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Dynamic Evaluation of Low-Carbon Energy Transformation Readiness and Obstacle Factors: Evidence from China and Kazakhstan

Wei Wei

Farabi Business School, Al-Farabi Kazakh National University, Almaty, 050040, Kazakhstan

ABSTRACT

Low-carbon energy transition is critical for fossil-energy-dependent economies under global carbon neutrality goals. Taking China and Kazakhstan as comparative cases, this study develops a dynamic evaluation framework for low-carbon energy transformation readiness from 2015 to 2024. An entropy-weighted composite evaluation model is used to measure readiness from four dimensions: energy structure and carbon lock-in, low-carbon energy development, clean electricity development, and renewable energy demand pressure. An obstacle degree model is then applied to identify the key structural constraints. The results show that China's readiness level remained consistently higher than Kazakhstan's and followed an overall upward trend, driven mainly by renewable energy expansion, low-carbon electricity development, and declining electricity carbon intensity. Kazakhstan remained constrained by fossil fuel dependence, high electricity carbon intensity, and limited clean energy supply. Obstacle analysis indicates that fossil fuel dependence and electricity carbon intensity are common barriers in both countries, while China faces stronger pressure from energy demand growth and Kazakhstan faces greater constraints from insufficient renewable and low-carbon energy development. The study contributes by integrating dynamic readiness evaluation with obstacle factor identification and provides comparative evidence for low-carbon transformation in fossil-energy-dependent economies.

KEYWORDS

Low-carbon energy transition; Transformation readiness; Obstacle degree model; Entropy-weighted evaluation; China; Kazakhstan

1 Introduction

Global carbon neutrality goals are accelerating the transformation of energy systems. China and Kazakhstan are both fossil-energy-dependent economies, but they differ markedly in economic scale, resource endowment, policy capacity, and renewable energy development. China has promoted renewable deployment and electricity decarbonization under its dual-carbon strategy, whereas Kazakhstan still relies heavily on fossil fuels and faces persistent constraints from carbon-intensive electricity generation.

Existing studies have examined renewable energy, carbon reduction, green finance, ESG performance, and transition risks, but comparative quantitative research on China and Kazakhstan remains limited. In particular, few studies integrate dynamic transition readiness evaluation with obstacle factor identification over a consistent 2015–2024 period. To address this gap, this paper constructs an entropy-weighted readiness evaluation framework and combines it with an obstacle degree model to identify the dominant constraints affecting low-carbon transformation. The results provide evidence for differentiated transition pathways in fossil-energy-dependent economies.

2 Literature Review

Low-carbon energy transition is widely regarded as a systemic transformation involving energy structure, technological innovation, policy incentives, investment mechanisms, and organizational capacity. Zhou et al. [1] emphasized the need to understand transition from an energy-system and engineering-management perspective, while Cai et al. [2] found that clean electricity development and technological innovation improve carbon reduction performance in China ' s power sector. Darke and Karatayev [3] provided comparative evidence that China and Kazakhstan differ significantly in energy structure and sustainable energy development capacity.

At the corporate and policy levels, green finance, ESG performance, carbon markets, and clean energy investment have been identified as important drivers of low-carbon transformation [4-8]. Studies on Kazakhstan further show that fossil fuel dependence, infrastructure limitations, institutional uncertainty, and carbon-market design remain major barriers [9-10]. However, existing research often focuses on single policy instruments or single-country cases. A unified comparative framework that combines energy structure, low-carbon electricity, renewable development, and demand pressure is still insufficient. This study therefore evaluates the dynamic readiness of China and Kazakhstan and identifies obstacle factors affecting transition capability.

* **Corresponding Author:** Wei Wei, weiwei37264@gmail.com

3 Methodology, Indicator System, and Evaluation Model

3.1 Research Framework and Indicator System

This study evaluates low-carbon energy transformation readiness in China and Kazakhstan from 2015 to 2024. The research process includes three steps: constructing the indicator system, calculating entropy-weighted readiness scores, and identifying key obstacles. The selected indicators reflect both transition capacity and structural constraints. The data are mainly collected from the Our World in Data complete energy dataset, which integrates statistics from the Energy Institute, Ember, BP Statistical Review, and other international energy databases.

Table 1 Indicator system for low-carbon energy transformation readiness

Dimension	Code	Indicator	Attribute
Energy structure and carbon lock-in	X1	Fossil fuels share of primary energy consumption	Negative
	X2	Coal share of primary energy consumption	Negative
Low-carbon energy development and emission pressure	X3	Low-carbon energy share of primary energy consumption	Positive
	X4	Carbon intensity of electricity	Negative
Clean electricity development capacity	X5	Renewable electricity share of total electricity generation	Positive
	X6	Low-carbon electricity share of total electricity generation	Positive
Renewable energy development and demand pressure	X7	Renewables share of primary energy consumption	Positive
	X8	Primary energy consumption growth rate	Negative

3.2 Entropy-weighted Readiness Evaluation

To reduce the influence of dimensional differences, positive and negative indicators are standardized as follows:

$$x'_{itj} = (x_{itj} - \min x_j)/(\max x_j - \min x_j),\ x'_{itj} = (\max x_j - x_{itj})/(\max x_j - \min x_j) \quad (1)$$

The entropy method is adopted to determine the objective weights of indicators according to their dispersion across the 20 evaluation units formed by two countries and ten years. The core calculation is expressed as:

$$p_{itj} = x'_{itj}/\Sigma x'_{itj},\ e_j = -k\Sigma p_{itj}\ln(p_{itj}),\ d_j = 1 - e_j,\ w_j = d_j/\Sigma d_j \quad (2)$$

The comprehensive readiness score and dimension score are calculated as:

$$S_{it} = \Sigma w_j x'_{itj},\ D_{itk} = \Sigma j \in k\ w_j x'_{itj} \quad (3)$$

where S_{it} denotes the low-carbon energy transformation readiness score of country i in year t, and D_{itk} denotes the score of dimension k. A higher value indicates stronger transition readiness.

3.3 Obstacle Degree Model

To identify restrictive factors, the obstacle degree model combines indicator weight and deviation from the ideal value. The obstacle degree is calculated as:

$$I_{itj} = 1 - x'_{itj},\ O_{itj} = w_j I_{itj}/\Sigma(w_j I_{itj}) \times 100\%,\ O_{itk} = \Sigma j \in k O_{itj} \quad (4)$$

where O_{itj} denotes the obstacle degree of indicator j. A larger value indicates a stronger restrictive effect on low-carbon transition readiness. The latest year, 2024, is used to identify the most current barriers and policy priorities.

4 Empirical Results and Obstacle Analysis

4.1 Dynamic Readiness Evaluation

The comprehensive readiness scores show that China remained consistently ahead of Kazakhstan during 2015–2024. China's score increased from 0.319 in 2015 to 0.413 in 2024, reflecting renewable energy expansion, low-carbon electricity development, and declining electricity carbon intensity. Kazakhstan's readiness level remained lower and more volatile because of persistent fossil fuel dependence and weak renewable energy development.

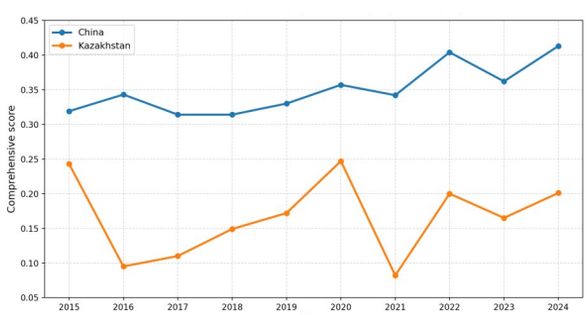

Figure 1 Trends in comprehensive scores of low-carbon energy transformation readiness in China and Kazakhstan (2015–2024)

At the dimension level, China improved continuously in low-carbon energy development and clean electricity capacity, while rapid growth in primary energy demand continued to create transition pressure. Kazakhstan's low readiness was mainly associated with high fossil fuel dependence, high electricity carbon intensity, and insufficient

renewable energy penetration.

4.2 Entropy Weight Results

The entropy-weight results indicate that carbon intensity of electricity (X4), fossil fuels share of primary energy (X1), low-carbon energy share (X3), and primary energy consumption growth rate (X8) have the strongest discriminatory power in evaluating transition readiness. Coal share (X2) receives a low weight because its variation across the evaluation samples is relatively limited.

Table 2 Entropy weights of indicators

Indicator	Entropy value	Difference coefficient	Weight
X1	0.934	0.066	0.168
X2	0.998	0.002	0.004
X3	0.934	0.066	0.168
X4	0.933	0.067	0.173
X5	0.969	0.031	0.079
X6	0.960	0.040	0.102
X7	0.945	0.055	0.142
X8	0.936	0.064	0.164

4.3 Obstacle Factor Analysis

The obstacle degree results for 2024 show that fossil fuel dependence (X1) and electricity carbon intensity (X4) are the main common barriers in both countries. However, their structural constraints differ. For China, the major barriers are fossil fuel dependence, electricity carbon intensity, and primary energy consumption growth. This suggests that demand growth and system integration pressure have become important constraints on further decarbonization. For Kazakhstan, the main barriers are fossil fuel dependence, electricity carbon intensity, low-carbon energy share, and renewables share of primary energy, indicating stronger constraints from clean energy supply and fossil fuel lock-in.

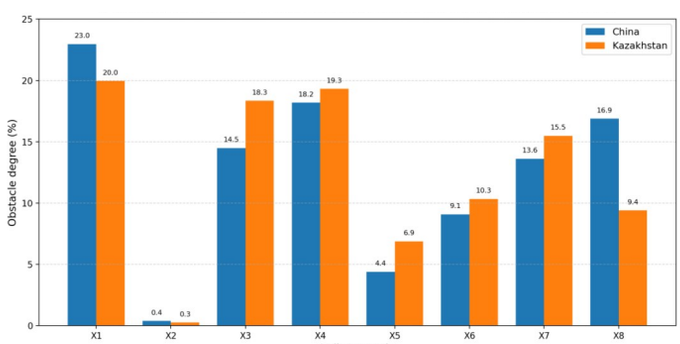

Figure 2 Comparison of main obstacle factors in China and Kazakhstan in 2024

Overall, the results confirm that energy structure optimization and electricity decarbonization are the key determinants of low-carbon transformation readiness in fossil-energy-dependent economies.

5 Discussion and Policy Implications

The findings show that China and Kazakhstan require differentiated low-carbon transition pathways. China has achieved relatively stronger readiness because of renewable expansion, low-carbon electricity development, and policy support under the dual-carbon strategy. Its next-stage transition should focus on system flexibility, renewable energy integration, energy storage, smart grids, and demand-side management. These measures can reduce the pressure caused by rapid energy demand growth and improve the utilization of low-carbon electricity.

Kazakhstan needs a more gradual transition pathway focused on reducing fossil fuel lock-in and expanding clean energy supply. Priority should be given to renewable energy infrastructure, grid modernization, low-carbon investment mechanisms, and improved carbon governance. For fossil-energy-dependent economies, the transition cannot rely only on renewable capacity expansion; it also requires electricity decarbonization, institutional incentives, and coordinated policy support.

6 Conclusion

This study constructs a dynamic evaluation framework for low-carbon energy transformation readiness in China and Kazakhstan using the entropy-weighted composite evaluation method and the obstacle degree model. Based on data from 2015 to 2024, the study evaluates readiness trends and identifies key barriers affecting low-carbon transformation.

The results show that China's readiness level remained consistently higher than Kazakhstan's, mainly because of renewable energy expansion and low-carbon electricity development. Kazakhstan remained constrained by fossil fuel dependence, high electricity carbon intensity, and limited renewable energy capacity. Obstacle analysis further confirms that fossil fuel dependence and electricity carbon intensity are the major common barriers in both countries, while China faces stronger pressure from energy demand growth and Kazakhstan faces stronger constraints from insufficient clean energy supply.

The main contribution of this study is the integration of dynamic readiness evaluation and obstacle factor identification in a China – Kazakhstan comparative framework. Future research may incorporate firm-level ESG performance, carbon-market mechanisms, and scenario simulation to improve the practical applicability of the evaluation framework.

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