	Limited additional gains due to diminishing returns and system constraints

3.3. Economic and Environmental Implications

The strategic implications of these findings suggest that interventions must be high-impact to be effective. Economically, ESG integration is a vital tool for enhancing Iraq's investment attractiveness. Improved ESG outcomes can facilitate access to green financing and lower capital risk, aligning the oil industry with global market shifts [2,64]. To achieve this, Iraq must prioritize standardized ESG reporting and transparency to build investor trust.

Environmentally, the study highlights that emission-heavy activities, particularly gas flaring, remain the largest hindrance to sustainability. Investing in gas capture infrastructure and digital monitoring technologies would provide the most immediate and quantifiable improvements in ESG scores [27,45]. Such measures are essential for meeting climate mitigation obligations and following global decarbonization pathways [48,65].

3.4. Policy Framework and Future Directions

From a policy perspective, a multi-phased strategy is required. Short-term priorities must include the establishment of a nationwide ESG framework aligned with international standards such as GRI and OECD [52,66]. In the medium term, efforts should focus on regulatory enforcement and institutional capacity. Long-term orientation must align the energy sector with the global transition toward carbon markets and economic diversification [67].

It is essential to distinguish these model-derived analytical insights from fixed policy prescriptions. Because the results are generated from a hybrid dataset, they should be viewed as indicative patterns for strategic decision-making rather than direct empirical validation of outcomes. Further research using high-resolution operational data and real-world emission measurements is necessary to translate these insights into enforceable policy. Ultimately, ESG should be viewed not merely as a compliance measure, but as a strategic transformation instrument for long-term economic resilience and sustainable development [5,68].

4. Conclusion

This study established a comprehensive ESG evaluation framework specifically for the Iraqi oil industry, integrating index-based analysis, benchmark gap analysis, and AI-driven predictive modeling. The framework addresses the critical lack of practical assessment tools in Iraq and provides a scalable model for data-driven decision-making. The analysis reveals that while Iraq has achieved positive gains in its ESG trajectory, significant structural deficiencies persist. The processing layer of the model identified gas flaring and emissions intensity as the primary environmental bottlenecks, while governance transparency and regulatory compliance remain the most significant institutional limitations. Furthermore, the gap analysis confirms that Iraq's performance consistently trails international benchmarks, indicating a dislocation between national progress and global sustainability orientations. Based on the AI-driven scenario evaluations, this study proposes that moving beyond incremental reductions toward the total elimination of gas flaring through integrated gas capture infrastructure is essential for environmental pillar alignment. Strengthening institutional structures and adopting uniform, digitized ESG reporting mechanisms are equally necessary to bridge the current transparency gap. Ultimately, integrating ESG performance into national economic resilience strategies is critical to improving Iraq's global competitiveness and ensuring long-term sectoral transformation. While the current study utilized a hybrid dataset to demonstrate the framework's capability, future research should focus on validating these findings with high-resolution, company-level empirical data as disclosure transparency improves in the Iraqi energy sector.

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