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Scenario Analysis of Risks and Opportunities in Kazakhstan's Industrial Transition to Carbon Neutrality

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Abstract
The transition to carbon neutrality represents a strategic imperative for large industrial companies in Kazakhstan in the context of global climate challenges and increasingly stringent environmental requirements. The purpose of this study is to develop an integrated risk and opportunity management framework for industrial decarbonization in Kazakhstan based on scenario modelling and expert assessment. The study uses a mixed methodological approach combining quantitative and qualitative methods of analysis. The empirical basis of the study was made up of sectoral data on greenhouse gas emissions in Kazakhstan's industry for 2015-2024, official statistics from government agencies, corporate non-financial reports, as well as the results of 32 semi-structured expert interviews with representatives of industrial companies, government regulators and international organizations. The results of the study show that Kazakhstan's industrial CO_2 emissions increased 18.1% from 224.7 million tonnes (2015) to 265.4 million tons (2024), with metallurgy accounting for 35.9%, energy 28.1%, oil and gas 22.8%, and chemicals 13.4%. Scenario analysis shows that under the business-as-usual scenario, emissions could increase to 322.5 million tons of CO_2 by 2050, while the moderate scenario reduces emissions to 102.3 million tons (55% compared to 2024), and the ambitious scenario to 35 million tons (-84%). This research extends sustainability theory by demonstrating how to transition economy characteristics-legacy infrastructure, resource dependence, institutional capacity-shape decarbonization pathways, providing actionable insights for climate policy formulation and corporate strategy in resource-rich developing nations.

KEYWORDS
Economy, Transition Economy, Carbon Neutrality, Decarbonization, Green Transformation, Climate Strategy, Energy Transition, Sustainable Development

1 | INTRODUCTION

In the context of the global climate crisis and strengthening international commitments to reduce greenhouse gas emissions, the transition to carbon neutrality is becoming a central element of strategic development for industrial companies worldwide (Fankhauser et al., 2022). The Republic of Kazakhstan, as a country with an economy heavily dependent on carbon-intensive industries-metallurgy, energy, the oil and gas sector, and the chemical industry-faces particular challenges in the decarbonization process (Karatayev & Clarke, 2016).

Kazakhstan's adoption of commitments to achieve carbon neutrality by 2060 and ratification of the Paris Agreement have created a new paradigm for domestic industrial companies (President of the Republic of Kazakhstan, 2023). According to the updated Nationally Determined Contribution (NDC), Kazakhstan plans to reduce greenhouse gas emissions by 15% by 2030 compared to 1990 levels (Republic of Kazakhstan, 2023). This requires large-scale transformation of the industrial sector, which accounts for more than 60% of the country's total CO_2 emissions (Ministry of Ecology of the RK, 2024).

Large industrial companies in Kazakhstan face the need to simultaneously address several challenges: maintaining competitiveness in international markets amid the introduction of cross-border carbon regulation (hereinafter – CBAM), modernizing outdated production facilities, attracting investment in green technologies, and developing human capital to manage low-carbon processes (Montalvo et al., 2018).

The process of industrial decarbonization is characterized by high uncertainty and a range of risks, including technological, financial, regulatory, market, and social (Bataille et al., 2018). At the same time, it creates significant opportunities for innovation, efficiency improvements, access to new capital markets, and the strengthening of companies' reputations as responsible corporate citizens (Kiehbadroudinezhad et al., 2023; Kobashi et al., 2025).

Despite growing attention to carbon neutrality issues in the scientific literature, research specifically focusing on risk and opportunity management in the context of transition economies and carbon-intensive industries remains limited (Lioubimtseva & Henebry, 2009). Existing work predominantly focuses either on the technical aspects of decarbonization or on the macroeconomic consequences of climate policy, paying insufficient attention to the micro-level of decision-making in the corporate sector.

This study addresses this research gap through three distinct contributions. First, methodologically, we integrate LEAP-based quantitative scenario modelling with qualitative expert insights and SWOT-risk matrix analysis, thereby providing reproducible computational procedures that are lacking in prior conceptual studies. Second, empirically, we present the first comprehensive assessment of sectoral-level (metallurgy, energy, oil and gas, chemicals) decarbonization pathways in Kazakhstan with explicit quantification of investment requirements ($140-450 billion range), technological trajectories, and socio-economic trade-offs across multiple 2050 scenarios. Third, transition management theory demonstrates that legacy infrastructure lock-in, resource dependence, and institutional capacity constraints in resource-rich transition economies necessitate distinct decarbonization strategies relative to those of developed nations, thereby informing actionable frameworks for climate policy formulation in similar contexts (Azerbaijan, Mongolia, Uzbekistan). The purpose of this study is to develop an integrated risk and opportunity management framework for industrial decarbonization in Kazakhstan based on scenario modelling and expert assessment. To achieve this objective, the study addresses the following tasks:

(1) systematization of theoretical approaches to risk and opportunity management in

the context of sustainable development and decarbonization;

(2) identification and assessment of key risks and opportunities of the transition to carbon neutrality for various sectors of the Kazakh industry;

(3) analysis of the current state and dynamics of greenhouse gas emissions in the industrial sector of the Republic of Kazakhstan;

(4) development of decarbonization scenarios and assessment of their socio-economic consequences;

(5) formulation of recommendations for risk management and opportunity realization for industrial companies and government authorities.

2 | LITERATURE REVIEW

The concept of carbon neutrality is based on the need to balance anthropogenic greenhouse gas emissions with their absorption to limit global warming, in accordance with the goals of the Paris Agreement (IPCC, 2018). Industrial decarbonization is the systematic reduction of the carbon intensity of production processes through the introduction of low-carbon technologies, improved energy efficiency, a transition to renewable energy sources, and the application of carbon capture and storage technologies (Rogelj et al., 2018).

Several theoretical approaches to analyzing decarbonization processes have emerged in the scientific literature. Ecological modernization theory views the transition to a low-carbon economy as an opportunity for innovation and enhanced competitiveness (Vakulchuk & Overland, 2021). The concept of carbon lock-in emphasizes the role of technological, institutional, and behavioral barriers that impede rapid transition to sustainable practices (Unruh, 2000; Seto et al., 2016). Transition theory focuses attention on the multi-level nature of socio-technical systems transformation (Geels, 2011; Köhler et al., 2019). The concept of a just transition plays an important role in understanding decarbonization processes, emphasizing the need to account for the social consequences of climate policy and to ensure the protection of workers and communities dependent on carbon-intensive industries (McCauley & Heffron, 2018; Stevis & Felli, 2020). For transition economies such as Kazakhstan, this aspect is particularly significant given the high dependence of the national economy on the extraction and export of carbon resources (Overland & Sovacool, 2020).

The literature on corporate climate risk management identifies several categories of risks associated with the transition to a low-carbon economy. Physical risks arise from the direct impacts of climate change on companies' operational activities (Kahn et al., 2021). Transition risks are associated with the process of adapting to a low-carbon economy and encompass political and regulatory risks, technological risks, market risks, and reputational risks (Sansyzbayev et al., 2025). Regulatory risks for industrial companies include the introduction of carbon pricing, tightening of environmental standards, and reporting requirements (Aldy & Stavins, 2012). The EU's CBAM is particularly relevant for export-oriented companies, as it may significantly affect the competitiveness of products from countries with high carbon-intensity production (Mehling et al., 2019; Cosbey et al., 2019). Technological risks are associated with the need for large-scale investments in production modernization amid high uncertainty regarding technological trajectories and commercial viability of low-carbon solutions (Aubakirova et al., 2023). For heavy industry, such as metallurgy and cement production, technological challenges are particularly significant due to the complexity of decarbonizing high-temperature processes (Bataille et al., 2018).

Financial risks include stranded assets, increased cost of capital for companies with high carbon footprints, and potential losses from delayed transition. Research shows that investors are increasingly incorporating climate risks into their investment decisions, as reflected in the growth of ESG investing (Dimson et al., 2020). Simultaneously, the transition to carbon neutrality creates significant opportunities for companies. Investments in energy efficiency can substantially reduce operating costs, with relatively short payback periods (Wang et al., 2022). Development and implementation of low-carbon technologies open new markets and create competitive advantages (Ambec et al., 2013). Access to green financing, including green bonds, concessional loans, and grants, is becoming an important source of capital for decarbonization projects (Flammer, 2021; Fatica & Panzica, 2021). Improved environmental image and ESG performance contribute to attracting investment, increasing customer loyalty, and strengthening positions in markets with high environmental requirements (Friede et al., 2015; Fatemi et al., 2018).

Analysis of international experience shows a diversity of approaches to industrial decarbonization. The European Union implements a comprehensive climate policy, including the Emissions Trading System (EU ETS), promotion of innovation through research and development programs, and support for the circular economy (Pahle et al., 2018). Germany provides a successful example of energy-sector transformation (Energiewende), with the large-scale development of renewable energy sources (Amini et al., 2015). China, as the largest emitter of greenhouse gases, is actively investing in low-carbon technologies and clean energy development, while simultaneously facing challenges associated with the structural transformation of its carbon-intensive economy (Zhao et al., 2022). The national emissions trading system, launched in 2021, became the world's largest by emissions coverage (Zou et al., 2021). Gulf countries, whose economies have traditionally depended on the oil and gas sector, are developing diversification strategies with an emphasis on renewable energy and the development of a hydrogen economy (Munawer, 2018). Saudi Arabia and the UAE are investing billions of dollars in solar energy and green hydrogen production (Tawalbeh et al., 2021).

For Kazakhstan, the experience of countries with similar economic structures is of particular interest. Research shows that countries with carbon-intensive economies can successfully implement decarbonization with long-term political will, institutional support, and investments in human capital (Kern et al., 2019; Sovacool et al., 2020). However, the process requires careful management of social consequences, including worker retraining and support for regions dependent on carbon-intensive industries (Healy & Barry, 2017).

Studies on the decarbonization of Kazakhstan's industry have become more numerous in recent years, reflecting the topic's growing relevance. Karatayev and Clarke (2016) analyze the potential of renewable energy in Kazakhstan, noting rich solar and wind energy resources alongside existing institutional and financial barriers to their development. Vakulchuk and Overland (2021) investigated pathways for energy-sector decarbonization, emphasizing the need to modernize outdated infrastructure and improve energy efficiency.

Turekulova et al. (2023) analyzed the readiness of Kazakh companies to implement ESG principles and decarbonization, identifying a significant gap between declared goals and actual actions. The authors emphasize the importance of developing a national carbon accounting and reporting system and of creating incentives for private investment in green technologies. An important contribution to understanding the socio-economic aspects of decarbonization has been made by works analyzing the impact of climate policy on regional development and employment in carbon-intensive regions of Kazakhstan (Aubakirova et al., 2023). These studies emphasize the need to develop just transition programs that ensure social protection and create alternative employment opportunities.

Despite the growing number of works, the issue of risk and opportunity management at the micro-level-the level of individual companies and industries-remains insufficiently studied. There is a need for comprehensive research that integrates the technological, economic, institutional, and social dimensions of decarbonization, while accounting for the specific characteristics of the Kazakh industrial sector. The present study aims to fill this gap. following section.

3 | RESEARCH METHODS

This study employs a mixed-methods approach that integrates quantitative and qualitative methods to provide a comprehensive analysis of the risks and opportunities of industrial decarbonization in Kazakhstan. The study's conceptual framework integrates risk management theory, sustainable development, and strategic management approaches. The research is structured into several interconnected stages:

(1) systematic analysis of statistical data on greenhouse gas emissions and energy consumption of industrial enterprises;

(2) expert interviews with representatives of large industrial companies and regulatory authorities;

(3) scenario modelling of decarbonization trajectories;

(4) SWOT analysis and risk matrix assessment;

(5) development of recommendations and a roadmap.

The study's temporal horizon covers 2015-2024 for retrospective analysis and projects development scenarios through 2050 in accordance with national climate goals. The sectoral focus of the study is concentrated on four key sectors of the Kazakh industry: metallurgy, energy, the oil and gas sector, and the chemical industry, which account for more than 85

Quantitative data were collected from several sources: official statistics from the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the RK, reports from the Ministry of Ecology and Natural Resources of the RK, corporate sustainability reports of the largest industrial companies, and databases of international organisations (IEA, World Bank, OECD). In total, more than 150 corporate reports and 80 regulatory and strategic documents were analyzed.

Qualitative data were obtained through a series of semi-structured expert interviews conducted from March to August 2024. The sample included 32 experts representing various stakeholders: top managers and heads of sustainability departments at large industrial companies (18), representatives of government agencies (8), and experts from international organizations and consulting companies (6). Interview duration ranged from 45 to 90 minutes. Expert selection was carried out based on criteria of experience relevance, position held, and sectoral representation. To ensure confidentiality and obtain maximally candid responses, interviews were conducted with guarantees of anonymity. All interviews were recorded with respondents' consent and transcribed for subsequent analysis. Data saturation was achieved after 28 interviews, with the subsequent 4 interviews confirming the absence of new themes.

Descriptive statistics, trend analysis, and scenario modelling were applied to analyse quantitative data. CO_2 emissions dynamics were analyzed using the index method and decomposition analysis to identify factors affecting changes in carbon intensity. The LEAP (Long-range Energy Alternatives Planning System) model, widely used for energy and climate planning, was employed to forecast future emissions trajectories. The LEAP model configuration for Kazakhstan's industrial sector included the following key parameters:

(1) baseline year 2015 with historical calibration through 2024;

(2) four sectoral modules (metallurgy, energy, oil and gas, chemicals) with sector-specific emission factors;

(3) technology database containing 45 decarbonization technologies with associated costs ($/tonne CO_2 abated), implementation timelines, and technical potentials;

(4) fuel mix parameters including emission intensities (tCO_2/TJ) for coal (94.6), natural gas (56.1), and oil products (73.3);

(5) annual GDP growth projections (3.5-4.2%) and industrial output elasticities (0.85-1.15) as demand drivers;

(6) renewable energy penetration rates varying by scenario (BAU: 3-8%, Moderate: 15-30%, Ambitious: 40-70%);

(7) carbon price trajectories ($0-15/tonne in BAU, $20-40 in Moderate, $80-150 in Ambitious scenarios);

(8) technology learning rates (5-15% cost reduction per doubling of capacity) for emerging technologies like hydrogen and CCUS.

Emissions were calculated using the IPCC Tier 2 approach: $E = AD \times EF \times (1\text{-}ER)$, where E represents emissions, AD is activity data (energy/material consumption), EF is the emission factor, and ER is the emission reduction rate from implemented technologies. Model validation was performed on historical data from 2015-2024, achieving a mean absolute percentage error (MAPE) of 4.3

Development of decarbonization scenarios was based on IPCC methodology and considered three main trajectories: baseline scenario (business-as-usual), assuming continuation of current trends; moderate scenario, envisioning gradual strengthening of climate policy aligned with Kazakhstan's NDC commitments; ambitious scenario, oriented toward achieving the Paris Agreement's 1.5°C pathway targets by 2050, which is more aggressive than Kazakhstan's national carbon neutrality goal of 2060. For each scenario, necessary investments, technological trajectories, and socio-economic consequences were assessed.

Risk matrix construction involved systematic assessment of identified risks and opportunities across two dimensions: probability of realization (P) rated on a 0-1 scale based on expert consensus (0-0.3 low, 0.3-0.7 medium, 0.7-1.0 high), and impact magnitude (I) on business operations rated on a 0-1 scale considering financial, operational, and strategic consequences. The risk priority score (RPS) was calculated as $RPS = P \times I \times W$, where W denotes sector-specific weighting factors (metallurgy 1.2, energy 1.15, oil and gas 1.1, chemicals 1.0) reflecting sectoral emission intensity and exposure to climate policies. Risks scoring RPS greater than 0.6 were classified as critical, requiring immediate mitigation strategies, 0.3-0.6 as moderate, requiring monitoring and contingency planning, and less than 0.3 as low, requiring awareness. The SWOT framework integrated qualitative expert assessments with quantitative data: Strengths and Weaknesses were evaluated through analysis of company-level capabilities (technology readiness levels 1-9, financial capacity metrics, human capital indicators), while Opportunities and Threats were assessed through external market analysis (green premium potential, regulatory policy trajectories, competitive landscape shifts). Cross-impact analysis examined SWOT element interactions using a 5×5 matrix to identify strategic priorities maximizing strengths-opportunities alignment and minimizing weaknesses-threats exposure.

Qualitative data from interviews were analyzed using thematic analysis method. Transcripts were coded in NVivo using both inductive and deductive approaches. Initial codes were grouped into thematic categories, which were subsequently combined into broader themes that reflected key risks, opportunities, and strategic priorities. The integration of quantitative and qualitative data was conducted during the interpretation of results. Quantitative data on emissions and economic indicators were contextualized through the lens of expert assessments and practitioners' opinions. Triangulation of multiple data sources and analytical methods ensured the reliability and validity of the results obtained.

This study has several limitations that must be considered when interpreting the results. First, the availability and quality of greenhouse gas emissions data at the individual enterprise level are limited, owing to incomplete corporate reporting and differences in accounting methodologies. Second, the expert sample, while representative of large industrial companies, does not cover small and medium-sized businesses. Third, the high degree of uncertainty regarding future technology development and political decisions limits the accuracy of long-term forecasts. Fourth, the figures presented in this manuscript are constrained by the original data visualization formats provided in corporate and government reports; while efforts were made to enhance clarity, readers should note that some graphical elements reflect source document limitations rather than analytical choices. Enhanced vector-format visualizations are planned for subsequent publications.

4 | RESULTS

Analysis of greenhouse gas emissions dynamics in Kazakhstan's industrial sector for the period 2015-2024 reveals a sustained upward trend in total CO_2 emissions, despite individual periods of decline. This growth is driven by the expansion of production capacity and increased industrial output. Figure 1 demonstrates that total industrial emissions increased from 224,7 million tons of CO_2 in 2015 to 265,4 million tons in 2024, representing a 18,1% increase.

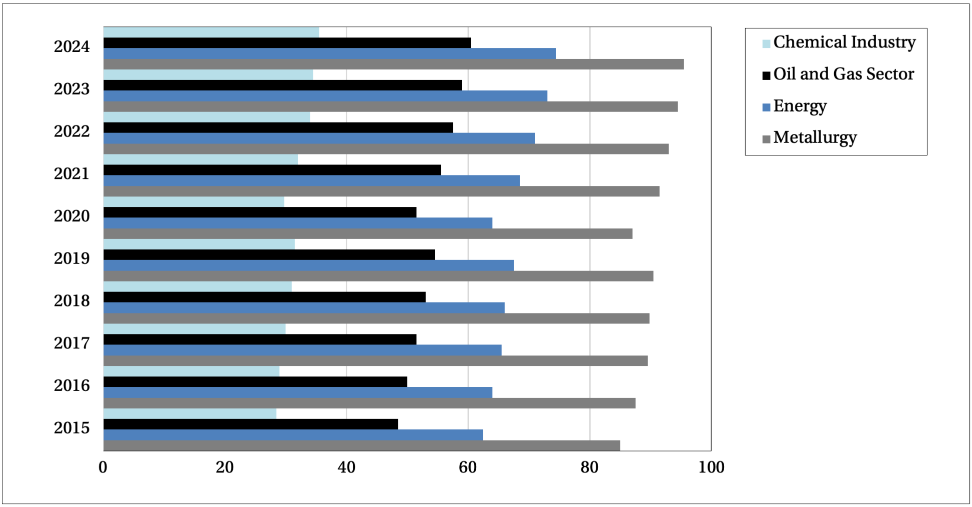

Figure 1 GHG emissions by industrial sectors in Kazakhstan, 2015–2024

The sectoral structure of emissions is characterized by dominance of the metallurgical sector, which accounts for 35,9% of total industrial emissions in 2024 (95,5 million tons of CO_2). The energy sector generates 28,1% of emissions (74,5 million tons), the oil and gas sector - 22,7% (60,3 million tons), and the chemical industry - 13,2% (35,1 million tons). Notably, emissions growth rates differ across sectors: the highest rates are observed in the chemical industry (23.2% over the period) and the oil and gas sector (23.8%), while in metallurgy and energy, the growth was more moderate (12.1% and 19.6%, respectively). An important indicator is the carbon intensity of industrial production, which averages 425,6 tons of CO_2 per million US dollars of value added, significantly exceeding global averages and indicators of developed countries. This reflects the outdated technological base of the Kazakh industry and the predominance of energy-intensive production. A positive development is the recent trend toward reducing specific carbon intensity in some sectors, which is linked to the implementation of modernisation projects and energy-efficiency improvements. Descriptive statistics for key indicators indicate substantial variability across companies and sectors (Table 1).

Table 1 Descriptive statistics of indicators for industrial companies of Kazakhstan for 2015–2024

Indicator	Mean	Median	Std. Deviation	Minimum	Maximum
Total CO_2 emissions (million tons)	265,4	263,8	15,7	245,1	295,8
Carbon intensity (tons CO_2/million USD)	425,6	420,3	35,2	380,5	485,7
Share of RES (%)	3,8	3,5	1,2	2,1	6,2
Investments in decarbonization (billion USD)	2,4	2,2	0,8	1,2	4,1
Number of enterprises with carbon neutrality targets	17	–	4,5	12	26

Note: compiled by the authors

The standard deviation of total CO_2 emissions is 15,7 million tons, indicating significant heterogeneity among enterprises in terms of the scale of their environmental impact. The share of renewable energy sources in the industrial sector remains extremely low, averaging only 3,8%, with a maximum of 6,2% among the most progressive companies. Investments in decarbonization average 2,4 billion US dollars per year. The median value (2,2 billion dollars) indicates that most companies invest less than the average. The number of enterprises that have established carbon-neutrality targets increased from 12 in 2015 to 26 in 2024, indicating growing awareness of the importance of the climate agenda.

Based on SWOT analysis conducted using data from expert interviews and documentary sources, a comprehensive matrix of risks and opportunities for the transition to carbon neutrality for industrial companies in Kazakhstan was developed. The analysis identified key strengths (availability of natural resources for RES and large industrial capacity), weaknesses (high carbon intensity and technological lag), opportunities (access to green financing and new markets), and threats (regulatory risks and competition from low-carbon producers). Figure 2 presents the positioning of key risks and opportunities along the axes of probability of realisation and level of impact on the business.

Regulatory risks are assessed by experts as the most significant (probability 0,85, impact 0,90). These risks include the introduction of stricter carbon pricing, tightening of environmental standards, and, especially, the impact of the EU's CBAM. According to respondents' estimates, CBAM could increase export product costs by 15%-35% for the most carbon-intensive sectors. "The introduction of CBAM is a game-changer. We will have to either pay enormous carbon fees or radically change production technologies" notes the head of the sustainability department of one of the large metallurgical companies.

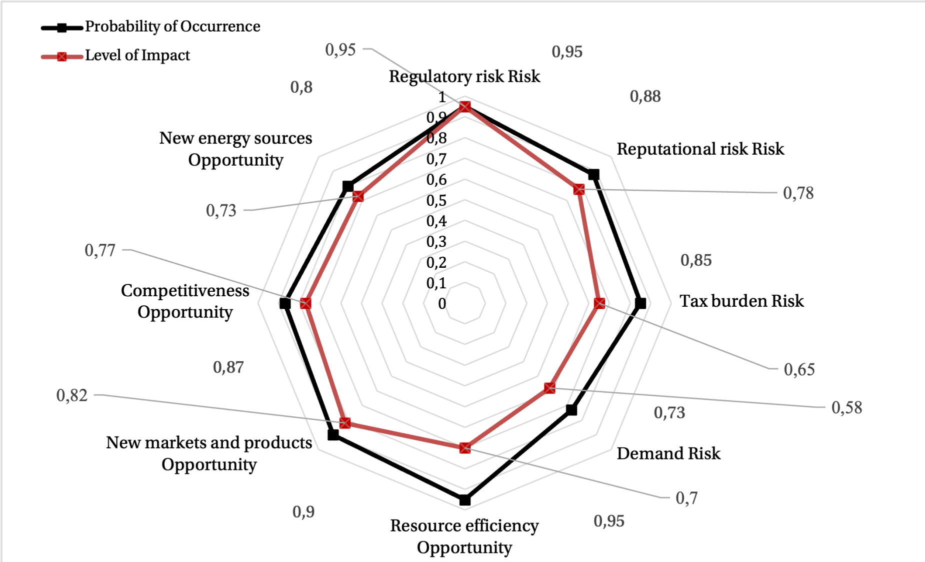

Figure 2 Risk and opportunity matrix for the transition to carbon neutrality

Financial risks (probability 0,75, impact 0,85) are associated with the need for large-scale capital investments amid limited access to long-term financing. Experts point to the high cost of borrowed capital in Kazakhstan and the insufficient development of green financing instruments. Modernization of a single metallurgical plant is estimated at 1,5-2,5 billion US dollars, which is comparable to the annual revenue of an average enterprise in the sector. Technological risks (probability 0,70; impact 0,75) arise from uncertainty regarding optimal technological pathways for decarbonization, particularly in heavy industry. Many promising technologies, such as hydrogen metallurgy and carbon capture and storage, are in early stages of commercialization. Dependence on imported technologies creates risks to technological sovereignty and increases implementation costs.

Market risks (probability 0,65, impact 0,80) include changes in demand structure, increased competition from companies that have already implemented decarbonization, and volatility in energy prices. Reputational risks (probability 0,60; impact 0,70) are associated with growing expectations from investors, customers, and the public regarding companies' environmental responsibility.

Alongside risks, the transition to carbon neutrality creates significant opportunities. Improving energy efficiency (probability 0,80; impact 0,85) is considered the most accessible and economically attractive strategy. According to expert estimates, the potential for reducing energy consumption in industry is 20-30% with investment payback periods of 3-5 years. "We have already implemented several energy efficiency projects that not only reduced our emissions but also provided substantial savings on energy costs" shares the production director of a large chemical company.

Implementation of new technologies (probability 0,65; impact 0,90) creates opportunities to develop competitive advantages and enter new markets. The development of green hydrogen production, CO_2 capture, and the circular economy can position Kazakh companies as technological leaders in the region. Access to green financing (probability 0,70, impact 0,75) is becoming increasingly realistic as the sustainable finance market develops and investor interest in ESG indicators grows. Strengthening competitive advantages (probability 0,75; impact 0,80) entails improving reputation, enhancing investment attractiveness, and ensuring long-term access to European markets. "Customers are already asking about the carbon footprint of our products. In 5-10 years, this will become a mandatory requirement for operating in international markets," predicts an export manager at a metallurgical company.

Analysis of decarbonization plans of Kazakh industrial companies reveals different priorities and approaches depending on sectoral specifics. Figure 3 illustrates the distribution of investments across decarbonization strategies by key industrial sectors.

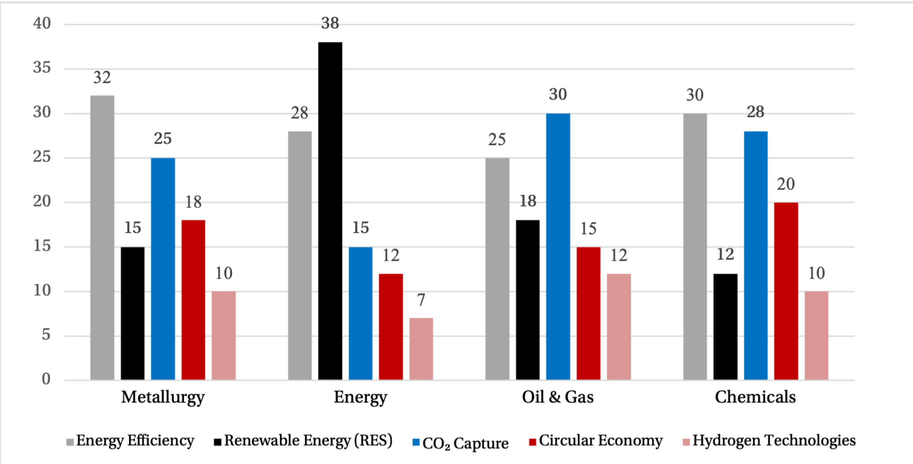

Figure 3 Distribution of investments in decarbonization strategies by sectors

For the metallurgical sector, priority areas are improving energy efficiency (32% of investments) and CO_2 capture technologies (25%). This reflects the high carbon intensity of production and the limited availability of short-term technological alternatives. Hydrogen metallurgy is regarded as a long-term prospect and currently accounts for only 10% of investment. Development of the circular economy, including waste utilization and material reuse, receives 18% of investments.

In the energy sector, renewable energy sources receive the largest share of investments (38%), consistent with the national goal of increasing the share of RES in the energy balance to 15% by 2030. Kazakhstan has significant solar and wind energy potential, and the development of these resources is becoming a key priority for decarbonization. Improving the energy efficiency of thermal power plants accounts for 28% of investments, and CO_2 capture technologies account for 15%.

The oil and gas sector focuses on CO_2 capture technologies (30% of investments), driven by sector-specific conditions and the availability of geological formations suitable for carbon storage. Reducing associated gas flaring and methane leaks (25% of the energy efficiency category) is also an important direction. The development of green hydrogen production accounts for 12% of investments, reflecting a diversification strategy.

The chemical industry directs the largest share of investments (30%) to energy efficiency, including process optimization and equipment modernization. The circular economy and waste processing receive 20% of investments, reflecting the sector's potential for closed production cycles. CO_2 capture technologies attract 28% of investments, especially in ammonia and methanol production.

Expert interviews revealed that the choice of decarbonization strategies is determined not only by technological feasibility but also by financing availability, regulatory requirements, and market factors. "We would like to invest more in breakthrough technologies such as hydrogen, but banks are not ready to finance projects with long payback periods and high technological risks," comments the financial director of an energy company.

Based on analysis of technological capabilities, economic conditions, and political factors, three scenarios for the development of industrial CO_2 emissions in Kazakhstan through 2050 were developed. Figure 4 demonstrates emissions trajectories under different scenarios.

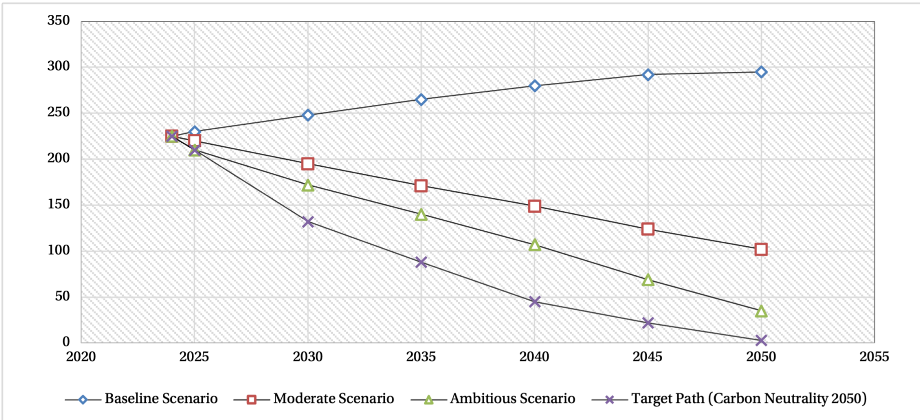

Figure 4 Forecast scenarios for reduction of CO_2 emissions in Kazakhstan's industry for 2024-2050

The baseline scenario (business-as-usual) assumes continuation of current trends without significant strengthening of climate policy. Under this scenario, emissions continue to rise, reaching 322,5 million tons of CO_2 by 2050. This scenario accounts for natural energy-efficiency improvements resulting from technological progress and the replacement of outdated equipment, but does not assume deliberate decarbonization efforts. Implementing this scenario contradicts national climate commitments and will pose significant regulatory and market risks to the Kazakh industry. This contradiction manifests in the following aspects: first, the baseline scenario assumes emissions growth of 19,2% by 2050 compared to 2024, while Kazakhstan's updated NDC provides for a 15% emissions reduction by 2030 relative to 1990 levels, and the Carbon Neutrality Strategy through 2060 requires substantial emissions reductions in the coming decade. Second, maintaining carbon-intensive production makes the Kazakh industry extremely vulnerable to the EU's CBAM, which will impose additional carbon costs of 50-120 US dollars per ton on exported products and may lead to a loss of competitiveness in the European market. Third, ignoring global climate trends increases the risk of excluding Kazakh companies from international supply chains, where requirements for product carbon footprints are becoming increasingly important.

The moderate scenario envisions gradual strengthening of climate policy and implementation of medium-efficiency decarbonization technologies. Emissions begin to decline after

2027, reaching 102,3 million tons of CO_2 by 2050-a 55% reduction compared to 2024. This scenario assumes: introduction of carbon pricing at 20-40 dollars per ton of CO_2, increasing the share of RES in the energy balance to 30%, modernization of 60% of production capacity with implementation of energy efficiency technologies, and limited deployment of CO_2 capture technologies.

The ambitious scenario is oriented toward achieving the goals of the Paris Agreement and assumes aggressive decarbonization using advanced technologies. Emissions decline to 35 million tons of CO_2 by 2050-an 84% reduction. Key elements of this scenario include: carbon pricing at 80-150 dollars per ton of CO_2, RES share in the energy balance reaching 70%, large-scale implementation of hydrogen technologies in metallurgy and chemical industry, deployment of carbon capture, utilization and storage (CCUS) technologies at 80% of large industrial facilities, and transition to circular economy with utilization of 90% of industrial waste.

The target path to carbon neutrality assumes achieving net-zero emissions by 2050, in accordance with the Paris Agreement's 1.5°C pathway, which is more ambitious than Kazakhstan's official national target of 2060. This scenario requires substantial effort through a combination of radical emissions reductions and compensation mechanisms, which are the most costly, but it ensures full compliance with global climate science recommendations and eliminates long-term regulatory risks associated with international climate frameworks.

Assessment of investment needs shows that the moderate scenario requires cumulative investments of 180-220 billion US dollars through 2050, while the ambitious scenario requires 350-450 billion dollars. These amounts include both direct costs for decarbonization technologies and investments in infrastructure modernization, RES development, and human capital. "Such sums are beyond the capabilities of individual companies and even entire industries. Comprehensive financing mechanisms are needed, including government support, international financing, and private capital" emphasizes a representative of an investment bank specializing in green financing.

Socio-economic consequences differ between scenarios. The ambitious scenario, despite high initial costs, ensures the creation of 150-200 thousand new jobs in RES sectors, hydrogen production, and green technologies. Simultaneously, it requires the retraining of 80-100 thousand workers from carbon-intensive industries. The moderate scenario assumes a smoother transition with lower social costs, but also lower potential for creating new added value.

Based on the conducted analysis, a multi-level risk and opportunity management system for decarbonization was developed for industrial companies in Kazakhstan. The system comprises strategic, tactical, and operational levels and assumes the integration of climate factors across all aspects of corporate governance.

At the strategic level, companies are recommended to: 1) develop a long-term climate strategy with establishment of science-based targets for emissions reduction (Science Based Targets); 2) integrate climate risks into the corporate risk management system in accordance with TCFD recommendations; 3) create corporate governance structures for oversight of climate strategy implementation, including board-level committees; 4) develop a top management compensation system linked to achievement of climate goals.

At the tactical level, key elements include: 1) implementation of carbon accounting and reporting systems in accordance with international standards (GHG Protocol, ISO 14064); 2) development of a decarbonization project portfolio with assessment of economic efficiency and prioritization; 3) establishment of partnerships with technology providers, financial institutions, and research organizations; 4) development of personnel competencies in climate management and green technologies.

Tactical measures ensure practical implementation through carbon accounting systems (e.g., GHG Protocol, ISO 14064), the development of decarbonization project portfolios with efficiency assessments, partnerships with technology providers and financial institutions, and the development of personnel competency in climate management. The operational level includes: implementation of energy management in accordance with ISO 50001 standard; optimization of production processes to reduce emissions and energy consumption; monitoring of key performance indicators (KPIs) in decarbonization; engagement of suppliers in emissions reduction programs throughout the value chain.

Operational measures include energy management implementation (ISO 50001), production process optimization for emissions reduction, monitoring key performance indicators, and supplier engagement in reduction programs throughout the value chain (addressing Scope 3 emissions which constitute 60-80% of total carbon footprint for many industrial companies).

Special attention should be paid to regulatory risk management, which requires: 1) active participation in formation of national climate policy through industry associations; 2) monitoring of international regulatory trends and their potential business impact; 3) preparation for CBAM introduction through emissions data collection and seeking reduction pathways; 4) use of the transition period before full CBAM implementation for production modernization.

Special attention should be paid to regulatory risk management through active participation in policy formulation, monitoring international trends, preparing for the implementation of CBAM, and leveraging the 2026-2034 transition period for production modernisation.

To realize decarbonization opportunities, companies are recommended to: 1) actively engage with international financial institutions for access to green financing; 2) position low-carbon products in markets with high demand for sustainable goods; 3) participate in pilot projects for implementing breakthrough technologies with government support; 4) develop cooperation with international technology leaders for knowledge and competency transfer.

To realize decarbonization opportunities, companies should engage with international financial institutions for green financing, position low-carbon products in sustainable markets, participate in pilot technology projects with government support, and develop cooperation with international technology leaders for knowledge transfer.

5 | CONCLUSION

This study provides a comprehensive analysis of the risks and opportunities faced by large industrial companies in Kazakhstan during the transition to carbon neutrality. The research results confirm that industrial decarbonization is a large-scale challenge that requires significant investments, technological innovations, and institutional changes. At the same time, it opens important opportunities for production modernization, enhanced competitiveness, and creation of new added value.

Key findings of the study include the following. First, Kazakhstan's industrial sector is characterized by high carbon intensity, with emissions continuing to rise despite declared climate goals. Total industrial emissions increased by 18.1% during the period 2015-2024, indicating an insufficient decarbonization effort. Second, the main transition risks are associated with regulatory uncertainty, high capital costs, technological challenges, and limited access to financing. The introduction of CBAM poses a particular threat to export-oriented companies and necessitates preemptive measures.

Third, decarbonization strategies differ by industry, reflecting their technological specifics and economic capabilities. For metallurgy, energy efficiency and CO_2 capture technologies are priorities; for the energy sector, RES development; for the oil and gas industry, carbon capture and hydrogen production. Fourth, scenario analysis shows that achieving the Paris Agreement's carbon neutrality target by 2050 (more ambitious than Kazakhstan's national 2060 goal) is technically feasible but requires cumulative investments of 350-450 billion US dollars and radical transformation of the industrial sector, while the moderate scenario aligned with the 2060 national target requires 180-220 billion US dollars.

Fifth, successful management of the transition to carbon neutrality requires an integrated approach that combines strategic planning, technological innovation, financial mechanisms, and human capital development. Coordination between business, government, and the financial sector is critically important. Sixth, international cooperation, technology transfer, and access to green financing are key success factors, particularly for a transition economy.

The practical significance of the study lies in the development of specific recommendations for various stakeholders.

For industrial companies: (1) integrate climate factors into strategic planning and corporate governance systems; (2) start with energy efficiency improvement projects as the most economically attractive; (3) actively engage with international partners for access to technologies and financing; (4) invest in personnel competency development.

For government agencies: (1) create a stable and predictable regulatory framework with long-term signals for investors; (2) implement effective carbon pricing mechanisms with gradual increase in carbon price; (3) provide targeted support for decarbonization projects through tax incentives, subsidies, and government guarantees; (4) develop infrastructure for RES and hydrogen economy; (5) implement just transition programs for workers and regions dependent on carbon-intensive industries.

For the financial sector: (1) develop green financing instruments, including green bonds, concessional loans, and specialized funds; (2) integrate ESG factors and climate risks into investment decision-making processes; (3) create mechanisms for co-financing large decarbonization projects with participation of international financial institutions.

The study's limitations open directions for future work. More detailed technical and economic studies of the decarbonization of specific production processes, considering local conditions, are needed. It is important to deepen the analysis of social aspects of the transition, including the impact on employment, population income, and regional development. The development of tools to assess the effectiveness of various policy measures supporting decarbonization is required. A promising direction is comparative analysis of decarbonization experience in countries with similar economic structures.

In conclusion, the transition to carbon neutrality is not only an environmental necessity but also a strategic opportunity to modernize Kazakh industry. Companies that proactively manage this transition will be able to strengthen their competitive positions, gain access to new markets and financing sources, and contribute to the country's sustainable development. Delay, however, threatens growing regulatory and market risks that could undermine business viability. The time for action is now.

AUTHOR CONTRIBUTION

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CONFLICT OF INTEREST

No conflict of interest/competing interest is reported by the authors.

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