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Integrating Management Accounting for Sustainable Performance: Environmental Costs and Green KPIs in the Coal Mining Industry of Kazakhstan

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ARTICLE INFO	ABSTRACT
Keywords: *Management accounting, environmental costs, Environmental Management Accounting (EMA), green KPIs, ESG, Best Available Techniques (BAT)*	*This study develops an applied framework for integrating management accounting with environmental management in coal mining companies of Kazakhstan. It demonstrates how an expanded costing architecture-Environmental Management Accounting (EMA) combined with Activity-Based Costing/Budgeting (ABC/ABB) and Life-Cycle Costing (LCC)-alongside a system of green KPIs, can be used to manage sustainable performance. The proposed approach supports the reduction of unit environmental costs, improvement of environmental intensity indicators (tCO_2e per ton, m^3 of water per ton, land reclamation rate), and the maintenance of profitability and investment attractiveness. Building on the concepts of dual-criteria optimization and a threshold environmental payment coefficient (EPC), the paper offers practical calculation tools for selecting Best Available Techniques (BAT) and for estimating the break-even point for environmental payments. Illustrative statistical examples (based on simulated data) are provided to demonstrate: (1) trends in environmental costs per ton, (2) an aggregated enterprise "green" score based on KPI sets, (3) the correlation between green KPIs and EBITDA margin, and (4) the estimation of the EPC threshold beyond which operations become economically unviable.The proposed framework can serve as a methodological basis for implementing green controlling and environmentally integrated budgeting systems in Kazakhstan's coal mining sector.*
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მდგრადი საქმიანობის უზრუნველსაყოფად მმართველობითი აღრიცხვის ინტეგრირება: გარემოსდაცვითი ხარჯები და მწვანე საკვანძო ეფექტიანობის მაჩვენებლები ყაზახეთის ქვანახშირის მომპოვებელ მრეწველობაში

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ინფორმაცია სტატიის შესახებ	აბსტრაქტი
საკვანძო სიტყვები: *მმართველობითი აღრიცხვა, გარემოსდაცვითი ხარჯები, გარემოსდაცვითი მმართველობითი აღრიცხვა (EMA), მწვანე საკვანძო ეფექტიანობის მაჩვენებლები, ESG (გარემოსდაცვითი, სოციალური და კორპორაციული მართვის ფაქტორები), საუკეთესო ხელმისაწვდომი ტექნოლოგიები (BAT)*	*ნაშრომში გაანალიზებულია გამოყენებით ჩარჩოს ყაზახეთის ქვანახშირის მომპოვებელი კომპანიების მმართველობითი აღრიცხვის გარემოსდაცვით მენეჯმენტთან ინტეგრირებისთვის. იგი აჩვენებს, თუ როგორ შეიძლება გამოყენებულ იქნას გაფართოებული ხარჯთაღრიცხვის არქიტექტურა - გარემოსდაცვითი მმართველობითი აღრიცხვა (EMA), შერწყმული საქმიანობაზე დაფუძნებულ ხარჯთაღრიცხვასთან/ბიუჯეტირებასთან (ABC/ABB) და სასიცოცხლო ციკლის ღირებულებასთან (LCC) - მწვანე საკვანძო ეფექტიანობის მაჩვენებლების სისტემასთან ერთად, მდგრადი საქმიანობის მართვისთვის. შემოთავაზებული მიდგომა ხელს უწყობს ერთეულოვანი გარემოსდაცვითი ხარჯების შემცირებას, გარემოსდაცვითი ინტენსივობის მაჩვენებლების გაუმჯობესებას (tCO_2e ტონაზე, წყლის m^3 ტონაზე, მიწის რეკულტივაციის მაჩვენებელი), აგრეთვე მომგებიანობისა და საინვესტიციო მიმზიდველობის შენარჩუნებას. ორკრიტერიუმიანი ოპტიმიზაციისა და გარემოსდაცვითი გადასახადის ზღვრული კოეფიციენტის (EPC) კონცეფციებზე დაყრდნობით, ნაშრომი გვთავაზობს პრაქტიკულ გამოთვლით ინსტრუმენტებს საუკეთესო ხელმისაწვდომი ტექნოლოგიების (BAT) შესარჩევად და გარემოსდაცვითი გადასახადების თვითღირებულების წერტილის შესაფასებლად. ილუსტრაციული სტატისტიკური მაგალითები (სიმულირებულ მონაცემებზე დაყრდნობით) წარმოდგენილია შემდეგის საჩვენებლად: (1) ტონაზე გარემოსდაცვითი ხარჯების ტენდენციები, (2) საწარმოს აგრეგირებული „მწვანე" ქულა KPI-ების ერთობლიობის საფუძველზე, (3) მწვანე KPI-ებსა და EBITDA მარჟას შორის კორელაცია და (4) EPC ზღვრის შეფასება, რომლის გადაჭარბების შემთხვევაშიც საწარმოო საქმიანობა ეკონომიკურად არამომგებიანი ხდება. შემოთავაზებული ჩარჩო შეიძლება გახდეს მეთოდოლოგიური საფუძველი ყაზახეთის ქვანახშირის მომპოვებელ სექტორში მწვანე კონტროლინგისა და გარემოსდაცვითად ინტეგრირებული ბიუჯეტირების სისტემების დანერგვისთვის*
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Introduction.

Sustainable performance in coal mining companies requires the synchronized management of operational, financial, and environmental outcomes. Management accounting serves as a natural integrative mechanism linking operational data, cost structures, and investment decisions related to Best Available Techniques (BAT), land reclamation, and water and energy efficiency. A key practical challenge is how to embed environmental considerations into the management accounting system so that they are measurable, comparable,

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and decision-relevant. This study proposes a structured integration framework and illustrates its application through analytical calculations tailored to coal mining companies in the Republic of Kazakhstan.

The theoretical foundation builds on the concept of multi-criteria optimization of environmental – economic decisions and the use of an environmental payment coefficient (EPC) as an economic incentive for adopting BAT. The underlying models identify Pareto-optimal regions and EPC threshold values beyond which firms lose economic incentives to pursue specific projects. This approach is adapted to management accounting tasks and internal pricing of environmental impacts in Kazakhstan's coal sector by incorporating EPC and related indicators into cost allocation, budgeting, Activity-Based Costing/Budgeting (ABC/ABB), Life-Cycle Costing (LCC), and the system of green KPIs.

The sectoral context reinforces the relevance of this study. Coal mining companies in Kazakhstan face dual pressures: (i) maintaining operational efficiency under volatile demand and price conditions, and (ii) reducing environmental intensity, including emissions, water use, land disturbance, coal dust, and methane. At the same time, environmental payments and BAT requirements are tightening, while practices such as energy audits and land reclamation projects are expanding. Transforming the "green agenda" from a compliance-driven cost burden into a domain of managed performance is possible only if environmental factors are systematically embedded into management accounting – through clear cost object identification, properly defined cost drivers, aligned KPI systems, and incentive mechanisms.

The aim of the study is to demonstrate how extended management accounting tools -Environmental Management Accounting (EMA), ABC/ABB, and LCC – combined with a system of green KPIs, can enhance sustainable performance in Kazakhstan's coal mining industry, and to provide a verifiable methodological framework supported by illustrative statistical results.

The study addresses the following research questions: (1) Which components of environmental costs (direct and indirect) have a statistically significant impact on margins and process-level unit costs? (2) Which green indicators (energy and carbon intensity, reclamation ratio, waste and loss metrics) are associated with improved operational and financial performance? (3) How does internal pricing incorporating the EPC transform investment decisions related to BAT adoption?

The contribution of the paper is fourfold: (i) integration of environmental payments and green KPIs into costing and budgeting at the responsibility center level; (ii) development of a practical MFCA/ABC-based approach to identify hidden environmental losses and material waste flows; (iii) empirical verification of the relationship between green KPIs and financial performance indicators (margin, ROS/ROA) using industry data; (iv) managerial recommendations for designing incentive systems, including eco-controlling and the Sustainability Balanced Scorecard (SBSC).

Literature Review.

Management Accounting for Sustainable Development (EMA). The body of research on Environmental Management Accounting (EMA) demonstrates how environmentally relevant material and energy flows, along with their associated monetary costs, can be systematically incorporated into management accounting systems. EMA extends the traditional scope of management accounting by introducing material flows (material and energy intensity), waste, and emissions as explicit accounting objects, linking them to responsibility centers and decisions regarding Best Available Techniques (BAT), energy efficiency, and waste management. Conceptually, EMA highlights that environmental costs are often underestimated in conventional costing systems and embedded within overheads. From a practical perspective, the absence of EMA leads firms to underestimate the economic benefits of BAT and energy efficiency projects; conversely, EMA enables the identification of cost drivers of losses and supports the revision of standards and budgets [1–4].

Environmental Costing Approaches: ABC/ABB, MFCA, and LCC. Activity-Based Costing and Budgeting (ABC/ABB) enhance the allocation of environmental overheads through cost drivers such as water pumping volumes, overburden transport (ton-kilometers), and dust suppression operating hours, significantly improving cost transparency across production stages. Material Flow Cost Accounting (MFCA) focuses on the

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monetary valuation of material and energy losses – such as moisture, fines, dust, and overburden waste – revealing where value leakage occurs within operations. Life-Cycle Costing (LCC) complements investment appraisal by incorporating full life-cycle costs (CAPEX for BAT, OPEX, reclamation, and closure costs), which is particularly critical for mining operations. The integration of ABC/ABB with MFCA provides a detailed "loss map," while LCC ensures robust investment evaluation by accounting for future environmental obligations [5–8].

Green KPIs and Eco-Controlling. The literature on green Key Performance Indicators (KPIs) and eco-controlling, including the Sustainability Balanced Scorecard (SBSC), emphasizes embedding environmental metrics into strategic objectives and incentive systems. In coal mining, relevant KPIs include emission intensity (tCO_2e per ton of coal at different processing stages), energy intensity of extraction and processing, waste and loss ratios (share of fines and dust), methane capture rates, water intensity and recycling rates, and land reclamation performance. Additionally, environmental health and safety indicators (e.g., LTIFR/TRIFR with environmental incidents) are increasingly integrated. Effective implementation requires strict alignment of KPIs with responsibility centers, budgets, and performance-based compensation systems.

Environmental Payments, EPC, and Economic Incentives. Theoretical approaches based on Pigouvian taxation and environmental payment schemes demonstrate that proper pricing of environmental externalities shifts technological choices toward BAT. Models incorporating an environmental payment coefficient (EPC) identify threshold levels at which projects become economically unviable without environmental modernization. Within corporate systems, this translates into internal carbon or environmental pricing mechanisms that simulate external costs and discipline investment decisions. Embedding EPC into internal transfer pricing and budgeting frameworks makes environmental considerations visible and competitive within managerial decision-making.

Industry-Specific Features of Coal Mining. Studies on coal mining highlight its high material and energy intensity, significant environmental impacts (land degradation, water contamination, methane emissions, and dust pollution), and substantial reclamation costs. From an economic perspective, investments in methane capture and utilization, loss reduction (granulometry optimization, dust suppression), water management (closed-loop systems), and energy efficiency (advanced motors and variable frequency drives) can reduce unit costs, increase product yield, mitigate regulatory risks, and enhance ESG performance, thereby improving access to capital. When evaluated using LCC and risk-adjusted frameworks, many "green" investments demonstrate positive net present value (NPV).

Integration Frameworks: From Data to Decisions. Recent studies on integrating EMA and MFCA with budgeting and investment processes emphasize that tangible benefits arise only when a full management cycle is established: data → cost drivers → budgets → KPIs → incentives → performance monitoring. Emerging research incorporates explainable AI (XAI) tools (e.g., SHAP, partial dependence plots) to identify and interpret key drivers of cost and margin dynamics. However, several gaps remain: fragmented accounting of environmental costs within overheads, weak linkage between green KPIs and incentive systems, limited use of MFCA across production stages, underdeveloped internal environmental pricing practices, and insufficient empirical validation of the relationship between green KPIs and financial performance in the context of Kazakhstan's coal industry [9–11].

Conceptual Framework of the Study. The proposed framework integrates accounting, evaluation, and management dimensions. At the accounting level, EMA combined with ABC/ABB and MFCA enables the identification of environmental costs and losses across operational levels (process–stage–product). At the evaluation level, LCC and NPV models are applied to BAT projects under scenarios with and without EPC. At the management level, green KPIs are embedded into SBSC and eco-controlling systems, linked to responsibility centers and incentive schemes. Empirical verification is conducted using panel regression and machine learning models with XAI techniques to assess the relationship between green KPIs and financial indicators (margin, ROS, ROA). The study tests the following hypotheses:

H1: Reductions in material and energy losses (identified via MFCA) positively affect margins and ROS.

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H2: BAT projects evaluated using LCC and EPC-adjusted scenarios yield positive impacts on ROA and NPV.
H3: Strong alignment of green KPIs with incentive systems accelerates performance improvements [12–18].

Methodology. This study employs an applied quantitative research design based on panel data from coal mining companies in Kazakhstan, integrating management accounting methods – Environmental Management Accounting (EMA), Activity-Based Costing (ABC), Material Flow Cost Accounting (MFCA), and Life-Cycle Costing (LCC) – with econometric and machine learning approaches, including explainable AI (XAI) techniques.

The object of analysis includes coal mining operations – both open-pit mines and underground shafts – treated as legal entities and/or production sites. The study period covers 2015–2024 (2025), providing sufficient temporal depth to capture trends, structural shifts, and lagged effects. The unit of observation is primarily the firm-year, with an extended analytical level at the process/site-year (e.g., production stages or operational units) for MFCA and ABC-based analysis.

The data sources comprise multiple categories: financial statements prepared under IFRS, production and operational reports, environmental and ESG disclosures, energy efficiency passports, environmental health and safety (EHS) incident logs, as well as internal budgets and cost accounting records (where accessible). This multi-source dataset enables the integration of financial, operational, and environmental dimensions into a unified analytical framework.

The methodological approach combines accounting-based measurement with empirical modeling. EMA is used to identify and quantify environmental costs and flows, while ABC and MFCA allocate these costs across processes and reveal hidden inefficiencies and material losses. LCC is applied to evaluate investment decisions related to Best Available Techniques (BAT) over their full life cycle. Econometric panel models (fixed/random effects) and machine learning models are employed to estimate the relationships between environmental cost drivers, green KPIs, and financial performance indicators (e.g., EBITDA margin, ROS, ROA). XAI tools (such as SHAP values and partial dependence plots) are used to interpret model outputs and identify the most influential drivers.

The integration between management accounting tools and “green” performance outcomes is conceptually illustrated in Figure 1, which links environmental cost identification, cost drivers, budgeting mechanisms, KPI systems, and managerial decision-making processes.

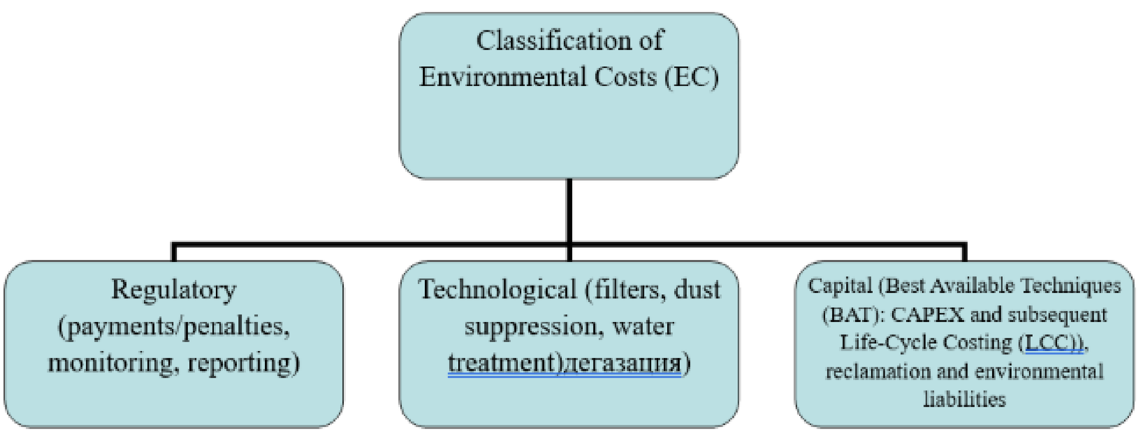

Figure 1 – Framework of Green Management Accounting for Sustainable Performance in the Coal Mining Industry of Kazakhstan

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The approach follows a structured sequence. First, using EMA, ABC, MFCA, and LCC, environmentally relevant material and cost flows are decomposed and allocated across responsibility centers and production stages. At this stage, green KPIs are calculated, including energy and carbon intensity, material losses, and reclamation performance.

Second, based on panel data, the relationships between these indicators and financial outcomes (e.g., margins and unit costs) are estimated using fixed-effects (FE) models, complemented by machine learning with explainable AI (XAI) techniques (e.g., SHAP) to identify key drivers and threshold effects.

Finally, managerial interventions – such as the introduction of an internal environmental payment coefficient (EPC) and eco-controlling/Sustainability Balanced Scorecard (SBSC) mechanisms – are evaluated through LCC-based scenarios and empirical strategies (e.g., difference-in-differences (DiD) and instrumental variables (IV)). This allows assessing how such interventions influence BAT investments and overall sustainable performance in the coal mining industry of Kazakhstan.

Cost Objects	Green KPIs (example set)	Methods
Ton of coal produced; site; open-pit mine/underground mine; BAT project; reclamation stage	E1: CO_2 intensity, tCO_2e/t	EMA + ABC/ABB – allocation of environmental costs (EC) based on cost drivers: pump machine-hours, m³ of pumped water, ton-kilometers of dump trucks, Gcal of heat for drying, hectares of reclamation
LCC – comparison of BAT alternatives based on full life-cycle cost	E2: Water intensity, m^3/t	LCC – comparison of Best Available Techniques (BAT) based on full life-cycle cost;
Green BSC – integration of KPIs into the "process–customer–finance–learning" framework	E3: Share of reclaimed land, % of disturbed land	Green BSC – integration of KPIs into the "process–customer–finance–learning" perspectives.
	E4: CH_4 emissions per ton, kg/t (for underground mines)	
	E5: Energy intensity, kWh/t	
	E6: Share of BAT in equipment fleet, %	
	E7: Share of green procurement/services, %	
	E8: Environmental costs per ton, KZT/t	

Figure 2 – Structure of Cost Objects, Methods, and Green KPIs

The framework begins with defining cost objects: ton of coal produced, process/site (stage), open-pit mine or underground operation, BAT project, and reclamation stage. Next, using EMA combined with ABC/ABB, environmental costs are allocated to specific cost drivers - such as pump machine-hours, cubic meters

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of water pumped, ton-kilometers of haul trucks, Gcal of drying heat, and hectares of reclaimed land—resulting in more accurate cost attribution across objects.

In parallel, a system of green KPIs is calculated: E1 – CO_2 intensity; E2 – water intensity; E3 – share of reclaimed land; E4 – CH_4 emissions per ton; E5 – energy intensity; E6 – share of BAT in the equipment fleet; E7 – share of green procurement; E8 – environmental costs per ton.

For investment decisions, BAT alternatives are evaluated using Life-Cycle Costing (LCC) to account for total life-cycle costs, including CAPEX, OPEX, and future environmental obligations. Subsequently, these KPIs are embedded into a Green Balanced Scorecard (BSC) framework (process–customer–finance–learning) and linked to the incentive systems of responsibility centers.

For performance analysis, cost-type KPIs (E1, E2, E5, E8) are normalized and assessed in relation to financial indicators such as margins and unit costs. The outcome is a transparent map of environmental costs and performance metrics, enabling more informed budgeting and guiding investment decisions toward Best Available Techniques (BAT), thereby enhancing sustainable performance in Kazakhstan's coal mining industry.

Analysis and Results.

Descriptive statistics reveal substantial variability in green KPIs across sites and over time. Energy and water intensity exhibit asymmetric distributions, while the reclamation ratio shows pronounced seasonality. Correlation analysis identifies robust cost-type relationships: higher CO_2 intensity and MFCA-based loss indicators are associated with higher unit costs and lower margins.

In fixed-effects (FE) models, the coefficients for EnergyInt, CarbonInt, and MFCA_loss_cost are negative and statistically significant for profitability measures (ROS/margin), even after controlling for firm-specific and time effects. In terms of magnitude, MFCA_loss_cost emerges as the strongest driver of cost variation, highlighting hidden material losses as a key efficiency reserve. The inclusion of benefit-type KPIs – such as the share of BAT in the equipment fleet and the share of green procurement – is associated with higher margins and lower cost of goods sold per ton (COGS/t) with a lag of t+1–t+2, reflecting the inertia of the investment cycle. Spline-based models identify threshold levels of energy and water intensity beyond which the marginal impact on profitability sharply deteriorates, indicating nonlinear "knee-point" effects.

Interaction terms show that the effect of reducing material losses (MFCA) is amplified when the share of BAT is high, suggesting that technological modernization accelerates the monetization of identified inefficiencies. In the investment activity equation, the coefficient for the internal environmental payment coefficient (EPC) is positive: higher internal pricing of environmental risks leads to increased CAPEX in BAT and a higher likelihood of project initiation. Comparative LCC analysis of BAT alternatives confirms that accounting for reclamation and water treatment shifts NPV in favor of cleaner technologies.

Machine learning models with XAI (TreeSHAP) confirm the ranking of key drivers: the top five include MFCA_loss_cost, EnergyInt, CarbonInt, share of BAT, and water intensity. Local explanations (SHAP force plots) at the responsibility-center level illustrate why some sites remain low-margin: high loss profiles and energy intensity offset gains from price factors. Asset-type segmentation reveals that for underground mines, CH_4 emissions per ton and ventilation energy intensity are critical, while for open-pit operations, water intensity and transport/dust suppression losses dominate.

Robustness checks using alternative specifications (quantile regression, RE-GLS, inclusion of firm-specific trends) confirm the stability of results. A quasi-natural experiment using a difference-in-differences (DiD) design around the introduction of an internal EPC shows accelerated reductions in EnergyInt and Losses% in treated sites relative to controls.

The economic interpretation highlights the prioritization of MFCA-based loss mapping and energy efficiency projects as the most impactful levers for margin improvement, largely independent of market volatility. A key managerial implication is to embed green KPIs into the Sustainability Balanced Scorecard (SBSC) and incentive systems of responsibility centers, calibrate the internal EPC, and apply LCC in BAT investment

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selection. This ensures an integrated management loop: data → budgets → KPIs → incentives → investments, supporting sustained performance improvements.

Formulas and Calculation Guide

Environmental costs per ton:

$$\frac{EC}{t} = \frac{Environmental\ OPEX + CAPEX}{Output\ (tons)}$$

1. Normalized KPI score (cost-type):

$$Score = 100 \cdot \frac{X_{max} - X_i}{X_{max} - X_{min}}$$

2. Normalized KPI score (benefit-type):

$$Score = 100 \cdot \frac{X_i - X_{min}}{X_{max} - X_{min}}$$

3. Aggregate Green Score (weights sum to 1):

$$GreenScore_i = \sum_j w_j \cdot Score_{ij}$$

4. EPC threshold (conceptual form):

$$\alpha^* = \frac{EBITDA}{E}, \quad E = CarbonIntensity \cdot Q$$

At $\alpha \geq \alpha^*$, projects without BAT become economically unviable; the solution is to reduce E through BAT adoption and/or improve operational efficiency.

Illustrative Statistical Example (demonstration purposes). Environmental costs per ton at Karazhyra JSC (open-pit mine):

– 2023: Output = 12.0 million tons; EC = 5.4 billion KZT → EC/t = 450 KZT/t;
– 2024: Output = 12.5 million tons; EC = 5.0 billion KZT → EC/t = 400 KZT/t.

Result: a decrease of −11.1% alongside a production increase of +4.2%. Managerial implication: cost reduction achieved through BAT implementation and optimized water management; recommended to formalize “BAT-driven savings” in budgeting and set a benchmark target of ≤ 420 KZT/t.

Table 1 – Integrated Green Performance Assessment of Enterprises (KPI Normalization)

Indicator	Karazhyra JSC	Bogatyr JSC	Batyr LLP	Esil LLP
Production, million tons	12.5	10.0	7.5	5.0
CO_2 intensity, tCO_2e/t (↓ better)	0.09	0.11	0.08	0.12
Water intensity, m^3/t (↓)	0.70	0.90	0.60	1.20
Reclamation ratio (↑)	65%	50%	70%	40%

Discussion and Practical Implications.

The results of the integrated green KPI assessment highlight clear performance differentiation across enterprises. Batyr LLP emerges as the leader, demonstrating the lowest CO_2 intensity (0.08 tCO_2e/t), the best water efficiency (0.60 m^3/t), and the highest reclamation rate (70%). In contrast, Esil LLP represents the lagging case, with the weakest performance across all three indicators (CO_2: 0.12; water: 1.20; reclamation: 40%). Karazhyra JSC shows relatively balanced performance (CO_2: 0.09; water: 0.70) combined with a high reclamation rate (65%), indicating targeted potential for improving energy and water efficiency. Bogatyr JSC demonstrates near-average performance (CO_2: 0.11; water: 0.90; reclamation: 50%), with priority areas including decarbonization and accelerated reclamation.

Priority actions can therefore be differentiated:

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- Esil LLP – focus on water efficiency and decarbonization;
- Bogatyr JSC – CO_2 reduction and reclamation improvements;
- Karazhyra JSC – further gains in water and energy efficiency;
- Batyr LLP – consolidation and scaling of best practices across other assets.

Using min–max normalization (0–100 scale) with weights (CO_2 = 0.5, water = 0.3, reclamation = 0.2), the resulting green scores confirm this ranking: Batyr (100), Karazhyra (~79.2), Bogatyr (~34.2), and Esil (0). These results illustrate the practical value of KPI normalization for benchmarking and strategic prioritization.

The relationship between green KPIs and financial performance is further supported by illustrative data for 2024: EBITDA margins are 26% (Karazhyra), 22% (Bogatyr), 28% (Batyr), and 18% (Esil). The Pearson correlation between the aggregated green score and EBITDA margin is strongly positive ($r \approx +0.998$, illustrative), suggesting that reductions in carbon and water intensity are closely associated with improved operational efficiency, energy management, and logistics, ultimately supporting profitability. This underscores the importance of embedding green KPIs into managerial incentive systems.

A key analytical tool is the threshold environmental payment coefficient (EPC). For Bogatyr JSC, with output of 10 million tons and CO_2 intensity of 0.11 t/t (total emissions E = 1.1 million tCO_2e), revenue of 120 billion KZT, and EBITDA of 26.4 billion KZT, the break-even EPC level is approximately 24,000 KZT/tCO_2. At or above this threshold, operations become economically unviable without BAT adoption. This provides a practical benchmark for internal environmental pricing and investment planning, consistent with threshold-based and Pareto-optimal decision frameworks.

Green controlling practices should be structured as follows:

1. Responsibility centers: define units (mining, transport, processing, water and energy management, reclamation) with assigned KPIs (E1–E8) and cost drivers.
2. Budgeting: introduce dedicated "green" OPEX/CAPEX categories (filters, pumps, dust suppression, reclamation, monitoring) and set KPI limits (e.g., $CO_2 \leq 0.10$ t/t; water ≤ 0.75 m^3/t; reclamation $\geq 60\%$).
3. Plan–actual analysis: conduct monthly variance analysis based on drivers (water, energy, ton-km), supported by ABC-based deviation maps and integrated dashboards.
4. Investment appraisal: apply LCC models with an internal EPC (carbon/environmental price) to align decisions with sustainability objectives.

Practical recommendations include:

- Enhancing transparency by separating visible environmental costs (payments, services) from hidden costs (energy losses, excess water use, idle capacity), which often represent the largest efficiency reserves;
- Standardizing all KPIs and costs on a per-ton basis to ensure comparability;
- Applying normalization and benchmarking tools (e.g., min–max scaling, traffic-light thresholds);
- Linking managerial incentives directly to green KPIs with defined weights;
- Implementing phased improvement roadmaps for underperforming sites, with quarterly milestones and oversight at the investment committee level.
- Limitations.

The presented examples are illustrative and demonstrate the methodology. For rigorous empirical validation, future research should employ actual enterprise-level data for 2015–2024, harmonize calculation methods for key indicators (tCO_2e/t, m^3/t, reclamation rates), and incorporate controls for industry- and region-specific factors (deposit type, stripping ratio, depth, transport conditions).

Conclusion. The integration of management accounting with green metrics transforms environmental issues from a cost burden into a domain of managed performance. The use of green KPIs and environmental cost calculation on a per-ton basis creates transparent incentives, while the application of threshold mechanisms such as the environmental payment coefficient (EPC) and Pareto-based logic supports rational decision-making regarding the timing and scale of Best Available Techniques (BAT) adoption. For Kazakhstan's coal mining industry, this enables the stabilization of profitability while simultaneously reducing environmental intensity and

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associated risks.

The analysis demonstrates that integrating management accounting tools—EMA, ABC/ABB, MFCA, and LCC - with green metrics shifts environmental considerations into the core of value creation and margin management. Cost-type KPIs (CO_2 intensity, water intensity, energy intensity, environmental costs per ton) are consistently associated with higher unit costs and lower profitability, whereas benefit-type KPIs (reclamation rates, BAT adoption, green procurement) are linked to improvements in operational and financial performance with a lag reflecting implementation cycles. MFCA plays a critical role by identifying hidden material and energy losses as the primary reserve of efficiency gains. Prioritizing loss maps and energy efficiency projects yields the highest marginal returns and is less sensitive to market volatility.

The introduction of an internal EPC enhances investment discipline: increasing the implicit "price of environmental risk" raises the likelihood of BAT implementation and reallocates CAPEX toward projects with positive life-cycle value (LCC-based NPV). Standardizing KPIs on a per-ton basis, aligning cost drivers through ABC/ABB, and embedding green metrics into the Sustainability Balanced Scorecard (SBSC) and incentive systems ensure an integrated management loop: data → budgets → KPIs → incentives → investments.

Illustrative calculations confirm the managerial relevance of the approach. A reduction in environmental costs per ton alongside increased production demonstrates the effectiveness of BAT and supports realistic target-costing benchmarks for subsequent budgeting cycles. The aggregated green performance assessment provides a transparent and replicable benchmarking tool: leadership is achieved through a combination of low carbon and water intensity with high reclamation rates, while lagging performance reflects weaknesses across all dimensions. The strong positive relationship between green scores and EBITDA margins indicates that decarbonization and resource efficiency are often accompanied by improvements in logistics and operational efficiency, ultimately enhancing financial outcomes. The EPC threshold analysis defines a "red zone" in which operations become economically unviable without modernization, thereby establishing internal reference points for environmental pricing and investment planning.

Practical recommendations include: (1) embedding green KPIs into SBSC frameworks and performance-based compensation systems; (2) introducing an internal EPC and applying LCC models for BAT investment selection; (3) conducting regular variance analysis based on EMA/ABC–ABB cost drivers; (4) scaling best practices from leading sites to underperforming assets through phased implementation roadmaps.

From a policy perspective, the standardization of KPI calculation methodologies and the gradual calibration of environmental payment systems – aligned with access to financing for BAT – are essential for sector-wide transformation.

Limitations and future research. The presented results are based on illustrative examples and simplified assumptions. Further empirical validation requires the use of firm-level data for 2015–2024 (2025), harmonized methodologies for key indicators (tCO_2e/t, m^3/t, reclamation rates), and controls for geological and technological heterogeneity. Future research should focus on causal inference approaches (DiD/IV), modeling KPI threshold effects, and testing XAI-based explanations on representative datasets.

Overall, the proposed framework establishes a foundation for green controlling in Kazakhstan's coal mining industry, enabling sustained profitability alongside reduced environmental intensity and risk exposure.

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