Low-Carbon Economic Development in a Megacity of China's Arid Region: A Case Study of Urumqi

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Abstract

To address global climate change, developing a low-carbon economy and reducing carbon dioxide emissions have become a broad international consensus. Taking Urumqi, a megacity in the arid region of northwestern China, as a case study, this paper systematically examines the status of urban low-carbon economic development from the perspectives of energy-consumption structure, energy-use efficiency, sectoral and industrial energy consumption, carbon emissions, and carbon-sink capacity. The study identifies the main characteristics and constraints of low-carbon development in Urumqi. The city exhibits a pronounced high-carbon development pattern, characterized by low energy efficiency, an imperfect energy mix, slow development of new and renewable energy, weak carbon-sink capacity, and insufficient awareness of low-carbon concepts. The arid-region setting, resource endowment, and prevailing economic and technological conditions jointly shape the high-carbon nature of Urumqi's energy consumption. In response to these problems, the paper proposes a series of policy measures and clarifies the responsibilities of government, enterprises, residents, research institutions, and financial institutions as the principal actors in the transition toward a low-carbon economy.

Keywords: low-carbon economy; megacity in an arid region; Urumqi

Introduction

Global warming caused by excessive fossil-fuel consumption has profound implications for energy security, ecological security, water security, and food security, and may even threaten human survival. It has imposed substantial losses on socioeconomic development and has prompted the international community to reconsider conventional development models. Against this background, low-carbon development has received growing attention from governments and international organizations [1]. Developed economies were among the earliest advocates of the low-carbon model and introduced a series of legislative and policy measures to facilitate the transition. Countries around the world have also sought to identify new sources of economic growth through low-carbon transformation [2].

The term “low-carbon economy” was formally advanced by the United Kingdom in its 2003 Energy White Paper, Our Energy Future: Creating a Low Carbon Economy. Since then, scholarship on low-carbon development has expanded rapidly. International research has focused mainly on three areas: (1) determinants of carbon emissions, the relationship between carbon emissions and economic growth, and the effects of emission reduction on industrial development [3-7]; (2) institutional arrangements such as carbon taxes and carbon trading [8-9]; and (3) the evolution and trends of low-carbon development in different countries [10-11]. Low-carbon development has also become an important component of China's national strategy [12], and Chinese scholars have examined industrial transition pathways [13-18], energy strategies under low-carbon constraints [19-20], and low-carbon economic policy [21-24].

Cities are central to the national economy, while also being major centers of energy consumption and carbon emissions. Their development trajectories therefore have a strong influence on national energy demand and

emissions [25], and cities play a crucial role in low-carbon transition [26]. Urumqi is a major city in China's northwestern arid region and an important component of the western urban system. It is positioned as a future international trade center linking China with Central and West Asia, an international cultural exchange center, a transnational regional liaison hub, and a major platform for economic cooperation between China and the five Central Asian countries [27]. The city's energy-use pattern is strongly shaped by the natural conditions of the arid region, its resource endowment [28-29], and its level of economic and technological development. Studying Urumqi's low-carbon transition is therefore valuable not only for improving the city's ecological and residential environment, but also for providing a representative pathway for low-carbon development in arid-region cities under a model of low input, low pollution, and high efficiency.

1. Study Area

Urumqi is located between 86°37′33″ and 88°58′24″ E and between 42°45′32″ and 44°08′00″ N, covering 14,875.5 km². It lies near the geographic center of the Eurasian continent, on the northern foothills of the central Tianshan Mountains and along the southern margin of the Junggar Basin. The city has a typical temperate semi-arid continental climate, with low precipitation, dry conditions, and long, cold winters. Urumqi is rich in natural resources and serves as the political, economic, cultural, and scientific and technological center of the Xinjiang Uygur Autonomous Region. In 2009, the municipality had a population of 2.4119 million, including 2.3188 million urban residents, a gross domestic product (GDP) of RMB 108.75 billion, and a per-capita GDP of RMB 38,249. The shares of the primary, secondary, and tertiary sectors in GDP were 1.53%, 42.93%, and 55.54%, respectively. Four major oilfields surround the city: the Tuha Oilfield to the east, the Tarim Oilfield to the south, the Junggar East Oilfield to the north, and the Karamay Oilfield to the west. Coal reserves are especially abundant, exceeding 10 billion tonnes, which has led to Urumqi being described as a “coal city on an ocean of oil.”

2. Data Sources

The data used in this study are mainly drawn from successive editions of the China Statistical Yearbook, Xinjiang Statistical Yearbook, and Urumqi Statistical Yearbook, together with the Urumqi Tenth Five-Year Clean Energy Plan and the Urumqi Energy Development and Energy-Conservation Plan (2008-2015).

3. Current Status of Low-Carbon Economic Development

3.1 Energy-Consumption Structure

Urumqi is a typical energy-consuming city. Over time it has developed an energy-consumption structure dominated by coal, petroleum, natural gas, and electricity. Previous studies indicate an increasing trend in coal-based energy consumption [30]. In 2007, the city consumed 14.72 million tonnes of raw coal, 1.8108 million tonnes of petroleum products, and 396 million m³ of urban natural gas (excluding industrial gas used by petrochemical and Xinjiang chemical enterprises). Wind-power consumption reached 600 million kWh, while other renewable-energy consumption was 22,400 tonnes of standard coal equivalent (tce). Coal accounted for the largest share of the energy mix and its share continued to increase (Figure 1).

居自治区第四位(图3)。

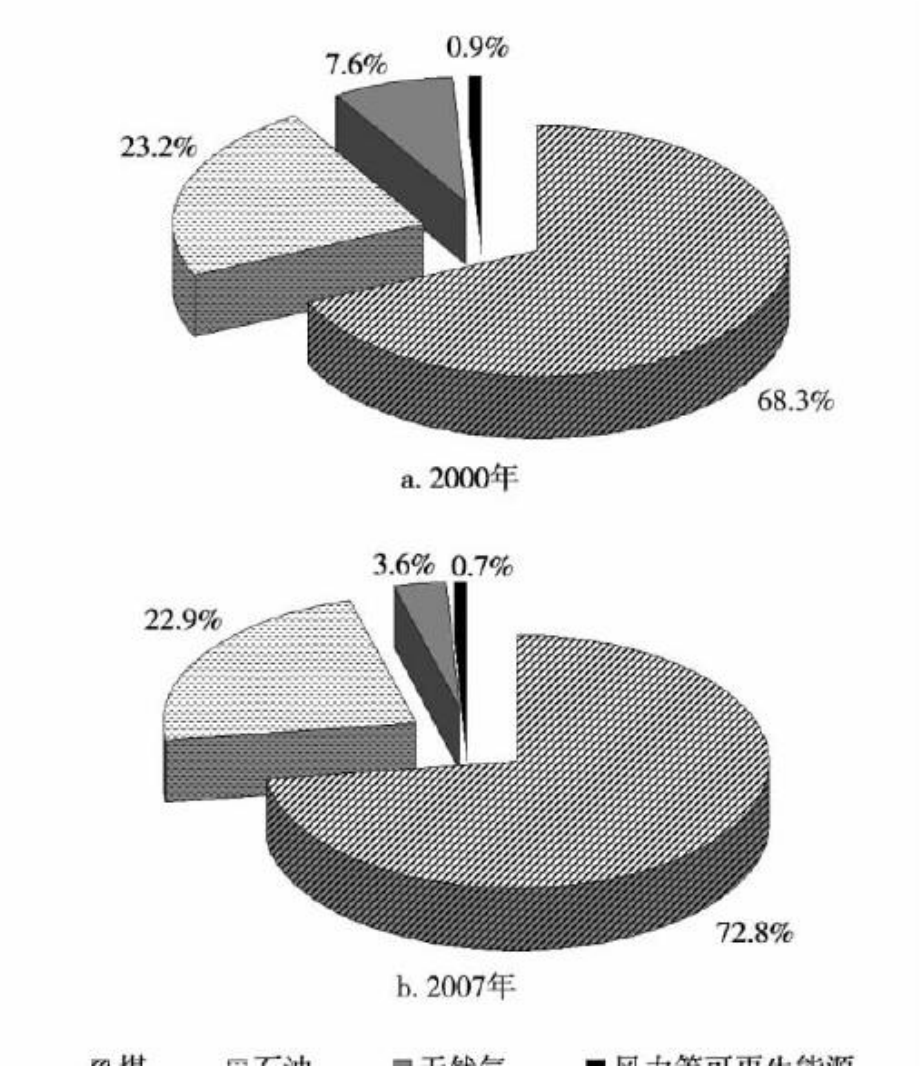


Figure 1. Changes in Urumqi's energy-consumption structure.

3.2 Energy-Use Efficiency

During the previous decade, Urumqi's energy consumption per RMB 10,000 of GDP declined rapidly, from 5.65 tce in 1996 to 2.4 tce in 2008 (Figure 2). Nevertheless, the city remained well above both the Xinjiang average and the national average. Compared with other prefecture-level areas in Xinjiang, Urumqi had relatively low energy-use efficiency: its energy consumption per RMB 10,000 of GDP ranked fourth highest in the autonomous region, after Shihezi, Karamay, and Aksu (Figure 3).

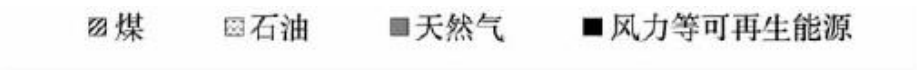


图 1　乌鲁木齐市能源消费结构变化情况

Fig. 1　Energy consumption structure changes of Urumqi

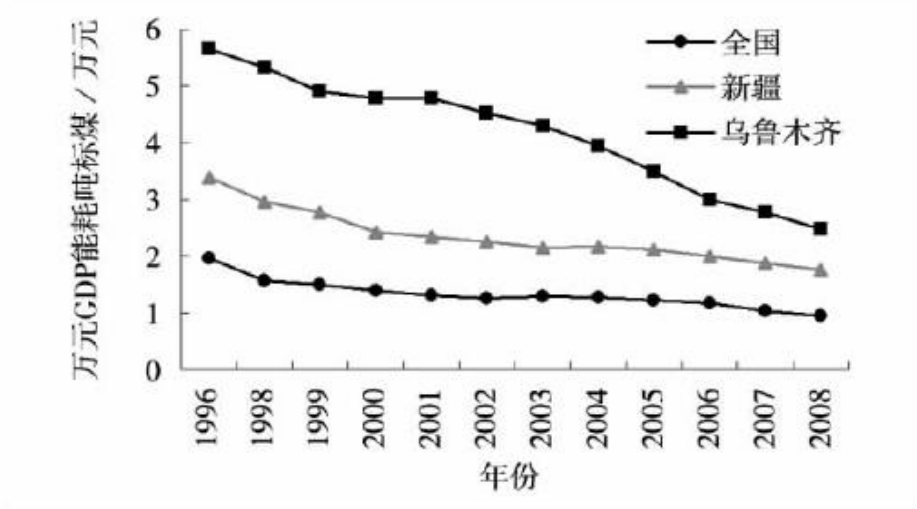


图 2　乌鲁木齐、新疆、全国万元 GDP 能耗对比

Fig. 2　Energy consumption per 10 000 Yuan of Urumqi，

Figure 2. Energy consumption per RMB 10,000 of GDP in Urumqi, Xinjiang, and China.

12.93%。

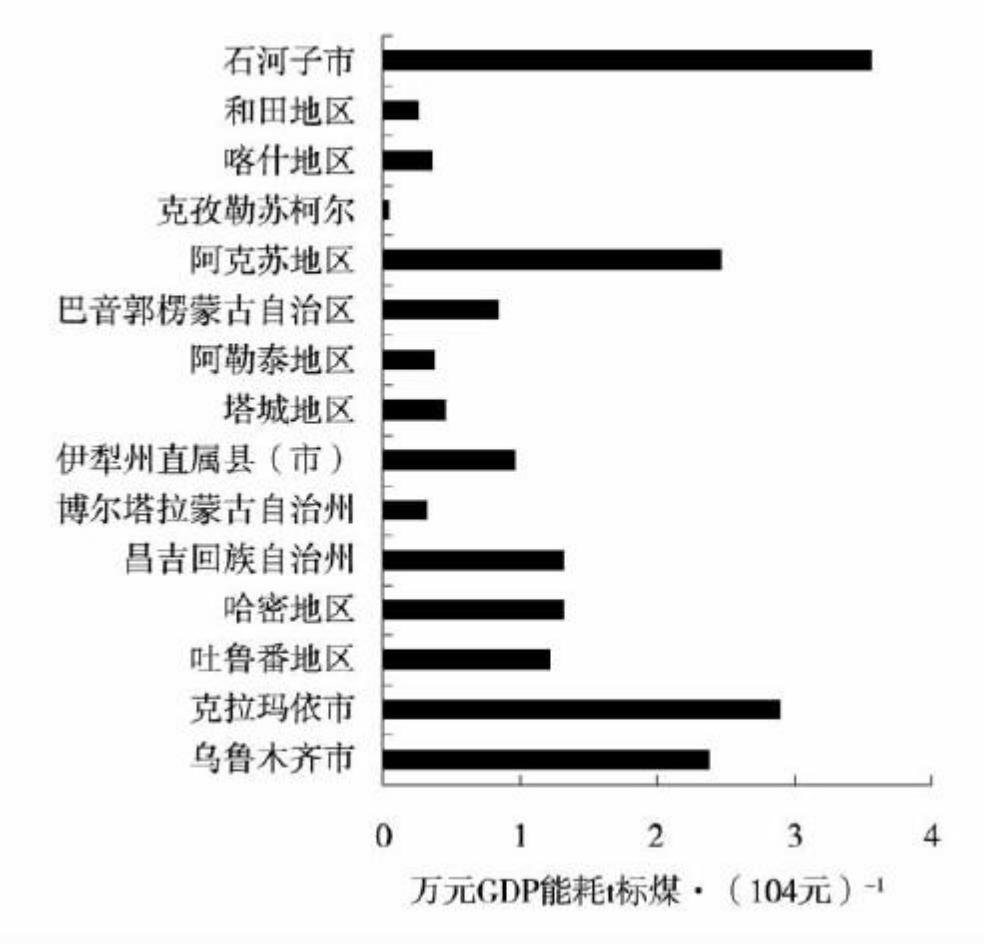


图 3　新疆各地州万元 GDP 能耗对比

Figure 3. Comparison of energy consumption per RMB 10,000 of GDP across prefecture-level areas in Xinjiang.

3.3 Energy Consumption by Sector and Industry

In 2007, total energy consumption in Urumqi was 181.696 million tce after deducting transformation and loss. The primary sector consumed 225,200 tce, accounting for 1.24% of the total; the secondary sector consumed 114.718 million tce, accounting for 63.14%; the tertiary sector consumed 4.3097 million tce, accounting for 23.72%; and household consumption and other uses accounted for 2.1629 million tce, or 11.90% of the total. Compared with 2000, the shares of the primary and secondary sectors declined, while the share of the tertiary sector increased (Figure 4). At the industrial level, metal smelting, heat and electricity supply, petrochemicals, and mining and beneficiation were the principal energy-consuming industries, accounting for 32.86%, 25.8%, 20.56%, and 12.93% of industrial energy consumption, respectively (Figure 5).

Fig. 3 Energy consumption per 10 000 Yuan comparison of different states

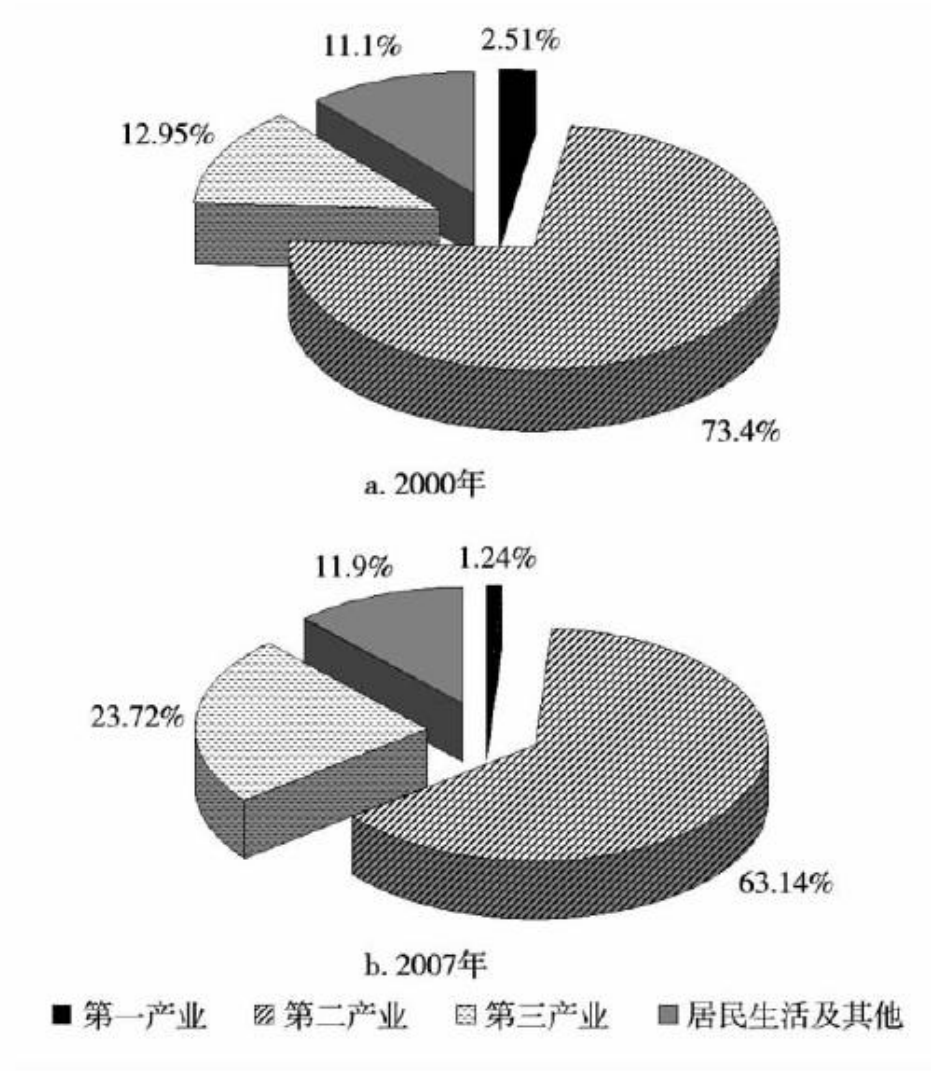


图 4 乌鲁木齐 2000 至 2007 年三次产业能源消耗变化

Fig. 4 Energy consumption changes of three industries

Figure 4. Changes in energy consumption among the three major sectors in Urumqi, 2000 and 2007.

达到 28.2 t/人，比新疆平均水平高出 13 – 20 t/人（图 7）。

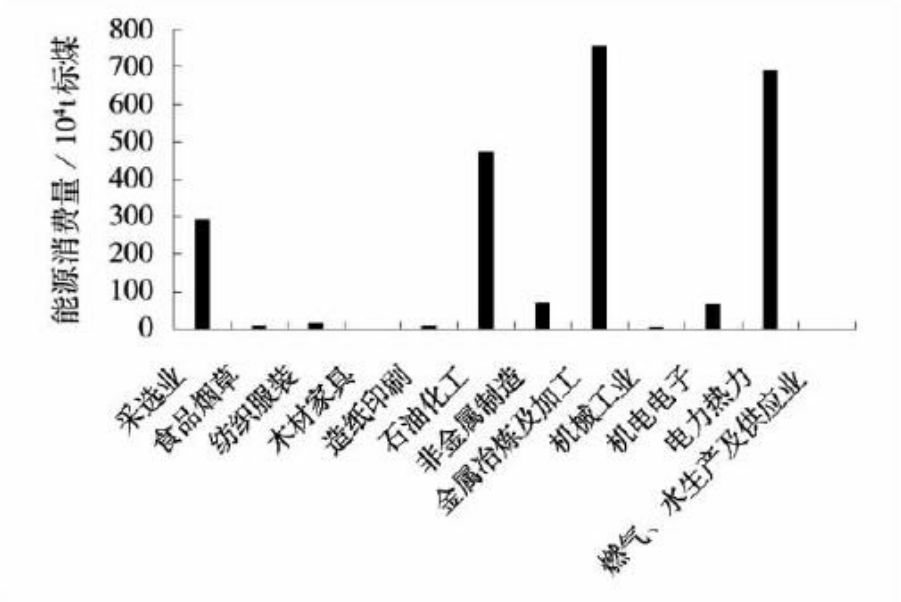


图 5　乌鲁木齐工业各部门能源消费情况

Figure 5. Energy consumption by major industrial sectors in Urumqi.

3.4 Carbon Emissions

Using standard carbon-emission coefficients, this study calculates total carbon dioxide emissions in Urumqi from 1996 to 2008. Total CO_2 emissions increased year by year (Figure 6), and Urumqi recorded the highest total emissions among the 15 prefecture-level areas of Xinjiang. Although CO_2 emissions per RMB 10,000 of GDP declined over time, they remained far above the national level. In 2008, Urumqi emitted approximately 2.3 tonnes of CO_2 per RMB 10,000 of GDP. Its carbon intensity was also high relative to other areas of Xinjiang, ranking fourth after Shihezi, Karamay, and Aksu. On a per-capita basis, CO_2 emissions rose from 17.5 tonnes per person in 1996 to 28.2 tonnes in 2008, approximately 13-20 tonnes per person above the Xinjiang average (Figure 7).

Fig. 5 Energy Consumption of Different Sectors of Urumqi

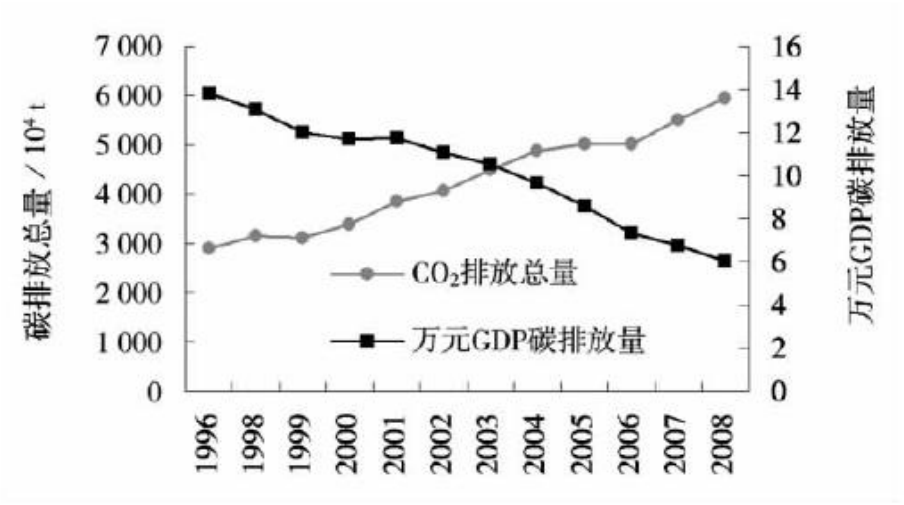


图 6 1996 – 2008 年乌鲁木齐二氧化碳排放量变化

Fig. 6 Carbon Emissions Changes of Urumqi from 1996 to 2008

Figure 6. Changes in CO_2 emissions in Urumqi, 1996-2008.

Fig. 6 Carbon Emissions Changes of Urumqi from 1996 to 2008

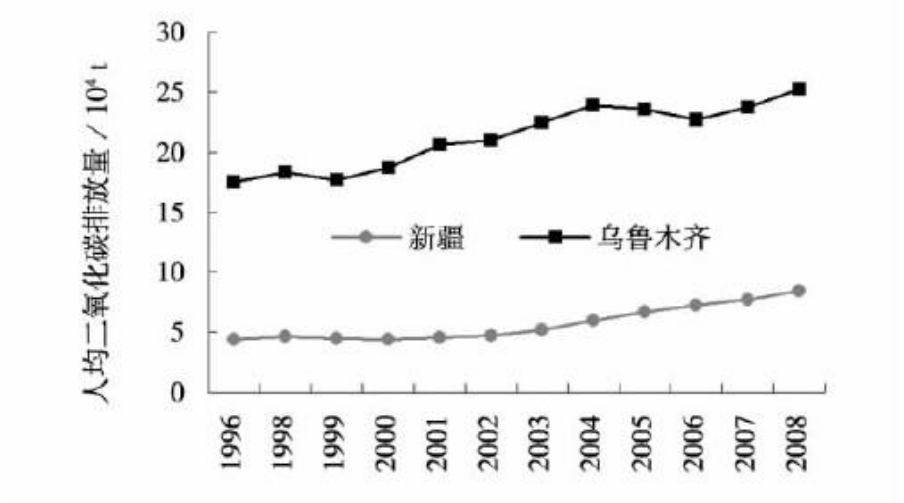


图 7 乌鲁木齐、新疆人均 CO_2 排放量对比

Fig. 7 Comparison between Urumqi and Xinjiang of carbon emissions

Figure 7. Comparison of per-capita CO_2 emissions in Urumqi and Xinjiang.

3.5 Carbon-Sink Capacity

Low-carbon development requires not only effective control of carbon sources but also expansion of carbon sinks. Afforestation, ecosystem restoration, agroforestry, and sustainable forest management can increase terrestrial carbon uptake. Increasing forest carbon sinks can offset part of the obligation to reduce CO_2 emissions, while market mechanisms can help compensate the ecological value created by forests [31].

In 2008, Urumqi had 61,700 hectares of forest land, including coniferous forest, broad-leaved forest, mixed forest, shrubland, sparse woodland, shelterbelts, roadside trees, and economic forests such as orchards. Total growing stock was 179,000 m^3. Grassland covered approximately 835,000 hectares. Existing research suggests that the carbon-sink capacity per unit area of grassland in China is only about one-thirtieth that of forests, while cropland has roughly balanced carbon-source and carbon-sink effects. Accordingly, this study estimates only forest and grassland carbon sinks. Forest carbon storage is calculated using the growing-stock method:

$$C_F = V_F\,\delta\rho\gamma + \alpha V_F\,\delta\rho\gamma + \beta\delta\rho\gamma \quad (1)$$

where C_F is the forest carbon sink; V_F is forest growing stock; δ is the biomass expansion factor converting growing stock to biomass stock (generally 1.90); ρ is the wood-density coefficient converting forest biomass stock to dry biomass (generally 0.45-0.50; 0.50 is adopted here); γ is the carbon-content coefficient converting dry biomass to carbon stock (generally 0.50); α is the conversion coefficient for carbon stored in understory vegetation and litter (0.195); and β is the coefficient for carbon stored in forest soils (1.244).

Using Equation (1), the forest carbon sink in Urumqi is estimated at 212,000 tonnes and the grassland carbon sink at 95,100 tonnes. The combined forest and grassland carbon sink is therefore approximately 307,000 tonnes, offsetting only 0.46% of the city's total carbon emissions in 2008.

4. Problems in Low-Carbon Economic Development

4.1 Resource Endowment and Economic-Technological Conditions Lock in a High-Carbon Energy Structure

Urumqi has abundant coal resources, favorable mining conditions, and relatively low coal-use costs, making coal the dominant source of energy. At the same time, its temperate semi-arid continental climate and limited precipitation constrain hydropower development. Renewable energy is represented mainly by wind power, yet high development costs and constraints in technology and finance have slowed utilization; only about 1.3% of the available wind resource had been developed. Solar resources are abundant and the solar-power industry started relatively early, but had not yet reached scale. These combined conditions have produced an energy system dominated by coal and characterized by lagging development of hydropower, wind power, solar energy, and other low-carbon sources. Coal and petroleum are therefore likely to remain dominant for decades, making the transition toward a low-carbon economy a long-term challenge.

4.2 Low Energy-Use Efficiency

Urumqi's energy consumption per unit of GDP and its carbon intensity are both higher than the Xinjiang and national averages, reflecting a development pattern characterized by high energy use, high emissions, and high pollution. Three factors are particularly important. First, energy production is extensive and conversion efficiency is low. Energy use relies heavily on conventional technologies, and key energy-intensive industries such as iron and steel, petrochemicals, and thermal power generation have relatively outdated technology. Second, Urumqi has long, cold winters, with a heating season lasting approximately six months. More than 3 million tonnes of coal are consumed annually for winter heating. Combined heat-and-power and coal-fired district heating dominate the system, while clean energy plays only a supplementary role. Distributed boilers still account for 19.11% of heated floor area and tend to be small, technologically outdated, and inefficient [32]. Third, a large proportion of buildings are not energy efficient. The central urban area contains approximately 99 million m^2 of buildings, more

than 60 million m² of which are non-energy-saving buildings. Thin walls and poorly sealed doors and windows create substantial heat losses. Average coal consumption for building heating is approximately 43 kg/m² (about 30 kg/m² of standard coal), nearly twice the national energy-efficiency design standard for civil buildings in northern China (17 kg standard coal/m²) [33].

Table 1. Heating structure of Urumqi in 2009

Heating mode	Area (10^4 m²)	Share (%)
Combined heat and power	1,350	13.12
Centralized coal-fired heating	6,320	61.44
Distributed boiler heating	1,966	19.11
Natural-gas heating	600	5.83
Other clean energy	50	0.49
Total building area	10,286	100

4.3 Fragile Ecological Environment and Weak Carbon-Sink Capacity

Natural forests and grasslands in Urumqi have experienced substantial degradation, urban green coverage remains low [34], and ecological water availability is limited. As a result, the city's carbon-sink capacity is weak. In 2008, forest and grassland sinks offset only 0.46% of carbon emissions generated by energy consumption, indicating a serious imbalance between emissions and natural sequestration capacity.

4.4 Limited Low-Carbon Awareness and Fragmented Practice

Urban decision makers, enterprises, financial institutions, and residents have limited understanding of the links among carbon reduction, climate change, and energy security. Awareness of the meaning, development pathway, and broader significance of low-carbon cities remains insufficient and is often confined to the narrow notion of developing a low-carbon economy [26]. Existing practices are scattered and experimental rather than forming a coherent low-carbon development framework. Legal and regulatory systems remain incomplete, supporting policies are insufficient, evaluation mechanisms are underdeveloped, and assessment criteria are unclear, making effective management and scientific evaluation difficult.

5. Policy Measures and Recommendations

5.1 Strengthen Industrial Energy-Efficiency Upgrading and Pursue a New Path of Industrialization

(1) Promote the development and consolidation of the Wudong, Dabancheng, and Aiweiergou mining areas. Integrate coal resources, cultivate large coal enterprises, encourage leading firms to restructure smaller mines, and close inefficient small mines in accordance with the law. Develop advanced coal-fired power-generation technologies, improve coal-conversion efficiency, and promote combined heat and power as well as multi-generation systems for heat, power, and cooling.

(2) Develop a circular economy and improve comprehensive resource utilization. Promote resource conservation, improve mining recovery rates and mineral-processing and smelting recovery rates, expand the comprehensive use of tailings and waste rock, and reduce waste and consumption of energy-intensive products.

(3) Strengthen energy management in high-energy-consuming enterprises. Introduce enterprise energy audits and statistical systems for energy efficiency, implement demonstration projects for industrial energy conservation, and focus on electricity, iron and steel, cement, chemicals, coking, building materials, textiles, heating, and other key energy-intensive sectors. Gradually reduce distributed coal-fired boilers, phase out small high-energy and high-pollution plants, and replace outdated energy-intensive equipment to achieve both technological and structural energy savings.

5.2 Build a Low-Carbon City and Pursue a New Path of Urbanization

(1) Strengthen the dissemination of building energy-saving technologies and standards and promote low-carbon buildings. Establish building energy-efficiency standards and labeling systems; raise and enforce energy-efficiency requirements; retrofit existing high-energy-consuming buildings; support research, development, and commercialization of energy-saving construction materials; use fiscal and tax incentives to encourage developers and consumers to invest in low-carbon buildings; and implement demonstration projects.

(2) Develop an integrated transport network that is convenient, efficient, and energy saving. Combine energy-efficiency and environmental labeling policies, accelerate the retirement of old high-energy and highly polluting vehicles, encourage economical low-emission household vehicles, promote electric vehicles and biofuel vehicles, strengthen public transport, and restrain excessive growth in petroleum consumption.

5.3 Encourage Household Energy Conservation and Low-Carbon Lifestyles

(1) Strengthen public awareness of low-carbon living and promote green-energy programs. Encourage efficient office equipment, household appliances, and lighting in public facilities, hotels, shopping centers, and residential buildings; promote energy-storage air-conditioning systems, solar water heaters, and other energy-saving products; and expand efficient residential lighting programs.

(2) Improve energy-saving awareness within government institutions. Prioritize energy-efficiency retrofits of public facilities and government office buildings, establish energy audits for public buildings, improve procurement mechanisms, incorporate energy-saving products into government procurement catalogs, and give them purchasing priority so that government guidance and market mechanisms jointly advance energy conservation.

5.4 Optimize the Energy Mix and Develop Low-Carbon Energy

Gradually reduce the share of coal in total energy consumption. Expand wind-power development, particularly in Dabancheng; develop biomass energy; support electricity generation from municipal waste and biogas; accelerate exploration and assessment of geothermal, solar, and other renewable resources; promote photovoltaic power for lighting in public facilities and public-interest buildings; encourage integrated solar buildings; and establish pilot projects for large-scale solar power, biomass, geothermal, and other renewable-energy applications that substitute for conventional energy.

5.5 Optimize the Industrial Structure and Upgrade the Capital City's Economy

Use informatization to promote industrialization and deepen the strategy of transforming resource advantages into economic advantages. Continue optimizing the industrial structure and development model and follow a new path of industrialization characterized by high technological content, strong economic performance, low resource consumption, low environmental pollution, and full utilization of human resources. Foster strategic emerging industries in new energy, new materials, electronic information, energy conservation and environmental protection, and biomedicine. Gradually relocate highly energy-intensive primary processing industries while increasing the share of modern services, particularly knowledge-, technology-, and management-intensive services, in regional GDP.

5.6 Increase Investment in Urban Greening and Enhance Carbon-Sink Capacity

Carbon sinks primarily refer to the capacity of forests to absorb and store carbon dioxide and can generate tradable value in international carbon markets. Forests are major reservoirs and sinks of greenhouse gases and therefore play an important role in responding to global climate change [35]. Urumqi should increase urban green coverage and forest area and, within the constraints imposed by ecological water availability in an arid-region city, actively develop carbon-sink forests.

5.7 Strengthen Energy-Conservation Outreach and Foster Low-Carbon Consumption

Public communication should be strengthened and campaigns should be organized to build resource-saving government agencies, enterprises, communities, and schools. Key energy-consuming enterprises should be held accountable for energy-saving targets; schools should provide education on national resource conditions and energy conservation; and community platforms should disseminate practical energy-saving knowledge. Enterprises and residents should be encouraged to adopt more scientific patterns of energy use and consumption while improving living and production conditions, thereby creating a social environment in which energy-saving products and low-carbon practices become widely accepted.

6. Roles of Major Stakeholders in Low-Carbon Economic Development

Government, enterprises, residents, research institutions, and financial institutions are the main actors in low-carbon economic development and have distinct responsibilities. A successful transition requires coordinated action among all five groups, forming a “five-party cooperation” mechanism.

6.1 Government: Formulate Low-Carbon Plans and Coordinate Regional Development

Government should apply low-carbon principles across industrial, building, transport, and carbon-sink planning. It should optimize the industrial structure, phase out outdated capacity, develop high-technology industries and advanced services, establish effective building energy-efficiency policies, support producers of energy-saving materials, expand green buildings, strengthen public transport, guide residents toward transit and walking instead of private-car use, and invest in carbon-sink forests without jeopardizing domestic and productive water supplies. Government should also establish enterprise low-carbon evaluation systems and industry standards for low-carbon products and services, use appropriate incentives and penalties to regulate production, increase investment in low-carbon research, foster technology intermediaries, and strengthen education and communication on low-carbon development.

6.2 Enterprises: Improve Their Own Carbon Performance and Influence Upstream and Downstream Partners

Enterprises should retrofit energy-intensive equipment, optimize production processes, improve energy efficiency, and gradually increase the share of renewable energy. They should build a low-carbon corporate culture, raise employee and consumer awareness, and cultivate demand for low-carbon products. Environmental protection should be incorporated into long-term corporate strategy. Firms should extend their low-carbon footprint throughout supply chains and cooperate with government agencies, non-governmental organizations, industry associations, customers, consumers, and suppliers to establish greener industrial chains and sustainable circular-economy models.

6.3 Residents: Adopt Low-Carbon Consumption and Lifestyles

Residents should develop preferences for low-carbon products, use market demand to influence enterprise behavior, and exercise public oversight over government and corporate environmental practices. Low-carbon lifestyles should be promoted in workplaces, rural areas, communities, and schools through conservation of electricity, paper, food, and fuel. Energy-saving and solar appliances, public transport, walking, and other green travel modes should be encouraged, with the broader goal of establishing lifestyles characterized by low energy use, low pollution, and low waste.

6.4 Research Institutions: Develop Low-Carbon Technologies and Provide Technical Support

Research institutions should strengthen scientific talent development, enhance independent innovation, and prioritize medium- and long-term strategic technologies. International exchange should be expanded both to learn from advanced low-carbon technologies and to promote technology transfer. Priority research areas include wind and solar energy, energy-efficient transport systems, new-energy vehicles, intelligent transport, energy-saving

technologies for new and existing buildings, green-building technologies, efficient motors and electrical systems, renewable energy in buildings, carbon capture and storage, low-carbon chemical engineering, carbon-emission monitoring, and research on low-carbon economic theory, law, regulation, policy, and industrial and regional planning.

6.5 Financial Institutions: Support Low-Carbon Development with Financial Resources

Low-carbon finance in China was still at an early stage at the time of the study, and further development was needed in strategic planning, policy incentives, institutional architecture, and international coordination. Financial institutions can provide carbon-trading services and intermediary support, expand green credit, direct lending toward sectors and projects that meet low-carbon requirements, and use carbon-finance instruments to implement the principles of energy conservation, emission reduction, environmental protection, and green finance. Capital allocation toward low-carbon industries is essential for providing financial support to the transition.

前，我国低碳金融还处于起步阶段，在战略规　　资金保障。

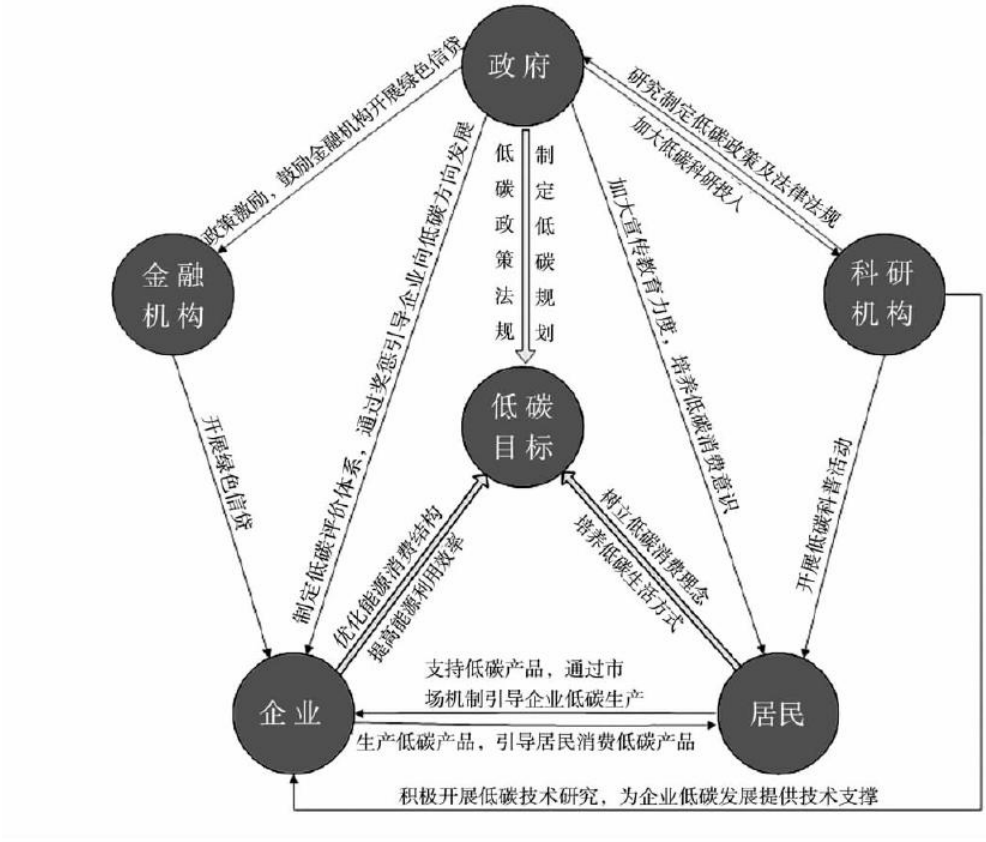


图 8　低碳经济发展“五方联动”模式

Figure 8. Five-party cooperation model for low-carbon economic development.

7. Conclusions and Discussion

This paper systematically analyzes Urumqi's low-carbon economic development from the perspectives of energy-consumption structure, energy-use efficiency, sectoral and industrial energy consumption, carbon emissions, and carbon-sink capacity. The arid-region setting, resource endowment, and economic and technological conditions determine the city's high-carbon energy pattern. Coal and petroleum are likely to remain dominant for decades, meaning that low-carbon transformation will be a long-term and difficult task. Key problems include low energy-use efficiency, an imperfect energy mix, slow development of new and renewable energy, weak carbon-sink capacity, and insufficient public understanding of low-carbon development.

Based on Urumqi's conditions, the study recommends seven main directions: (1) strengthen industrial energy-efficiency retrofits and pursue a new path of industrialization; (2) build a low-carbon city and promote a new model of urbanization; (3) encourage household energy conservation and low-carbon lifestyles; (4) optimize the energy mix and expand low-carbon energy; (5) optimize the industrial structure and upgrade the capital city's economy; (6) increase greening investment and carbon-sink capacity; and (7) strengthen energy-conservation communication and cultivate low-carbon consumption. Government, enterprises, residents, research institutions, and financial institutions should assume corresponding responsibilities and cooperate throughout this process.

Because of data-availability constraints, the empirical analysis relies mainly on information up to 2008. This limits the timeliness of the study, but does not alter its basic assessment of the principal problems and overall tendencies of low-carbon economic development in Urumqi.

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