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Assessment of Carbon Transition Risks in Kazakhstan's Industrial Economy

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ABSTRACT

The transition to a low-carbon economy is increasing pressure on industrial companies, especially in resource-dependent countries where a significant share of production, exports, and investment is tied to carbon-intensive sectors. The purpose of the article is to assess the risks of the carbon transition in Kazakhstan's industrial economy and to identify the main factors influencing enterprises' carbon risk levels. The methodological basis of the study includes the calculation of the composite carbon risk index (CRI), correlation analysis, panel regression with fixed effects, and the construction of a matrix of carbon transition risks and opportunities. The empirical base of the study covers the period 2011-2025 and includes data from the Bureau of National Statistics of the Republic of Kazakhstan, the Ministry of Energy of the Republic of Kazakhstan, reports from international organizations, as well as annual and ESG reports from 12 large industrial companies in Kazakhstan. The results show that for 2011-2025. The CRI index decreased from 0.72 to 0.53, and the industry's carbon intensity decreased by 18.4%. Panel regression showed that the main factors of carbon risk are carbon intensity of production (β=0.614; p<0.001), outdated equipment (β=0.441; p<0.01), and green financing (β=-0.383; p<0.01). The model explains 71.2% of the intra-company variation in CRI. The greatest reduction in risk was noted in the electric power industry (-31.8%), the lowest in the mining sector (-8.8%). The results confirm the need for technological modernization, expansion of green financing, and the development of industry-specific mechanisms to manage carbon transition risks.

KEYWORDS: Industry, Industrial Economy, Low Carbon Economy, Low Carbon Development, Decarbonization, Carbon Transition, Climate Risk

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Оценка рисков углеродного перехода в промышленной экономике Казахстана

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АННОТАЦИЯ

Переход к низкоуглеродной экономике усиливает давление на промышленные компании, особенно в ресурсозависимых странах, где значительная часть производства, экспорта и инвестиций связана с углеродоемкими секторами. Цель статьи заключается в оценке рисков углеродного перехода в промышленной экономике Казахстана и определить основные факторы, влияющие на уровень углеродного риска предприятий. Методологическая основа исследования включает расчет композитного индекса углеродного риска (CRI), корреляционный анализ, панельную регрессию с фиксированными эффектами, а также построение матрицы рисков и возможностей углеродного перехода. Эмпирическая база исследования охватывает период 2011–2025 гг. и включает данные Бюро национальной статистики РК, Министерства энергетики РК, отчетов международных организаций, а также годовые и ESG-отчеты 12 крупных промышленных компаний Казахстана. Результаты показывают, что за 2011–2025 гг. индекс CRI снизился с 0,72 до 0,53, а углеродоемкость промышленности сократилась на 18,4%. Панельная регрессия показала, что основными факторами углеродного риска являются углеродоемкость производства ($\beta=0{,}614$; $p<0{,}001$), устаревшее оборудование ($\beta=0{,}441$; $p<0{,}01$) и зеленое финансирование ($\beta=-0{,}383$; $p<0{,}01$). Модель объясняет 71,2% внутрефирменной вариации CRI. Наибольшее снижение риска отмечено в электроэнергетике (-31,8%), наименьшее — в горнодобывающем секторе (-8,8%).Полученные результаты подтверждают необходимость технологической модернизации, расширения зеленого финансирования и разработки отраслевых механизмов управления рисками углеродного перехода.

КЛЮЧЕВЫЕ СЛОВА: промышленность, промышленная экономика, низкоуглеродная экономика, низкоуглеродное развитие, декарбонизация, углеродный переход, климатический риск

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INTRODUCTION

The adoption of the Paris Agreement in 2015 marked a fundamental turning point in the operating environment for industrial companies worldwide. Substantially reducing greenhouse gas emissions by 2030-2050 calls for a wide-ranging restructuring of production systems, investment strategies, and business models (IPCC, 2023). According to World Bank estimates, annual global investment in the energy transition must exceed four trillion US dollars by 2030 (World Bank, 2023).

The global carbon transition is reshaping competitive dynamics across every major industrial sector. For resource-dependent emerging economies, the challenge is structurally distinct from that faced by advanced economies with diversified industrial bases and mature green finance infrastructures. These countries face a compound dilemma: they must simultaneously manage the fiscal and employment consequences of reducing their reliance on carbon-intensive export revenues while mobilising the large-scale capital required for industrial modernisation. The International Energy Agency (IEA, 2021) estimates that emerging and developing economies need to triple their clean energy investment by 2030 to remain on a net-zero pathway - yet they currently attract only one-fifth of global clean energy finance. This gap between investment needs and available capital defines the central policy challenge for resource-dependent industrializing nations, with Kazakhstan as a relevant case.

For resource-dependent emerging economies, the carbon transition takes on particular weight. On one side, powerful inertial forces are at work: infrastructure, established value chains, employment, and fiscal revenues are deeply tied to carbon-intensive industries (Frankel, 2010). On the other hand, external pressure is mounting: the European Union's Carbon Border Adjustment Mechanism (hereinafter – CBAM), tightening ESG disclosure requirements from international investors, and the shift of leading development banks toward greener lending portfolios all push in the same direction (Grubb et al., 2022).

Kazakhstan provides a relevant case for analysing carbon transition risks in a resource-dependent economy. The country ranks 19th in the world in CO_2 emissions and is among the top 10 exporters of oil and coal (IMF, 2024). At the same time, Kazakhstan has committed to achieving carbon neutrality by 2060 and reducing greenhouse gas emissions by 15% relative to 1990 levels by 2030. The industrial sector generates around 40% of national CO_2 emissions while contributing more than 35% of GDP (Kurbanova et al., 2024). In 2013, Kazakhstan launched its own emissions trading system, KazETS, one of the first systems of this kind in Asia (Howie et al., 2020).

Despite the growing importance of the carbon transition, scholarly work on climate risk management in emerging market contexts remains limited. Most theoretical and empirical studies focus on advanced economies with mature green finance infrastructures (Dietz et al., 2016; TCFD, 2023; Bolton & Kacperczyk, 2021). Research on Central Asia remains relatively sparse and tends to focus primarily on energy policy rather than on firm-level carbon risk assessment and corporate risk governance (Karatayev & Hall, 2020).

The purpose of the article is to assess the risks of the carbon transition in Kazakhstan's industrial economy and to identify the main factors influencing enterprises' carbon risk levels. Three specific objectives guide the inquiry: 1) track Carbon Risk Index (hereinafter – CRI) dynamics across sectors and analytical sub-periods; 2) identify the main determinants of firm-level carbon risk through fixed-effects panel regression; and 3) build a practically oriented risk management matrix. The study contributes to the literature by applying a composite CRI index to Kazakhstan's industrial sector, providing firm-level empirical evidence on carbon transition risks, and integrating quantitative and qualitative methods into a single analytical framework.

LITERATURE REVIEW

The conceptual foundation of this study is based on the climate risk taxonomy developed by the Task Force on Climate-related Financial Disclosures (hereinafter – TCFD). This framework distinguishes between two broad categories of climate-related risks: transition risks and physical risks. Transition risks arise during the shift toward a low-carbon economy and include regulatory changes, such as carbon taxes and the expansion of emissions trading systems; technological shifts, including the decreasing cost of renewable energy and the increasing cost of carbon-intensive technologies;

market changes related to shifts in demand for carbon-intensive products; and reputational risks associated with environmental performance (Venturini, 2022). Physical risks, in turn, include acute climate events, such as extreme weather, and chronic climate changes that may affect productive capacity, infrastructure, and asset values over the long term (Dietz et al., 2016; Kahn et al., 2021).

The dynamic capabilities framework provides an important theoretical basis for understanding how firms adapt to external pressures. Teece et al. (1997) argue that firms with well-developed capabilities for sensing opportunities, reconfiguring resources, and adjusting business models are better positioned to respond to structural changes. Resource dependence theory accounts for the strategic inertia that resource-extractive firms display in the face of climate pressures: the greater an organisation's reliance on carbon-intensive assets and embedded institutional relationships, the stronger its resistance to transformation (Aldy & Stavins, 2012). The tension between resource-dependency inertia and adaptive capacity defines the core managerial challenge of the carbon transition.

A large body of ESG investment research confirms a link between sustainability performance and financial outcomes. The meta-analysis by Friede et al. (2015), drawing on more than 2,200 studies, found a positive or neutral relationship between ESG and financial performance in 90% of cases. Pedersen et al. (2021) introduced the concept of an ESG-efficient frontier, demonstrating that incorporating ESG constraints into investment strategies does not meaningfully reduce returns in diversified portfolios. Green bond issuance represents an important financial mechanism through which firms can signal environmental commitment and improve access to capital. Flammer (2021) demonstrated that green bonds are associated with a lower cost of debt and stronger environmental signaling. In contrast, Christensen et al. (2022) showed that improved environmental disclosure can positively affect ESG ratings.

Taken together, the ESG investment literature establishes that sustainability performance and financial outcomes are positively linked across a wide range of markets and asset classes. However, this aggregate finding obscures important variation: the mechanisms by which ESG factors, and carbon risk in particular, affect firm value remain contested, and the evidence base is disproportionately drawn from developed markets with mature regulatory frameworks.

Bolton and Kacperczyk (2021) made an important contribution to the theoretical grounding of carbon risk as a distinct financial risk category by showing that investors systematically demand a premium for holding shares in high-emission firms. Sautner et al. (2023) developed a firm-level measure of climate change exposure from earnings call transcripts and found a significant positive relationship between perceived climate risk and stock return volatility. Turning to bond markets, Huynh and Xia (2021) documented that climate news risk widens credit spreads for carbon-intensive issuers.

For managers, the evidence on how corporate actions mediate climate risk exposure is especially valuable. Hossain and Masum (2022) found that CSR engagement significantly reduces firm-level climate change risk. Using cross-country data, Mbanyele and Muchenje (2022) showed that firms with more advanced climate risk management systems display greater financial resilience. The role of shareholder pressure is also well documented. Flammer et al. (2021) found that shareholder activism on climate issues drives voluntary disclosure of transition risks and the adoption of more ambitious emissions targets.

The firm-level carbon risk literature has produced robust findings for developed markets, particularly in the context of the EU ETS. However, the applicability of these findings to emerging economies remains uncertain: institutional frameworks, capital market depth, and the political economy of carbon pricing differ substantially between settings. The following sub-section reviews the more limited but growing body of evidence specific to Kazakhstan and Central Asia.

Kazakhstan occupies a distinctive position in the emerging-market climate policy literature. Karatayev and Hall (2020) conducted a comparative study of energy security in Kazakhstan and Russia, concluding that extreme resource dependence leads to chronic underestimation of transition risks in national strategic planning. (Shen et al., 2021) examined the decoupling between GDP growth and CO_2 emissions, detecting only 'weak' decoupling in the industrial sector - that is, a relative decline in emission intensity alongside absolute growth in total emissions.

Several studies have specifically examined Kazakhstan’s emissions trading system, KazETS. Howie et al. (2020) compared its effectiveness with South Korea’s ETS and identified several systemic weaknesses, including the over-allocation of free allowances, low carbon prices, and insufficient verification mechanisms. Sansyzbayev et al. (2025) analyzed the socio-economic constraints on Kazakhstan's low-carbon transition, highlighting vested interests, energy security concerns, and employment stability as the main barriers. They showed that Kazakhstan accounts for more than 75% of regional emissions, yet its emissions-intensity gap relative to other Central Asian countries has not narrowed.

Comparing the three streams of literature reviewed above reveals a structural disconnect: theoretical frameworks for climate risk management (TCFD, resource dependence, dynamic capabilities) are well-developed; empirical carbon risk research for developed markets is extensive, but the intersection of these two bodies of work in an emerging-economy, firm-level context - and specifically for Central Asia - remains almost entirely unexplored.

Three gaps in the existing literature stand out. First, quantitative firm-level carbon risk studies for Central Asia are virtually absent; most work operates at the country or sector level. Second, ETS research for Kazakhstan does not connect the institutional design of carbon policy to corporate risk management strategies (Howie et al., 2020; Sansyzbayev et al., 2025). Third, green finance research in emerging markets is poorly integrated with work on industrial decarbonisation (Hong et al., 2020). Therefore, there is a need for a more comprehensive assessment of the risks of the carbon transition in Kazakhstan's industrial economy. This article addresses these gaps by providing firm-level empirical evidence on carbon transition risk assessment and management in Kazakhstan's industrial sector.

METHODOLOGY

The study covers the period from 2011 to 2025. The starting year was selected to provide a two-year baseline before the launch of Kazakhstan's emissions trading system, KazETS, in 2013 (Howie et al., 2020). The upper boundary of 2025 allows the analysis to capture the early period of EU CBAM tightening; however, data for 2024–2025 are treated as preliminary and interpreted with caution.

The empirical base of the study draws on several complementary data sources. National-level indicators on industrial output, energy consumption, and fixed capital investment were obtained from Kazakhstan's Bureau of National Statistics. In contrast, data on the national energy balance, CO_2 emissions, and the KazETS registry were obtained from Kazakhstan's Ministry of Energy. Information on green finance was taken from EBRD and World Bank reports, and firm-level data were derived from the annual and ESG reports of 12 major industrial companies. In addition, international datasets from Our World in Data, the Global Carbon Project, and the IEA were used for comparative benchmarking.

The sample includes 12 large industrial companies from five carbon-intensive sectors: oil and gas (KazMunayGas, KazTransOil), metallurgy (ArcelorMittal Temirtau, Kazakhmys), mining (KazMinerals, ENRC), chemicals (KazAzot, Karabatan LLP), and power generation (Samruk-Energo, KEGOC, EEC). Selection criteria: participation in KazETS, availability of public reporting, and output exceeding KZT 1 billion. The sample collectively accounts for roughly 65% of industrial CO_2 emissions in Kazakhstan. The representativeness of this purposive sample rests on two grounds. First, by emission volume, these 12 firms account for the dominant share of Kazakhstan's industrial carbon footprint, so their trajectories well capture any economy-wide pattern in carbon risk dynamics. Second, the firms span all five major industrial sub-sectors defined by the Bureau of National Statistics, ensuring cross-sector heterogeneity. The principal limitation is the exclusion of small and medium-sized enterprises, which account for approximately 35% of industrial emissions but lack systematic public environmental reporting; this boundary is explicitly acknowledged in the limitations section of the conclusion.

The dependent variable is the CRI, a composite indicator designed to assess firms' exposure to carbon transition risks. The construction of the index draws on the TCFD framework. It combines five normalised dimensions of carbon risk: production carbon intensity, technological obsolescence, regulatory exposure, reputational risk, and limited access to green finance. The CRI for firm *i* in year *t* is calculated as follows (1):

$$CRI = 0.35CI_{norm} + 0.25EQ_{norm} + \\ + 0.20REG_{norm} + 0.10REP_{norm} + 0.10FIN_{norm} \quad (1)$$

where:

CRI – the Carbon Risk Index of firm *i* in year *t*;

CI – the production carbon intensity, measured as tones of CO_2 per KZT millions of gross value added;

EQ – the share of physically obsolete equipment older than 25 years;

REG – the regulatory intensity index;

REP – the reputational risk index (media sentiment score);

FIN – the inverse share of green finance.

All sub-indices are normalised using the min-max method across the full panel, so that higher values indicate greater carbon transition risk. The Reputational Risk Index (REP) is derived from a structured media-content analysis: for each firm-year observation, we identified all relevant Kazakh- and Russian-language news items mentioning the company in an environmental or emissions context, coded each item as negative (-1), neutral (0), or positive (+1), and computed the proportion of negative items in total coverage; this proportion was then min-max normalised so that higher values indicate greater reputational risk.

The explanatory variables include production carbon intensity CI_{it} - production carbon intensity; EQ_{it} - share of obsolete equipment; GF_{it} - share of green finance in the firm's investment portfolio (green bonds, ESG loans, climate funds); REG_t - regulatory intensity index (ETS allowance price × share of covered emissions); $SIZE_i$ - natural log of total assets, included as a control variable since larger firms generally operate more developed risk management systems. Regulatory exposure is calculated as the annual KazETS allowance price multiplied by the share of firm-level emissions covered by KazETS. Firm size is measured as the natural logarithm of total assets and is included as a control variable, since larger firms may have more developed risk management systems (Dang et al., 2018).

In summary, the model structure is as follows. Dependent variable is the CRI_{it}, which measures the carbon transition risk exposure of firm (i) in year (t). The variables CI_{it} and EQ_{it} capture firm-level operational characteristics; GF_{it} captures financial strategy. The regulatory variable, REGt, is time-varying and common to all firms within a given year.

The fixed-effects regression model is specified as follows (2):

$$CRI_{it} = \beta_0 + \beta_1 CI_{it} + \beta_2 EQ_{it} + \beta_3 GF_{it} + \\ + \beta_4 REG_t + \beta_5 SIZE_{it} + \alpha_i + \gamma_t + \varepsilon_{it} \quad (2)$$

where:

CRI_{it} – the Carbon Risk Index of firm i in year t;

CI_{it} – the production carbon intensity;

EQ_{it} – the share of obsolete equipment;

GF_{it} – the share of green finance;

REG_t – the regulatory exposure;

$SIZE_{it}$ – the firm size;

α_i – firm fixed effects;

γ_t – year fixed effects;

ε_{it} – idiosyncratic error term.

Since several explanatory variables are also used in constructing the composite CRI, the regression results are interpreted as an explanatory decomposition of carbon risk dynamics rather than as a strict causal estimate. The choice of the FE estimator is supported by the Hausman test (χ^2=18.4, p<0.01) (Hausman, 1978). Heteroskedasticity was assessed using the White test (White, 1980), and standard errors were clustered at the firm level to account for serial correlation. Multicollinearity was diagnosed using variance inflation factors, with all VIF values below 4.2. The final panel consisted of 180 firm-year observations, covering 12 firms over 15 years.

RESULTS

The empirical analysis is presented sequentially in the results section. First, the general dynamics of carbon transition indicators in Kazakhstan's industrial sector are considered; then the relationships among key variables are analyzed; and finally, the results of a regression assessment of carbon risk factors are presented. Additionally, the dynamics of the CRI index across the main industrial sectors were compared, and a matrix of risks and opportunities for the carbon transition was developed. The data obtained shows multidirectional dynamics. On the one hand, the carbon intensity of the industrial sector has been gradually decreasing, indicating improved production efficiency. On the other hand, the absolute volume of CO_2 emissions continued to grow, except for a temporary decrease in 2020 related to the pandemic recession in economic activity. This situation reflects the effect of weak decoupling: relative carbon intensity decreases while total emissions continue to increase.

Table 1 presents the key carbon transition indicators for Kazakhstan's industrial sector over the period 2011–2025, including CO_2 emissions, emission intensity, the share of renewables, KazETS allowance prices, and the CRI index.

Table 1. Key carbon transition indicators for Kazakhstan's industrial sector for 2011-2025

Year	CO_2 emissions, Mt	Emission intensity*	Renewables share, %	ETS price, KZT/t	CRI index
2011	227.4	6.82	0.8%	-	0.72
2013	235.8	6.71	1.0%	200	0.71
2015	233.5	6.48	1.3%	200	0.68
2017	232.7	6.21	1.7%	300	0.63
2019	241.6	5.98	2.4%	500	0.60
2020	228.3	5.83	2.8%	500	0.58
2022	248.9	5.60	3.8%	750	0.55
2023	251.4	5.52	4.3%	1.000	0.54
2024	253.2	5.61	4.9%	1.200	0.55
2025	252.6	5.57	5.6%	1.500	0.53

Note: compiled by the authors based on the Bureau of National Statistics (2025)

Three structural conclusions emerge from these figures. First, the gap between falling intensity (-18.4%) and rising absolute emissions (+11.2%) shows that efficiency gains are being overtaken by the scale effect of economic growth and capacity expansion - a phenomenon widely described as the Jevons paradox and confirmed for Kazakhstan by Zhakiyev et al. (2024). Second, despite continuous increases in ETS prices from KZT 200 to KZT 1,500 per tonne, the level remains well below the social cost of carbon (approximately USD 80-100/t per IPCC, 2023), limiting the disciplining effect of the carbon market. Third, the share of renewables has grown from 0.8% to 5.6%. Nevertheless, it still lags far behind Kazakhstan's Green Economy Concept target of 30% by 2030, indicating an insufficient policy incentive structure for a large-scale transition.

The divergent dynamics of Kazakhstan's industrial carbon transition are illustrated in Figure 1.

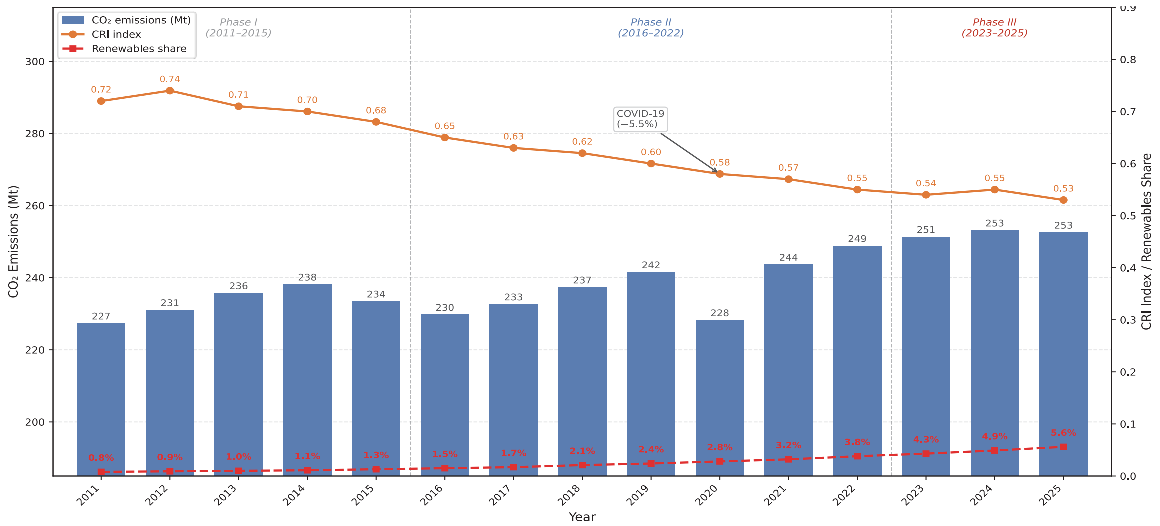

Figure 1. Dynamics of CO_2 emissions, CRI index and renewable energy share in Kazakhstan's industrial sector for 2011–2025

The chart shows that, despite a gradual decline in emission intensity and the CRI index, absolute CO_2 emissions continued to increase over most of the observed period. During the 'inertial phase' (2011-2015), the emission bars grow steadily while the CRI curve starts a modest downward drift, reflecting early organisational adjustments. In the 'regulatory activation' period (2016-2022), the CRI slope steepens in line with ETS price increases and the renewables share accelerates. The year 2020 is analytically important, the pandemic-driven drop in emissions did not produce any structural improvement - emissions rebounded to historical highs as early as 2021, confirming the path-dependent nature of heavy industrial infrastructure (Bolton & Kacperczyk, 2021). The 'transitional turbulence' phase (2023-2025) is characterized by rising absolute emissions alongside a moderating decline in CRI, reflecting a tension between new capacity additions that push up total emissions and improvements in risk management systems.

The dynamics of the KazETS allowance price are shown in Figure 2.

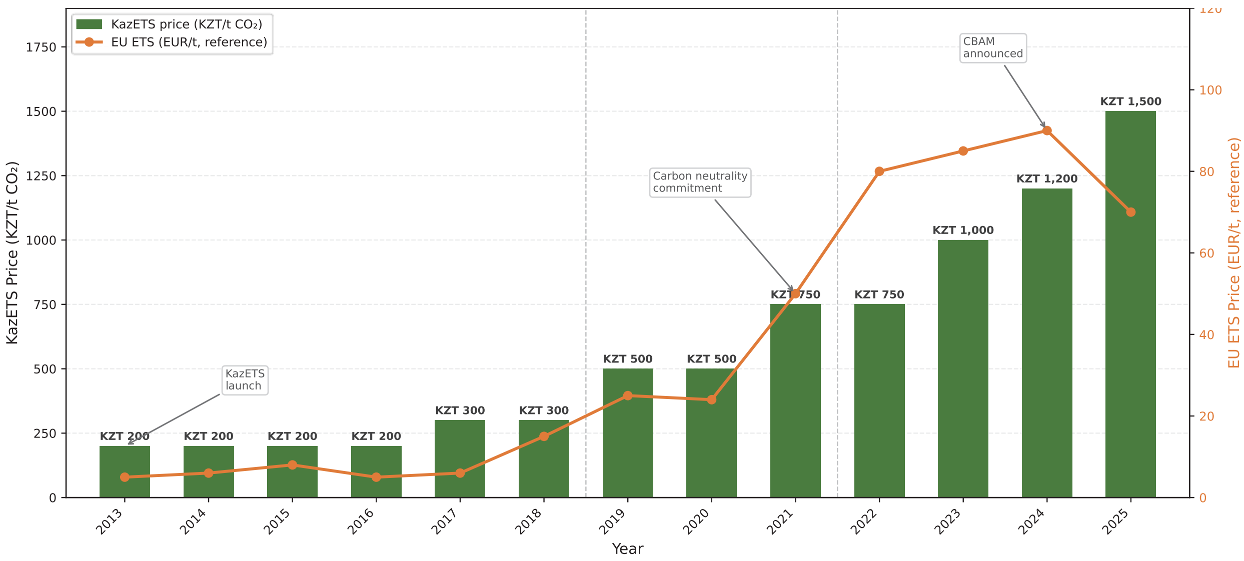

Figure 2. KazETS allowance price dynamics in Kazakhstan for 2013–2025

The chart illustrates a stepwise carbon price path typical of the 'soft start' design of cap-and-trade systems (Green, 2021). From 2013 to 2019, the price held in the KZT 200-500 per ton range (roughly USD 0.40-1.00 per ton) - exceptionally low by international standards: the EU ETS traded at EUR 5-25 per tonne over the same period. The acceleration from 2021 onward (KZT 750 to KZT 1,500) reflects two drivers: anticipation of the EU CBAM (Grubb et al., 2022) and Kazakhstan's adoption of a Carbon Neutrality Strategy in 2023. Yet at roughly USD 3.30 per tonne, the current price remains a largely symbolic signal - well below the USD 50-100 per tonne threshold widely considered necessary to drive major low-carbon capital expenditure (Dietz & Stern, 2015; Bai & Ru, 2024).

The Pearson correlation matrix in Table 2 reveals the theoretically expected pattern of associations.

Table 2. Pearson correlation matrix for the main variables

Variable	CRI	CI	EQ	GF	REG	SIZE
CRI (Risk index)	1.00					
CI (Carbon intensity)	0.74***	1.00				
EQ (Obsolete equipment)	0.61***	0.58***	1.00			
GF (Green finance)	–0.53**	–0.47**	–0.39**	1.00		
REG (Regulatory index)	–0.31*	–0.29*	–0.22	0.44**	1.00	
SIZE (Firm size)	–0.18	–0.21	–0.26*	0.31*	0.12	1.00
*** p<0.001; ** p<0.01; * p<0.05. N=180 (12 firms × 15 years). Standard errors clustered at the firm level.						

Note: compiled by the authors

The results show that the CRI index has a strong positive relationship with the carbon intensity of production ($r = 0.74$; $p < 0.001$) and a moderate positive relationship with the proportion of obsolete equipment ($r = 0.61$; $p < 0.001$). This means that enterprises with higher carbon intensity and a higher proportion of physically worn-out production assets face a higher risk of carbon transition. Green finance has a negative relationship with the CRI index ($r = -0.53$; $p < 0.01$), indicating lower carbon risk for companies with greater access to green financial instruments. The relationship between regulatory intensity and CRI is also negative but weaker (r = -0.31; $p < 0.05$). This may indicate that increased carbon regulation is encouraging companies to reduce carbon risks.

To provide a visual representation of the relationships among the main variables, a correlation heatmap is presented in Figure 3.

Figure 3. Pearson correlation heatmap

The heatmap reveals two variable clusters: a 'risk cluster' - CRI, CI, EQ -connected by mutually positive correlations of moderate to high magnitude; and a 'protective cluster' - GF, REG, SIZE - negatively associated with the risk cluster. The moderate positive correlation between GF and REG (r=0.44) is particularly noteworthy: stricter carbon regulation appears to push firms toward green finance instruments, an effect documented by Flammer et al. (2021) for developed markets and corroborated here for Kazakhstan for the first time. The negative but insignificant SIZE-CRI link suggests that the competitive advantages of scale in carbon risk management operate indirectly, mediated through GF and EQ rather than through size per se.

After examining the bivariate relationships among the variables, a fixed-effects panel regression was estimated to identify the main factors associated with firm-level carbon transition risk. The regression results are presented in Table 3.

Table 3. Fixed-effects panel regression results for the CRI

Variable	Coeff. (β)	Std. error	t-stat.	p-value
Intercept (β_0)	0.412	0.088	4.68	0.000
CI (Carbon intensity)	0.614***	0.071	8.65	0.000
EQ (Obsolete equipment)	0.441**	0.094	4.69	0.002
GF (Green finance)	-0.383**	0.102	-3.75	0.006
REG (Regulatory index)	-0.217*	0.086	-2.52	0.028
SIZE (Firm size)	-0.093	0.061	-1.52	0.142
R^2 (within)	0.712	-	-	-
F-statistic	38.6***	-	-	-
N (observations)	180	-	-	-
*** p<0.001; ** p<0.01; * p<0.05. Standard errors clustered at the firm level. Firm and year fixed effects included.				

Note: compiled by the authors

The model fits the data well, a within-R^2 of 0.712 means that the included variables account for over 71% of the within-firm variation in the CRI - a figure comparable to analogous panel studies in developed markets (e.g., Sautner et al., 2023), where R^2=0.68. The Hausman test (Hausman, 1978) (χ^2=18.4, p<0.01) firmly favours the fixed-effects over a random-effects estimator. The White test (White, 1980) detects no significant heteroskedasticity (p=0.34).

The carbon intensity of production has the strongest positive impact on the CRI index. The coefficient for the CI variable is 0.614 and statistically significant at p < 0.001. This shows that enterprises with higher carbon intensity are characterized by a higher risk of carbon transition. The second significant factor is the proportion of obsolete equipment. Green financing has a negative and statistically significant coefficient (-0.383; p = 0.006). This means that higher access to green financial instruments is associated with a reduction in carbon risk. For a more visual representation of the regression results, Figure 4 shows standardized coefficients for factors related to the carbon risk index.

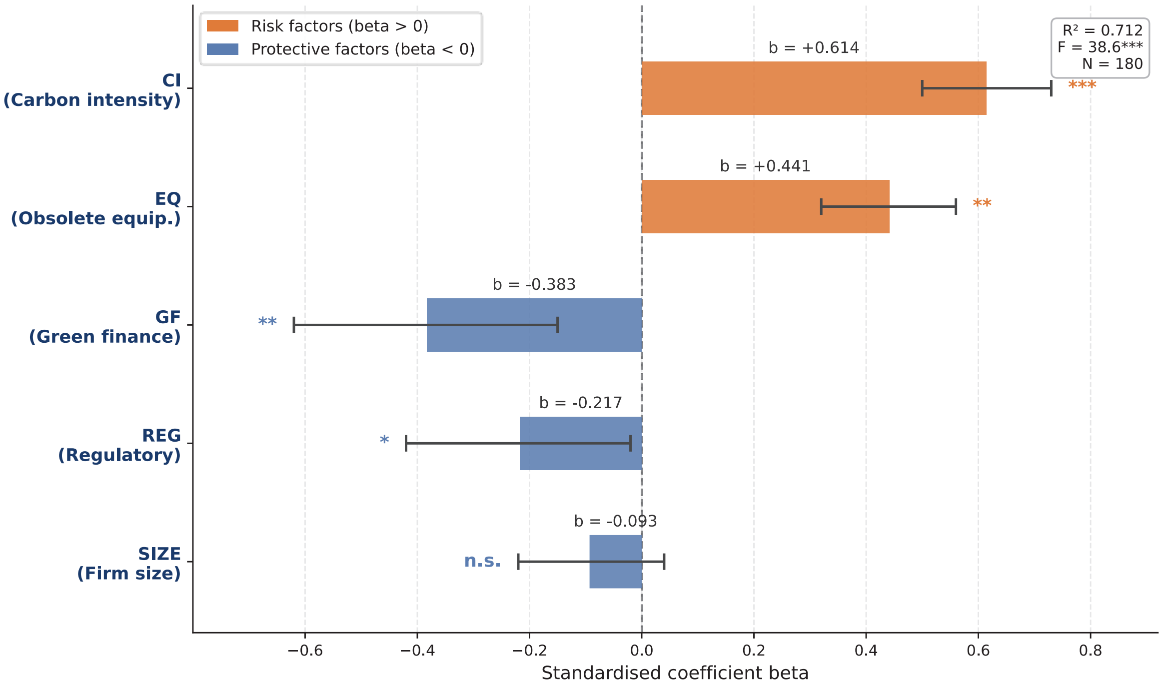

Figure 4. Standardised coefficients of factors associated with the CRI

Several findings stand out from the regression results. The dominant risk factor is carbon intensity (β = 0.614), which has the largest standardised effect and indicates that firms with more carbon-intensive production are associated with higher levels of carbon transition risk. This result is consistent with the theoretical predictions of Bolton and Kacperczyk (2021) and Venturini (2022). Technological obsolescence is the second important risk factor (β = 0.441), reflecting a structural problem characteristic of post-Soviet industry, in which outdated production assets make it more difficult to adapt to low-carbon requirements. Green finance (β = –0.383) has a negative and statistically significant coefficient, suggesting that access to sustainable finance instruments may reduce firms' vulnerability to carbon-related risks. This finding is broadly consistent with the results of Flammer (2021) in the context of sustainable finance. Finally, the insignificance of firm size (β = –0.093, p = 0.142) suggests that among Kazakhstan's large industrial firms, scale alone is not sufficient to reduce carbon transition risk; technological renewal and access to green finance appear to matter more.

To examine sectoral differences in carbon transition risk, the CRI dynamics were further decomposed by major industrial sectors. Table 4 presents the changes in the Carbon Risk Index across five sectors of Kazakhstan's industry over the period 2011–2025.

Table 4. CRI index by Kazakhstan industrial sectors for 2011-2025

Sector	2011	2015	2019	2022	2025	2011-2025
Oil and Gas	0.81	0.78	0.71	0.64	0.59	- 27.2%
Metallurgy	0.76	0.73	0.67	0.62	0.57	- 25.0%
Mining	0.68	0.64	0.61	0.60	0.62	- 8.8%
Chemicals	0.71	0.67	0.62	0.57	0.52	- 26.8%
Power generation	0.85	0.80	0.72	0.65	0.58	- 31.8%
Average	0.72	0.68	0.60	0.57	0.53	- 26.4%

Note: compiled by the authors

The data show that in 2011-2025, the carbon risk index decreased across all sectors considered, but the rate of decline varied. The most noticeable reduction in CRI is observed in the electric power industry (-31.8%), chemical industry (-26.8%), oil and gas sector (-27.2%), and metallurgy (-25.0%). The least pronounced decrease was recorded in the mining sector (-8.8%), where the index increased from 0.60 to 0.62 after 2022. This indicates a higher risk of carbon inertia in this sector. On average, the CRI for industrial sectors decreased from 0.72 in 2011 to 0.53 in 2025, indicating an overall reduction in carbon transition risks, while maintaining significant industry differences. This differentiation is consistent with Aghion et al. (2016) findings of sector-specific responses to carbon incentives: industries with greater technology substitution elasticity - oil and gas, power generation - convert regulatory signals into real-world improvements far more readily than mining, where technological choice is constrained.

Furthermore, Figure 5 illustrates the sectoral dynamics of the CRI in Kazakhstan's industry over the period 2011–2025.

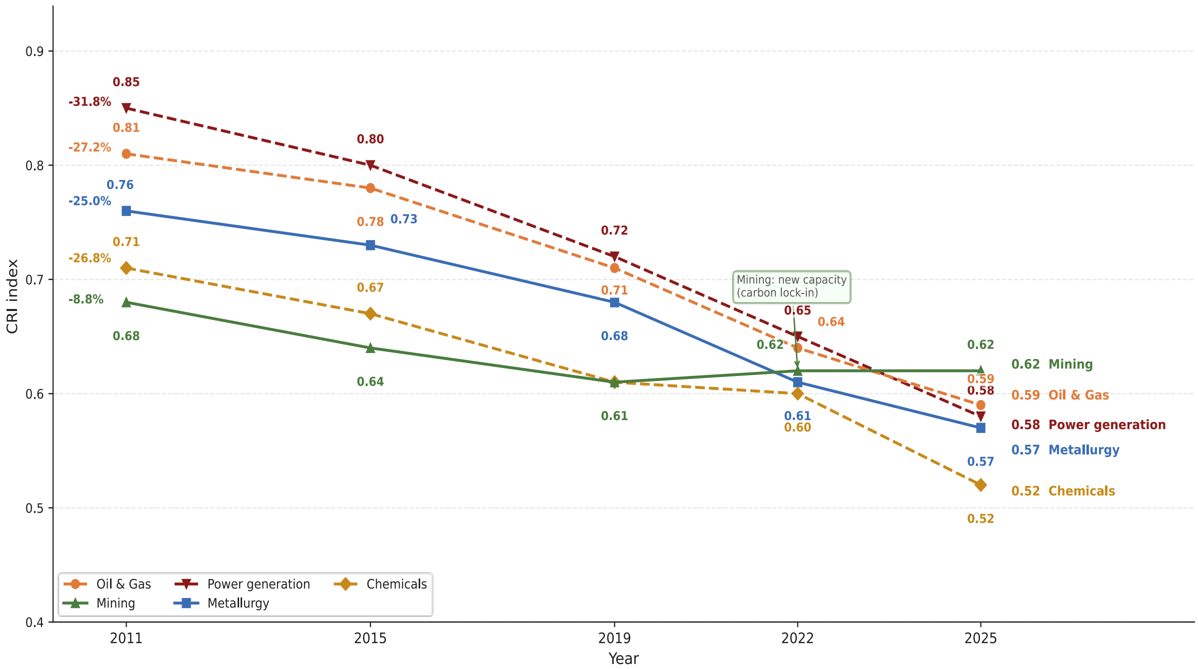

Figure 5. CRI index by Kazakhstan industrial sectors for 2011-2025

The chart highlights a strategically important phenomenon: the mining sector, which had the lowest starting CRI in 2011 (0.68), shows not improvement but deterioration by 2025 (0.62 - a 2.2% rise since 2022). This is a textbook instance of carbon lock-in (Frankel, 2010), caused by the commissioning of new mining capacity in 2022-2024 without integrating low-carbon technologies - investment decisions made on a 20–30-year operating horizon that locked in a high-emission technological trajectory. By contrast, power generation experienced the largest absolute decline in CRI (-0.27 points), attributable to direct regulatory pressure from KazETS, state renewable energy targets, and international modernization finance from the EBRD and the Green Climate Fund. Oil and gas occupy an intermediate position: despite a substantial CRI decline (-0.22 points), it retains the highest absolute risk level (0.59 in 2025), reflecting the sector's structural carbon intensity.

The matrix in Table 5 and Appendix 1 synthesises the regression results with content analysis of strategic documents from the 12 sample firms.

Table 5. Carbon transition risk and opportunity management matrix for Kazakhstan's industrial companies

Category	Type	Likelihood	Impact	Strategic response
Regulatory	Risk	High	High	Active KazETS participation; engagement on transition timelines; CBAM compliance planning
Rising carbon price	Risk	High	High	Reducing unit emissions; forward contracts on allowances
Technological obsolescence	Risk	Medium	High	Phased low-carbon modernisation; partnerships with technology leaders
Reputational (ESG)	Risk	Medium	Medium	TCFD-aligned ESG reporting; investor and NGO engagement
Green finance access	Opportunity	High	High	Green bond issuance; EBRD climate credit lines; ESG funds
Export ESG premium	Opportunity	Medium	High	Low-carbon product certification; CBAM readiness for EU markets
Hydrogen and renewables	Opportunity	Low	Very high	R&D investment; pilot projects; public–private partnerships; GCF funding
Resource efficiency	Opportunity	High	Medium	Energy audits; ISO 50001; circular economy principles

Note: compiled by the authors

The two-dimensional structure - likelihood of occurrence and magnitude of impact - follows TCFD methodology and enriches it with strategic recommendations tailored to Kazakhstan's institutional context (Zhakiyev et al., 2024). Three strategic clusters emerge from the matrix. The 'immediate priorities' cluster (top-right quadrant) brings together regulatory risk, carbon price risk, and the green finance opportunity - all three characterised by high likelihood and high impact. Notably, a key opportunity lies in the same quadrant as the most pressing risks, underscoring the symmetric nature of the carbon transition: firms that actively manage risks simultaneously unlock new financing sources (Flammer, 2021). The 'quick wins' cluster (bottom-right) comprises resource efficiency and ESG talent development - high likelihood combined with moderate impact makes these attractive near-term levers for corporate transformation. The 'long-term options' cluster (top-left) - hydrogen and new energy - features low near-term probability but exceptionally high potential impact, fitting the 'real options' logic in strategic management (Teece et al., 1997): early R&D investment creates the right, but not the obligation, to enter a transforming market.

DISCUSSION

The findings contribute to the literature on climate risk management in emerging markets along four dimensions.

Primacy of internal operational factors over regulatory signals. The largest coefficient is for carbon intensity (β=0.614), and the second largest for technological obsolescence (β=0.441), together indicating that the dominant determinants of carbon risk in emerging markets are firm-internal rather than regulatory. This contrasts with patterns observed in the EU ETS (Dechezleprêtre et al., 2023), where regulatory signals drive much of the observed variation in emissions outcomes. Theoretically, this is consistent with resource dependence logic (Aldy & Stavins, 2012): sunk investments in carbon-intensive infrastructure create institutional inertia that modest KazETS price signals cannot overcome.

Green finance as a structural buffer against carbon risk. The significant negative coefficient on GF (β = -0.383) raises questions about the mechanism of the impact. The paper hypothesizes three channels. The signalling channel: issuing green bonds or securing

ESG loans requires verification of environmental commitments, thereby incentivising genuine emission reductions (Christensen et al., 2022). The investment channel: access to cheaper green capital lowers barriers to low-carbon modernisation (Flammer, 2021). The monitoring channel: ESG lender disclosure requirements improve corporate climate risk governance (Hossain & Masum, 2022). A stark benchmark comparison emerges: green finance accounted for just 3.2% of sample firms' total investment in 2025, compared with 12-18% for comparable European companies. Closing this gap is a systemic policy task.

Carbon lock-in in the mining sector. The rising CRI in mining over 2022-2025 is a classic carbon lock-in episode (Frankel, 2010): capacity expansion decisions were made on a 20–30-year horizon without proper accounting for climate risk. Content analysis of company documents reveals that neither of the two mining firms in the sample had incorporated a 1.5°C scenario analysis into their strategic planning documents as of 2024 - a requirement that TCFD has recommended since 2017.

Policy implications. Kazakhstan's climate policy faces a triple challenge: 1) accelerating the ETS price trajectory toward an 'effective' level (USD 50+ per tonne by 2030) while managing competitiveness (Green, 2021; Dietz & Stern, 2015); 2) building a green finance infrastructure - national taxonomies, ESG reporting standards, and de-risking tools for international investors and 3) developing sector-differentiated decarbonisation roadmaps that respect the distinct starting points and technological constraints of each industry (Shao et al., 2022; IEA, 2021).

CONCLUSION

This study provides a systematic empirical assessment of carbon transition risk dynamics in Kazakhstan’s industrial sector over the period 2011–2025. Several key conclusions can be drawn.

First, Kazakhstan’s industry demonstrates improvement in relative carbon risk indicators, while absolute emissions continue to increase. The Carbon Risk Index declined from 0.72 to 0.53, and emission intensity decreased by 18.4%. However, total CO_2 emissions increased by 11.2% over the same period. This indicates a weak decoupling pattern, in which production becomes less carbon-intensive, but the overall scale of industrial emissions continues to grow.

Second, the regression results show that the main factors associated with the Carbon Risk Index are carbon intensity, the share of obsolete equipment, and access to green finance. Carbon intensity and technological obsolescence are positively associated with CRI, indicating that firms with more carbon-intensive production and outdated assets face higher transition risks. Green finance is negatively associated with CRI, suggesting that access to green bonds, ESG loans, and climate-related financing may reduce firms’ exposure to carbon transition risks. The model explains 71.2% of within-firm variation in the index.

Third, the results reveal substantial differences across industrial sectors. The strongest reduction in CRI is observed in power generation, followed by oil and gas, chemicals, and metallurgy. In contrast, the mining sector shows the weakest improvement, with a slight increase in the index after 2022. This suggests that the mining sector remains more exposed to carbon lock-in risks due to limited technological substitution and continued reliance on carbon-intensive production assets.

Fourth, the risk-opportunity matrix identifies the most relevant areas for carbon transition risk management. The key risks include regulatory pressure, rising carbon prices, technological obsolescence, and reputational risks related to ESG. At the same time, green finance, resource efficiency, CBAM preparedness, low-carbon product certification, and investment in renewable energy and hydrogen technologies represent important opportunities for industrial companies.

The study has several limitations. The sample includes only 12 large industrial firms and excludes small and medium-sized enterprises, as well as companies without systematic public environmental reporting. In addition, data for 2024–2025 are preliminary and should be interpreted with caution. The CRI is also based on available indicators and may not fully capture all sector-specific dimensions of carbon transition risk.

The findings suggest that reducing carbon transition risks in Kazakhstan’s industrial sector requires coordinated action by companies and policymakers. Industrial firms need to integrate climate-related risks into strategic and investment decision-making, rather than treating them only as a compliance issue. Policymakers, in turn, should strengthen the green finance ecosystem, improve carbon regulation, and support sector-specific decarbonisation pathways.

Particular attention should be given to expanding access to green finance. Firms with higher green finance exposure exhibit lower CRI values, indicating that sustainable finance can support technological renewal and improve corporate climate risk management. Early engagement with green finance instruments, low-carbon technology partnerships, and CBAM preparedness can help Kazakhstan's industrial sector reduce transition risks and strengthen its long-term competitiveness.

AUTHOR CONTRIBUTIONS

Conceptualization and theory: LK, ZD and ZM; research design: LK, ZD, ZM and DB; data collection: LK.; analysis and interpretation: LK, ZD, ZM and DB; writing - original draft preparation: ZD, ZM and DB; supervision: LK, ZD and DB; writing - review and editing: LK, ZD, ZM and DB; proofreading and final approval: LK. All authors have read and agreed to the published version of this manuscript.

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Appendix 1

Carbon transition risk and opportunity bubble matrix

X-axis - probability of occurrence; Y-axis - potential financial impact; bubble diameter - aggregate significance. Orange bubbles - risks; blue bubbles - opportunities. Quadrant boundaries are set at median values on both axes.