Journal of Mathematical Finance and Risk Management
ISSN: 3080-9983 (Print), ISSN: 3080-9991 (Online) | Vol. 1, No. 2, 2026

Carbon Lock-in Challenges and Unlocking Pathways for Resource-Based Cities in Sichuan Province under the "Dual-Carbon" oals

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Abstract: Based on carbon lock-in theory, this paper examines the manifestations, causes, and unlocking pathways of carbon lock-in in resource-based cities in Sichuan Province from three aspects: energy structure adjustment, institutional development, and changes in social behavior. The results show that carbon lock-in in these cities is mainly reflected in the strong inertia of traditional fossil fuel consumption, pronounced path dependence on resource-based industries, and clear regional differences. Energy, institutional, and social lock-in interact and reinforce one another, making low-carbon transition more difficult. Therefore, city-specific and differentiated policies should be adopted from three aspects—optimizing the energy supply structure, improving relevant policy measures, and strengthening social coordination—to break carbon lock-in constraints and promote the sustainable development and high-quality transition of resource-based cities in Sichuan Province.

Keywords: "Dual-carbon" goals; Resource-based cities; Carbon lock-in; Unlocking pathways.

1. Introduction

Resource-based cities rely mainly on the development and use of local natural resources, such as minerals, water, and forests, as well as related industries, to support their economies. According to the National Plan for Sustainable Development of Resource-Based Cities (2013–2020) issued by the State Council in 2013, a total of 262 cities in China are classified as resource-based cities and divided into four types—growing, mature, declining, and regenerative—based on their resource endowments and sustainable development capacity[1]. Overdependence on resource-based industries has led to a series of practical problems, including an undiversified industrial structure, high carbon emission intensity, and increasing pressure on the ecological environment[2]. Under the "dual-carbon" goals, these cities face both development pressure caused by declining benefits from resource development and constraints from existing high-carbon industrial systems and development paths, making low-carbon transition more urgent.

On the one hand, Sichuan Province has abundant clean energy resources, especially hydropower, providing a strong foundation for low-carbon transition. On the other hand, traditional industries still account for a relatively large share, coal consumption remains high, and regional differences in carbon emissions are evident. Path dependence on high-carbon development therefore persists[3]. Examining the manifestations, causes, and unlocking pathways of carbon lock-in in Sichuan is of practical significance for promoting the green and low-carbon transition of resource-based cities and supporting differentiated transition policies in similar regions.

2. Manifestations of Carbon Lock-in in Resource-Based Cities of Sichuan Province

According to the classification criteria of the National Plan for Sustainable Development of Resource-Based Cities, a total of 13 cities in Sichuan Province are designated as resource-based cities. Mature resource-based cities include Guangyuan, Guangan, Zigong, Panzhihua, Dazhou, Yaan, Liangshan, Mianzhu, and Xingwen. Resource development in these cities is relatively stable, and relatively well-developed industrial layouts have been established. Nanchong is classified as a growing resource-based city. Although it is still in the early stage of resource development, it has considerable development potential and room for upgrading. Luzhou and Huaying are declining cities, as their natural gas and coal resources, respectively, are gradually being depleted. Aba is currently the only regenerative city; its dependence on traditional resource-based industries has declined significantly, and new development models are gradually taking shape.

Resource-based cities differ in development stage, resource conditions, and industrial foundations, resulting in different degrees of carbon lock-in, transition pressure, and conditions for breaking lock-in. Mature cities have relatively stable resource-based industrial foundations and a large share of energy-intensive and high-carbon industries. Their established development paths therefore show strong inertia, leading to a relatively high degree of carbon lock-in. If growing cities continue to rely on traditional resource development methods during their early stage, dependence on high-carbon pathways may deepen. Declining cities face industrial contraction, growing employment pressure, and weakening development momentum as resources are depleted, although resource constraints may also create opportunities for industrial transition. Regenerative cities have largely reduced their traditional resource dependence and have gained experience in developing new industries. These clear differences among city types mean that the formation mechanisms and unlocking pathways of carbon lock-in should be analyzed according to each city's development stage and actual conditions. Therefore, a uniform approach is not suitable; targeted transition measures should be

formulated according to the resource endowments, industrial foundations, and development stages of different cities.

3. Unlocking Pathways for Carbon Lock-in in Resource-Based Cities of Sichuan Province

3.1. Low-Carbon Transition of the Energy Structure

3.1.1. Controlling Coal Consumption and Promoting Clean and Efficient Utilization

The key to addressing energy-related carbon lock-in is to optimize the structure of fossil fuel consumption, accelerate clean energy substitution, and build a modern green and low-carbon energy system. Sichuan Province should reduce fossil fuel consumption while improving the efficiency and environmental performance of resource development. While maintaining a reasonable production capacity, it should promote the intelligent upgrading of large and medium-sized coal mines, with a focus on large intelligent coal mine projects in Junlian and Guxu, to improve resource development efficiency and recycling rates. Green development in mining areas should also be strengthened by increasing the utilization of solid waste such as coal gangue and improving coalbed methane exploration and development technologies, thereby minimizing the adverse ecological impacts of coal mining. For energy-intensive industries such as steel, building materials, and chemicals, coal consumption should be reduced through process upgrading, equipment retrofits, and energy-saving technologies. Where conditions allow, higher-carbon fuels should gradually be replaced by natural gas and electricity, while the use of biomass and industrial solid waste as alternative fuels should be expanded to support regional sustainable development.

3.1.2. Leveraging Gas Resource Advantages to Optimize the Energy Consumption Structure

The in-depth development of natural gas and shale gas resources in the Sichuan Basin plays a pivotal role in building a clean and low-carbon energy supply system within the region. To fully implement the Implementation Plan for Carbon Peaking in Sichuan Provinces Energy Sector, it is necessary to accelerate technological innovation in natural gas and shale gas exploration and to foster national-level demonstration bases for high-yield oil and gas fields, thereby comprehensively enhancing the reliability and stability of clean energy supply capacity. In parallel, the construction of natural gas infrastructure and transmission networks should be expedited, with planning and development of natural gas pipelines, shale gas transmission corridors, and branch lines to improve the allocation efficiency and cross-regional dispatching capacity of natural gas resources. In end-use energy sectors such as transportation, the substitution of higher-carbon fuels with relatively low-carbon energy sources such as natural gas should be promoted based on local conditions, providing transitional support for adjustments to the energy consumption structure.

3.1.3. Expanding Renewable Energy Development to Increase Clean Energy Supply

Sichuan Province should capitalize on its abundant hydropower resources to accelerate the establishment of a clean energy supply system dominated by renewable energy. While continuing to leverage the foundational advantages of hydropower, the province should expedite the large-scale development of new energy sources such as wind power and photovoltaics, fostering a synergistic development pattern comprising hydropower, wind power, and photovoltaics. The power dispatching system should be continuously improved to enhance the complementarity of multiple energy sources (wind, solar, hydro) and cascade joint dispatching of river basins, thereby increasing the integration rate of renewable energy. Simultaneously, the electrification transformation of end-use energy sectors—including industry, transportation, and residential consumption—should be coordinated to raise the share of clean electricity in final energy consumption, thereby alleviating fossil fuel dependence on the demand side.

3.2. Systemic Restructuring of the Policy System

3.2.1. Strengthening Regional Coordination and Improving Carbon Lock-in Governance Mechanisms

Given the pronounced regional heterogeneity of carbon lock-in, unlocking it cannot be confined to individual cities or regions; rather, coordinated governance across areas must be enhanced. The government should establish a dynamic monitoring and early warning system for carbon lock-in, conducting continuous surveillance and early warnings for key regions, high-carbon industries, and critical links to identify emerging lock-in risks at an early stage [4]. Differentiated governance strategies should be implemented according to variations in resource endowments, industrial bases, and development stages across regions to improve policy targeting. For Sichuan Province specifically, cooperation with neighboring areas—including Chongqing, Yunnan, and Guizhou—in energy utilization, industrial transition, and carbon emission reduction should be intensified to mitigate "carbon leakage" caused by the cross-regional transfer of high-carbon industries. Particularly against the backdrop of the development of the Chengdu-Chongqing Economic Circle, further coordination in carbon reduction policies, green industry development, and carbon market construction should be pursued to establish a cross-regional collaborative emission reduction framework.

3.2.2. Improving Market Mechanisms to Strengthen the Momentum for Low-Carbon Transition

Market-based mechanisms can alter the cost-benefit relationships of high-carbon production modes, incentivizing enterprises to proactively reduce carbon emissions—a crucial tool for breaking institutional carbon lock-in. Resource-based cities in Sichuan Province should actively participate in carbon emissions trading, leveraging carbon price signals to raise the environmental costs of high-carbon production and urge enterprises to accelerate energy-saving retrofits and the adoption of low-carbon technologies. Concurrently, the regulatory role of fiscal and tax policies should be fully utilized by implementing differentiated policies based on sectoral carbon emission levels and transition difficulties. Strict access controls and scale restrictions should be imposed on energy-intensive and highly polluting industries, while financial subsidies and tax incentives should be provided for low-carbon technology R&D, clean energy promotion, and ecological restoration projects. Through the combined advancement of carbon markets, fiscal and tax policies, and green finance, the long-standing cost advantages of traditional high-carbon industries should be progressively altered, fostering a new market operation model that is fair, transparent, and aligned with sustainable development

objectives.

3.2.3. Optimizing the Assessment Mechanism and Reinforcing Low-Carbon Development Constraints

The performance evaluation criteria for local governments should be further adjusted by reducing reliance on economic growth as the sole measure of development effectiveness, and integrating resource conservation, ecological protection, and carbon reduction tasks into local government performance appraisal mechanisms. A multidimensional assessment of low-carbon development levels in resource-based cities should be achieved by incorporating indicators such as GDP energy intensity, carbon emission intensity, the share of clean energy, and ecological and environmental quality. Concurrently, a carbon lock-in risk assessment and early warning system should be developed in conjunction with performance evaluations, with focused monitoring of regions characterized by a high-carbon energy structure, high proportions of traditional high-carbon industries, and concentrated new high-carbon investments. Timely interventions—including industrial adjustments, project restrictions, and policy guidance—should be adopted to prevent the entrenchment of new high-carbon pathways. By reshaping the development incentives and behavioral constraints of local governments, greater emphasis can be placed on the quality of long-term transition rather than short-term economic growth.

3.3. Social Cognition and Behavioral Transformation

3.3.1. Transforming Resource-Dependence Mindsets and Cultivating a Consensus on Low-Carbon Development

To break social carbon lock-in, the first step is to change the long-standing resource-dependent mindset in resource-based cities. Owing to the historical legacy of resource development and the influence of traditional industrial culture, some resource-based cities harbor an ingrained perception of "development through resources," displaying strong attachment to traditional resource industries and insufficient awareness of the necessity of industrial transition and low-carbon development. Therefore, publicity and education on low-carbon development concepts should be strengthened to help governments, enterprises, and residents understand the interrelationships among resource depletion, environmental constraints, and industrial transformation, gradually reducing psychological dependence on traditional resource-based development models. In particular, public recognition of green transition should be enhanced through typical case studies, community education, and enterprise training tailored to the actual conditions of resource-based cities. In this way, low-carbon development can be transformed from a policy requirement into a shared understanding and voluntary action among social stakeholders.

3.3.2. Guiding Green Consumption Patterns and Shifting High-Carbon Lifestyles

Residents long-established consumption patterns and lifestyles also exhibit path dependence; hence, it is necessary to drive the gradual low-carbon transition of social behaviors from the demand side. The government should intensify publicity on green consumption and the dissemination of low-carbon lifestyle education, enabling the general public to gain a deeper understanding of energy conservation, green mobility, and low-carbon products, and to consciously reduce unnecessary energy consumption and resource waste. In the transportation sector, measures such as optimizing public transport resource allocation, improving bicycle and other non-motorized lane networks, and implementing purchase subsidies for new energy vehicles should be adopted to enhance the convenience of green travel for residents. In daily consumption, the use of energy-efficient appliances, green products, and recyclable goods should be promoted to cultivate conservation-oriented consumption habits. At the same time, reasonable incentive measures should be employed to lower the costs for residents in changing existing consumption behaviors, thereby transforming green consumption from a promoted practice into a stable daily lifestyle and reducing demand-side dependence on high-carbon products and services.

4. Differentiated Strategies Based on City Types

4.1. Mature Cities

For mature cities, the focus should be on the green upgrading of traditional industries and the optimization of industrial structures. While maintaining a reasonable scale of resource development, efforts should be accelerated in energy conservation, carbon reduction, and technological renewal in sectors such as steel, chemicals, and coal, to improve resource utilization efficiency. Leveraging existing industrial foundations, these cities should move toward advanced processing, new materials, and clean energy development, gradually reducing dependence on primary resource extraction. Transition directions should be determined based on the industrial base and resource advantages of each city. For instance, Panzhihua, drawing on its vanadium-titanium resources and clean energy advantages, should advance its vanadium-titanium industry from resource extraction and primary processing to advanced materials and high-end manufacturing, while cultivating clean energy industries such as hydrogen and photovoltaics. Zigong, building on its salt-chemical industry base and scientific and educational resources, should promote the refinement and high-end development of its traditional salt-chemical sector and cultivate strategic emerging industries such as new materials, energy conservation and environmental protection, and biomedicine. By advancing the synergistic development of both traditional industry transformation and emerging industry cultivation, mature cities can gradually weaken their dependence on existing high-carbon development pathways.

4.2. Growing Cities

For growing cities, the priority lies in preventing the emergence of new high-carbon pathways. During the processes of resource development and industrial expansion, low-carbon requirements should be integrated in advance, the deployment of energy-intensive and high-emission projects should be reasonably controlled, and alternative industries should be cultivated concurrently. Based on current oil and gas resources and industrial foundations, the oil and gas chemical industry should be steered from extensive processing toward deep processing and greener production. Simultaneously, emerging industries such as new materials, electronic information, and advanced manufacturing should be developed, along with specialty agricultural product processing and modern service industries, drawing on local agricultural resource advantages. By improving the industrial

layout and diversifying industry categories, dependence on a single resource-based industry can be reduced, curbing the risk of new carbon lock-in from the outset.

4.3. Declining Cities

Declining cities should progressively shift their development focus toward industrial substitution. While reasonably managing the pace of traditional industry phase-out, efforts should be accelerated to cultivate alternative industries, secure employment transitions, and strengthen public service guarantees to prevent significant employment and social pressures resulting from industrial withdrawal. Taking Luzhou as an example, leveraging its unique geographic advantages and industrial base, it should focus on developing emerging industrial clusters such as the Baijiu brewing industry, modern logistics, and modern commercial services, while promoting the green and refined transformation of the traditional chemical industry and developing a port-based economy along the Yangtze River. For other declining cities, suitable alternative industries should be selected based on their respective industrial foundations, ensuring that the orderly exit of traditional high-carbon industries aligns with the cultivation of new development drivers, thereby progressively reducing dependence on resource-based industries.

4.4. Regenerative Cities

Regenerative cities should consolidate the achievements of their transformation and enhance the quality of green development, ensuring that in the process of developing new industries, energy-intensive and high-emission development patterns are avoided. For example, Aba should rely on its favorable ecological environment and ethnic cultural resources to continuously promote green industries such as eco-tourism and cultural tourism, while prudently advancing clean energy development to strengthen the role of green industries in supporting the local economy. Greater emphasis should also be placed on ecological protection and the carrying capacity of resources and the environment, with rational control over development intensity to prevent new forms of resource dependence. By integrating ecological protection with green industry development, the development of regenerative cities can become more robust and sustainable.

5. Conclusions and Outlook

This paper concludes that there is a pronounced carbon lock-in phenomenon among resource-based cities in Sichuan Province, characterized by a strong inertia in traditional fossil fuel consumption, prominent path dependence on resource-based industries, and significant inter-city disparities. The emergence of this phenomenon is not attributable to a single factor but is the result of the interplay and mutual reinforcement of carbon lock-in across three dimensions—energy, institutional, and social. Unlocking carbon lock-in requires coordinated advancement across energy structure adjustment, institutional mechanism improvement, and social development pattern transformation, gradually reducing dependence on traditional high-carbon development models. Furthermore, differentiated measures should be adopted according to the distinct development characteristics of mature, growing, declining, and regenerative resource-based cities to enhance the targeting and effectiveness of low-carbon transition policies.

Acknowledgements

1). This research was funded by the 2026 Sichuan Provincial College Students Innovation Training Program: Research on Carbon Lock-in Challenges and Unlocking Pathways for Resource-Based Cities in Sichuan Province under the "Dual-Carbon" Goals (Project No. S202610615213).

2). This research was funded by the national Business Education and Scientific Research "15th Five-Year Plan" 2026 Project: Research on the Path of Regional Integrated Collaborative Development of Higher Education under the New Business Discipline (Project No. SKJYKT-2605565)

3). This research was also supported by a General Project of the Academic Research Special Fund for High-Level Research Teams under the Sichuan Provincial Philosophy and Social Sciences 14th Five-Year Plan 2025 Program: Mechanisms and Pathways of Digital-Green Synergy for Advancing Sichuan Provinces New Energy System (SC25T057).

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