

Article

Analysis of the Dynamic System Driving High-Quality Transformation of Resource-Based Regions Through Smart Eco-Innovation: Evidence from Daqing City, China

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Abstract: Economic transformation is an effective strategy for resource-based regions to avoid the “resource curse”. In China’s high-quality development stage, using new-generation IT to guide economic structure adjustment, industrial upgrading, and technological innovation is of great practical significance. It also helps regions achieve ecological and high-quality development. Based on SDM, this paper takes smart eco-innovation as the driving force for high-quality transformation. The system constructed is built from five aspects: innovation, coordination, green development, openness, and sharing. Additionally, based on the interrelationships among the subsystems, this paper constructs causal loop diagrams and flow diagrams. Taking Daqing City in China as an example, it conducts a scenario simulation of high-quality transformation driven by smart eco-innovation. The finding shows that the combined policy effects of smart eco-innovation are the most significant for the high-quality transformation of resource-based regions. This study provides a new perspective. It explores the transformation of resource-based regions driven by a “smart eco-style” approach and provides references for such regions in China.

Keywords: resource-based regions; smart ecology; high-quality development



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1. Introduction

Since the 21st century, rapid advancements in ICT have sparked a new round of technological and industrial transformations, reshaping the global economic landscape. Examples include the American Manufacturing Renaissance Act, Germany’s “Industry 4.0” strategy, and China’s Made in China 2025 action program. ICT is also driving the evolution of urban development concepts. Originating from IBM’s “Smarter Planet” in 2008, smart ecology has emerged as a key direction for modern cities [1]. Smart eco-cities integrate technologies like AI, big data, and cloud computing. Smart ecology emphasizes two core principles: intelligence and ecological sustainability. The goal is the comprehensive development of society, the economy, culture, and the environment [2]. In 2018, China introduced the concept of “harmonious coexistence between humanity and nature”. This was followed by the Overall Layout Plan for Digital China Construction in 2023, which provided policy support for smart ecology construction. Therefore, strengthening smart ecology construction is crucial for urban development.

The transformation of resource-based cities is a major challenge for many countries [3,4]. In China, resource-based regions have extracted over 52.9 billion tons of raw coal and 5.5 billion tons of crude oil. These regions have played a crucial role in forming China’s industrial system

and energy supply system. However, since 2000, they have faced issues like low resource efficiency and severe environmental damage, drawing high government attention. In 2021, the Chinese government approved the Implementation Plan for Promoting High-Quality Development of Resource-Based Regions during the 14th Five-Year period. This plan offers new opportunities for regions' transformation. In the context of "digital drive and smart development". China has adopted smart ecology as a new urban development pattern. This is strategically important. It helps integrate economic, social, and ecological benefits while supporting the high-quality transformation of China's resource-based regions.

When resource-based regions use smart technologies for eco-innovation, they create a smart ecological environment that is innovative, coordinated, green, open, and shared. Smart eco-innovation merges resource-based industries with the digital economy. It makes resources more efficient and creates an innovative environment. It also spawns new business forms like the smart economy, smart management, and smart livelihoods, driving coordinated social and economic development. Intelligent green tech boosts mineral resource efficiency and cuts pollutant emissions, pushing regional industries in a greener direction. Smart eco-innovation upgrades ecological, transportation, and communication resources. This enhances connections with developed areas and boosts regional openness. It also promotes the sharing of achievements. Building smart infrastructure, energy systems, and mining industry platforms has spurred the shared economy and service economy. Smart eco-innovation attracts key factors like talent, capital, tech, and information. It also promotes industrial coordination and new business formation, providing the momentum for high-quality transformation in resource-based regions.

In smart eco-city research, scholars mainly conducted analysis from three aspects: construction, evaluation, and effects of smart cities and eco-cities. Smart cities use advanced tech and data to conserve resources and boost ecological well-being [5–8]. Xu et al. argued building smart cities involves tech, infrastructure, policy, and human values, with a focus on public and economic benefits [9]. Battarra et al. ranked 38 cities and found key factors: e-government, economy, tech, human capital, ecology, education, and connectivity [10]. Guo et al.'s research indicated that smart cities in China help with energy savings and emission cuts [11]. Eco-cities focus on environmental sustainability and ecological balance [12]. Vandergert et al. created three urban models with eco-patterns like clean tech and ecological design, comparing eco-innovation methods from different cities [13]. Naphade et al. proposed that smart cities are innovative ecosystems, using modern tech to build smart eco-cities [14]. Bibri et al. suggested that smart eco-cities use the Internet of Things and big data technologies for sustainability, blending social, economic, and emerging tech like AI to drive urban comprehensive development [2].

The transformation of resource-based cities is crucial for economic growth, industrial upgrading, and social progress. Why transform? Theories like the life cycle [15,16], resource curse [17,18], and crowding-out effect [19] explain the urgency. For industrial transformation, studies focused on resource endowment, environmental regulation, and tech innovation [20,21], highlighting incentives for structure, innovation, and regulation. Social and economic transformation was also key, with studies on economic growth, income, and social welfare [22–24]. Green development is explored through environmental quality [25,26]. On transformation paths, scholars studied policy impacts and business turnover, analyzing economic and social effects [27–29]. Cała et al. found Europe's energy transition would shake up society, requiring public support and solutions for re-employment and mining area restoration [28]. Kim and Lin showed that government involvement was crucial for the economic transformation of resource-based regions [30].

"High-quality development" in China means better development with less input, more efficiency, and lower environmental costs [31]. Chinese studies covered the meaning,

evaluation, and influencing factors of high-quality economic development [32–34]. Studies have evaluated the transformation and sustainable development of resource-based cities in terms of regional resilience and carrying capacity [35–38]. Sustainable cities need social equity [39], environmental friendliness [40], and balanced growth [41]. To arrive there, studies suggested using digital tech [42], pollution control, and innovation [43]. New tech like AI and the Internet of Things boosted innovation, resource efficiency, and pollution reduction [44,45]. These technologies will drive “smart eco-style” development in resource-based regions.

Current studies on smart eco-cities, resource-based region transformation, and sustainable development offer useful strategies for guiding regional transformation. However, the existing literature pays little attention to the key role of smart eco-innovation in driving regional development, especially in new-generation IT. There is also a lack of specific analytical models for quantitative analysis in this area. To fill this gap, this paper performs SDM to drive the high-quality transformation of resource-based regions and explores the “smart eco-style” path.

Compared with previous studies, this paper offers new insights. First, it combines the high-quality transformation of resource-based regions with smart eco-innovation. This approach is forward-looking and innovative. It creates a smart-ecological framework, focusing on high-quality change, using smart eco-innovation as the driver and policy as the safeguard. This fills a gap in research on smart-ecological issues in regional transformation. Second, it performs SDM to drive the high-quality transformation of resource-based regions, identifying key patterns. Third, this paper builds a regional transformation drive system based on the principles of “innovation, coordination, green development, openness, and sharing”. It provides a fresh perspective for studying the “smart eco-style” transformation of resource-based regions.

2. Materials and Methods

2.1. System Dynamics Modeling (SDM)

Forrester introduced system dynamics [46] with the aim of analyzing and solving inventory management issues in corporate production. It uses computer simulations to explain cause-and-effect relationships and dynamic changes within systems. Scholars mainly use it to study complex systems [47]. SDM is concentrated on the relationships and mechanisms among various entities. They are applicable, data-driven, accurate, and realistic, fitting the needs of high-quality transformation in resource-based regions.

In the high-quality development stage, resource-based regions are no longer driven by simple factors like “investment dividend” or “demographic dividend”. Instead, a complex multi-factor dynamic system drives their development. Smart eco-innovation, spurred by IT, offers a new driver for regional high-quality development. To design a dynamic system for this transformation, we need to link the region’s information transfer, energy flow, and material cycling through information, capital, and material flows. This creates a tightly connected and stable system structure. We use smart eco-innovation as the driving force. From a holistic perspective, we build a dynamic system for the high-quality transformation of resource-based regions (as shown in Figure 1). Furthermore, this paper uses causal loop diagrams and stock-and-flow diagrams to illustrate relationships among system entities, clarifying interdependencies.

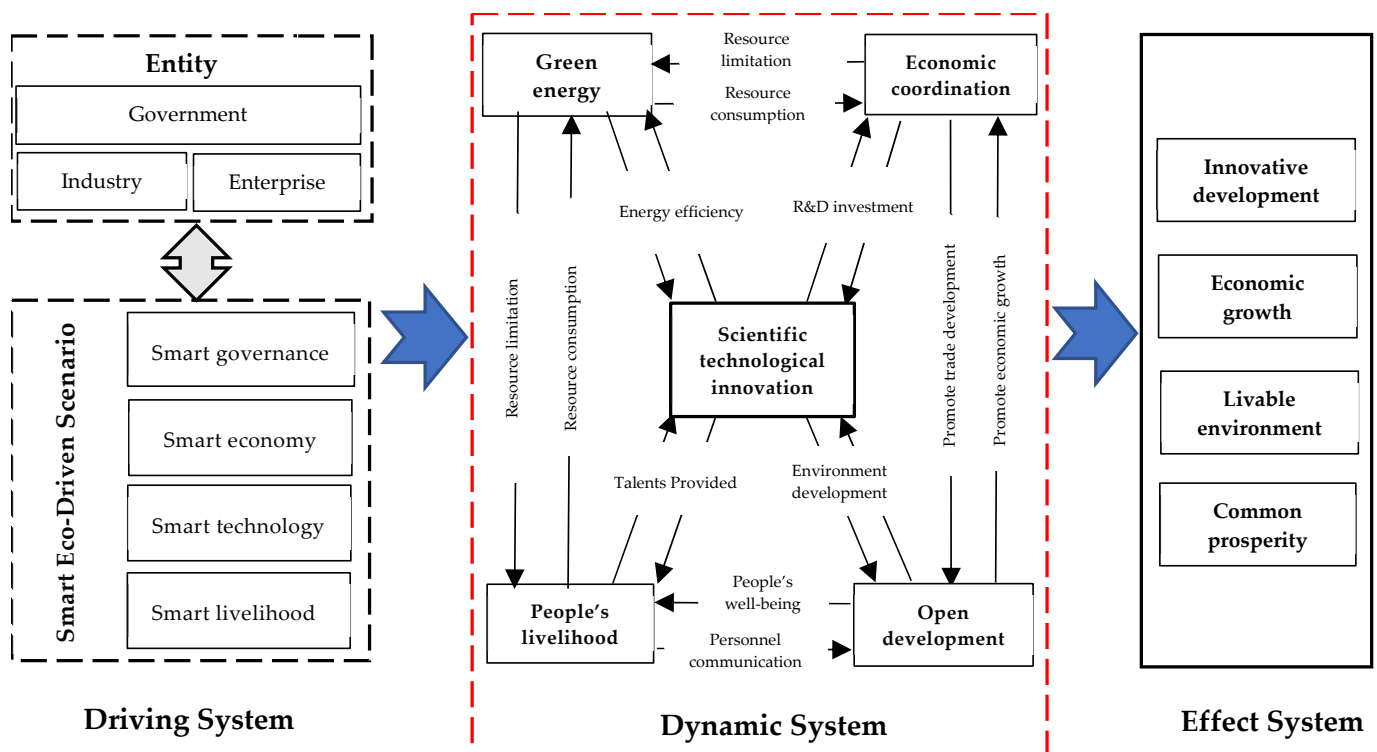


Figure 1. The system of smart eco-innovation-driven high-quality transformation in resource-based regions.

2.2. System Design

The design approach for the high-quality transformation dynamic system of resource-based regions is as follows: (1) Define the framework. (2) Establish system boundaries according to new development concepts, including innovation, coordination, green development, openness, and sharing. (3) Analyze interactions among subsystems within the context of smart eco-innovation and establish causal relationships for the dynamic system. (4) Based on the causal relationships and the driving relationships of smart eco-innovation, select relevant variables to construct the dynamic system flow diagram. Determine variable parameters and develop functional equations. (5) Test the SDM model through structural, consistency, and extreme condition tests. Refine the model to ensure it accurately represents real-world dynamics. (6) Apply SDM to simulate Daqing City. This includes designing policy scenarios, adjusting input variables, observing dynamic trends, analyzing simulation results, and providing recommendations.

The system shown in Figure 1 has multiple inputs, outputs, and feedback loops. It includes three main components: the driving system, the dynamic system, and the effect system.

(1) **Driving System.** The driving forces originate from both internal and external sources. Endogenous drivers, including governments, industries, and enterprises, are primary catalysts. They optimize the business environment, foster industrial development, create innovative conditions for enterprises, and build livable communities, all influenced by regional policies. Exogenous drivers, such as capital, new technologies, talent inflows, and data utilization, promote regional transformation through the foundation laid by endogenous drivers.

Therefore, governments, industries, and enterprises in resource-based regions need to create a high-quality development environment through integrated innovation. The government's capacity for reform and innovation, digital construction, and a smart business environment have the greatest impact on attracting external drivers. Industries optimize

their structure through digital transformation, smart energy, smart agriculture, emerging digital clusters, and tertiary sector development to form new industrial ecosystems. Enterprises, as implementers of industrial policies, benefit from the smart innovation environment, which supports regional high-quality transformation.

(2) Dynamic System. The dynamic system includes the economic system, energy system, population system, social system, environmental system, and technological system. Based on the existing research [48,49] and the development patterns of resource-based regions, this study constructs a dynamic system from five aspects: innovation, coordination, green development, openness, and sharing. This creates a scenario driven by smart eco-innovation. Among them, the innovation subsystem is the core. The five subsystems reflect technological innovation capacity, coordinated economic development, green energy status, open trends, and social welfare conditions, respectively.

(3) Effect System. This paper evaluates the effects based on the formation of regional innovation development, economic growth, livable environment, and common prosperity. These criteria reflect the effectiveness of the transformation dynamic system.

2.3. System Structural Relationships and Variable Setting

2.3.1. Causal Relationship

This paper examines the interrelationships among the five subsystems in the dynamic system from the perspective of smart eco-innovation. It identifies key elements and illustrates their feedback mechanisms using Vensim-PLE 10.2.2. The causal relationship diagrams are shown in Figure 2.

(1) Scientific and technological innovation subsystem. Regional scientific and technological innovation is influenced by the economy and human capital [50,51]. Increasing research and education expenditure in fiscal spending attracts social capital to invest in regional scientific research infrastructure, fostering a favorable ecosystem for scientific and technological investment. Consequently, local government and enterprise investments in these resources form a regional innovation ecosystem through three main feedback loops, as shown in Figure 2a.

(2) Economic coordination subsystem. Resource-based regions develop a smart investment ecosystem through investments in smart agriculture, smart energy, and smart cities. This promotes industrial structure adjustment [52–54] and coordinates regional industries and urban–rural areas [55]. It supports the intelligent transformation of resource-based industries and the ecological layout of regional smart industries, providing momentum for high-quality transformation. This subsystem generates three main feedback loops and three branches (as shown in Figure 2b).

(3) Green energy subsystem. The green energy subsystem focuses on balancing energy production, demand, pollution, and environmental protection [56,57]. Resource-based regions support regional high-quality development through smart energy investment and environmental protection. These actions guide green and low-carbon energy development and create an ecological and livable environment. This subsystem generates two main feedback loops (as shown in Figure 2c).

(4) Open development subsystem. A favorable open development environment attracts external factors and resources, providing financial, technological, and talent support for transformation [58]. Resource-based regions can foster an open development ecosystem by creating a smart business environment and attracting domestic and foreign capital. This injects financial momentum into regional industrial investment and transformation. This subsystem generates one main feedback loop (as shown in Figure 2d).

(5) People's livelihood subsystem. Resource-based regions enhance residents' well-being by constructing smart and livable environments, including smart education and

healthcare. This improves residents' happiness and establishes a smart foundational ecosystem for transformation. This subsystem generates three main feedback loops (as shown in Figure 2e).

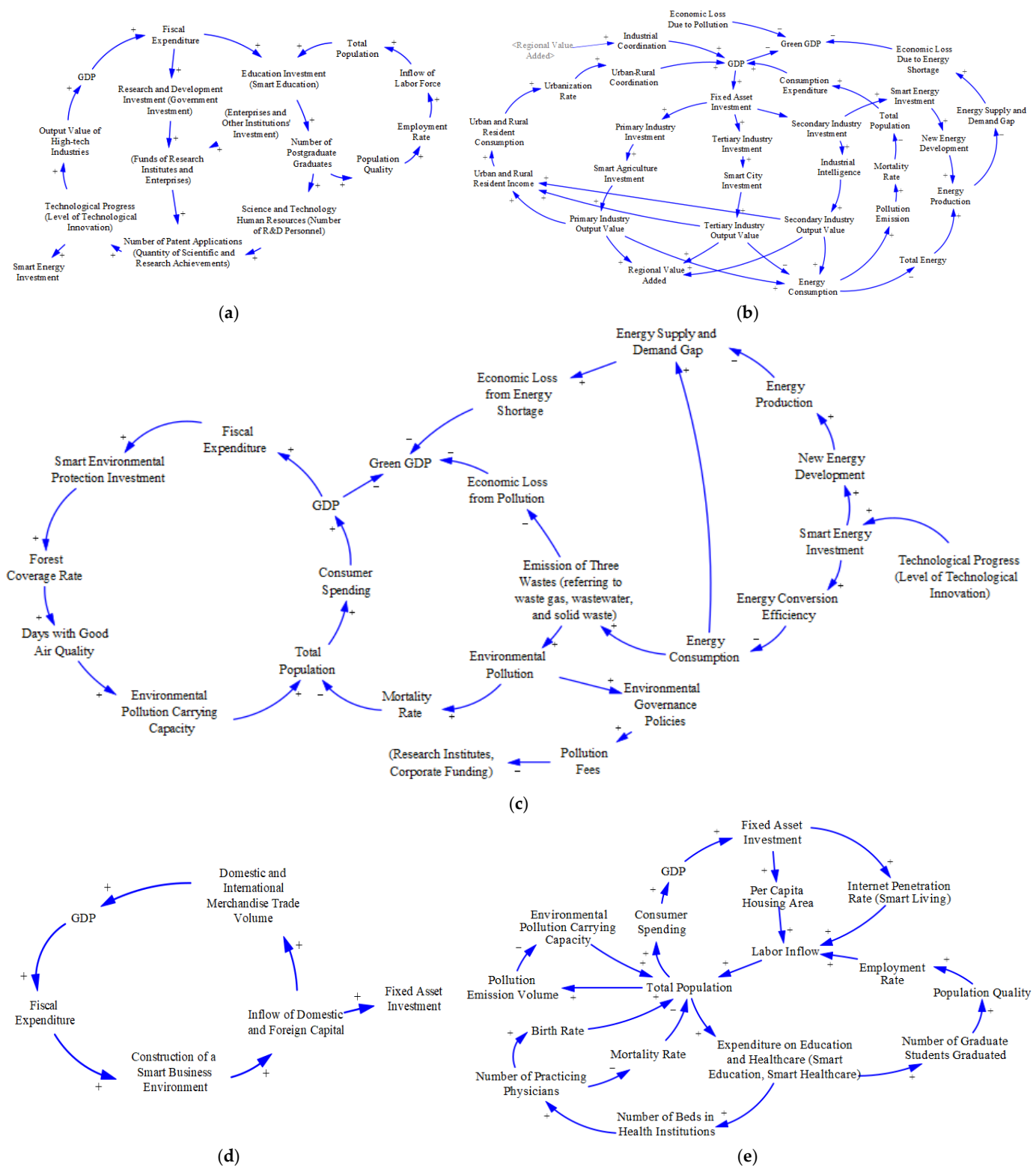


Figure 2. Causal loop diagrams of the five subsystems. (a) Scientific and technological innovation subsystem; (b) economic coordination subsystem; (c) green energy subsystem; (d) open development subsystem; (e) people's livelihood subsystem. The blue arrow indicates the effect of A on B. "+" indicates a promoting effect, while "-" indicates an inhibitory effect.

This paper integrates the interrelationships between key variables across subsystems. For example, it examines the relationship between smart energy investment in Figure 2c and new energy development in Figure 2b, the relationship between domestic and foreign capital inflows in Figure 2d and fixed asset investment, and the relationship between total population in Figure 2e and educational investment in Figure 2a. These relationships are used to describe causal feedback relationships in the system model, as shown in Figure 3.

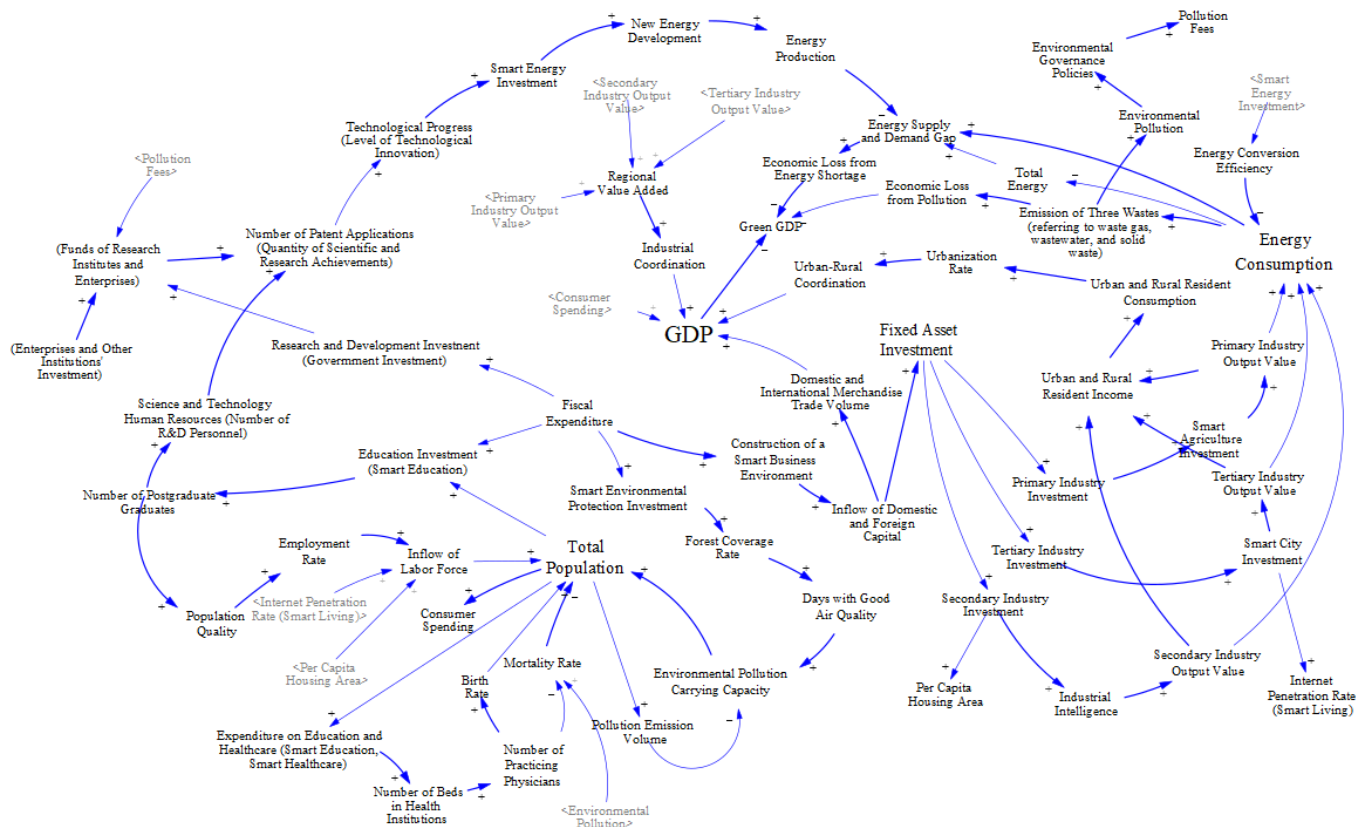


Figure 3. Causal loop diagrams of the whole system. The blue arrow indicates the effect of A on B. “+” indicates a promoting effect, while “−” indicates an inhibitory effect.

2.3.2. Flow Diagrams

This study, guided by the requirements for high-quality transformation and data availability, establishes logical relationships among factor variables in the dynamic system. The system model includes 81 variables, consisting of 10 state variables, 12 rate variables, and 45 auxiliary variables, with 14 constants (Table A1 in Appendix A). Based on functional relationships of key variables, the flow diagram is constructed using Vensim-PLE 10.2.2, as shown in Figure 4.

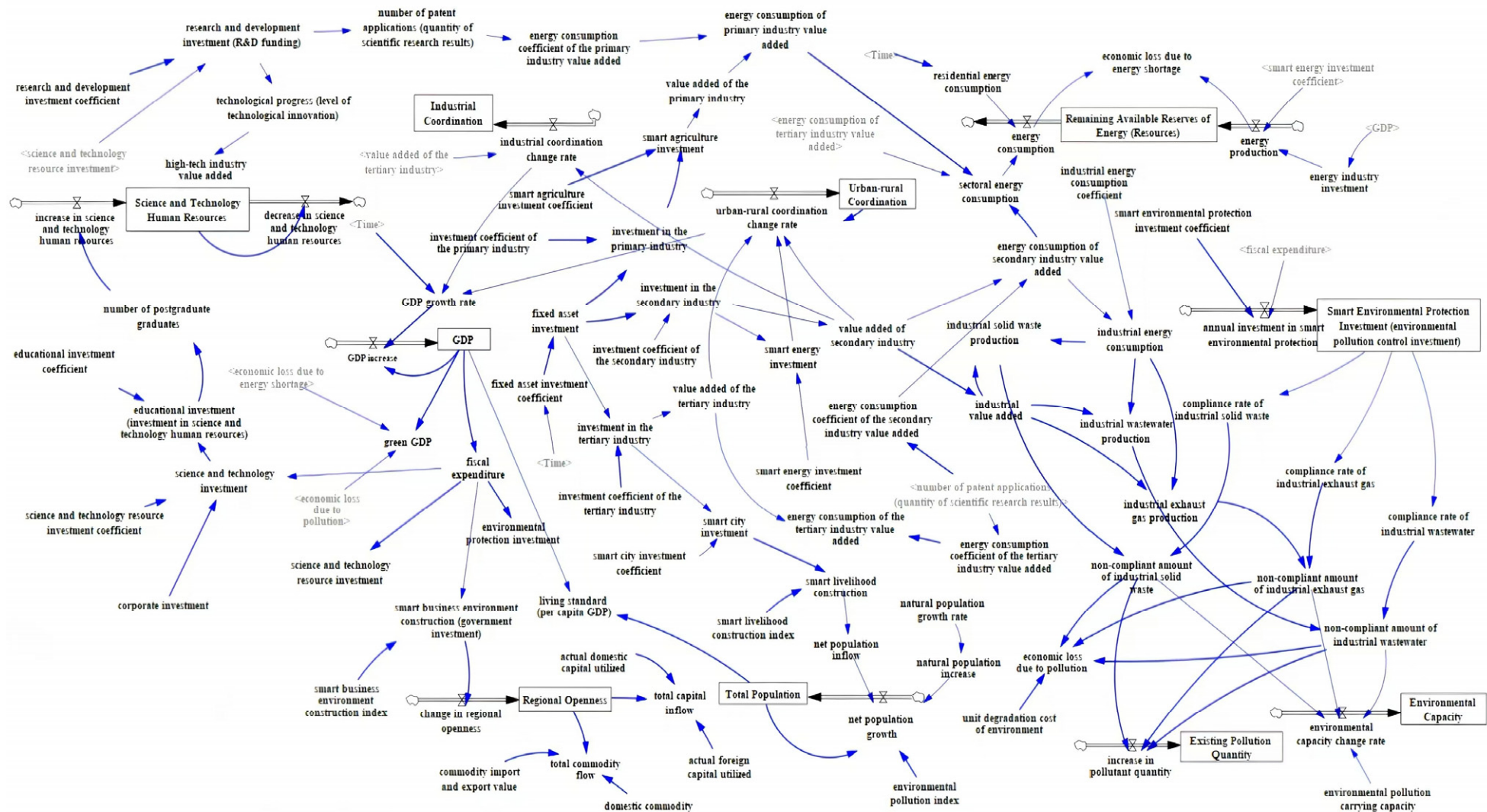


Figure 4. Flow diagram of the whole system.

2.3.3. Setting of Input and Output Variables

Based on the “government–industry–enterprise” smart eco-innovation-driven system, referring to the existing literature [59–61] and the actual situation of Daqing City, this study constructs a dynamic system model for high-quality transformation. The model includes six input variables: smart technology investment, industrial investment, smart energy construction, pollution control investment, smart business environment construction, and livelihood construction. These variables represent the subsystems of scientific and technological innovation, economic coordination, green energy, open development, and people’s livelihood, respectively. Corresponding to these inputs, six output variables are included: patent applications, GDP growth rate, remaining available energy reserves, pollution stock, total capital inflow, and total population. In the indicator design, smart and ecological indicators of input and output variables are integrated to achieve the target effects of high-quality transformation, as shown in Table 1.

Table 1. Input and output variables.

Input Variable	Output Variable	Effects
Smart technology investment	Patent applications	Innovative development; Economic growth; Livable environment; Common prosperity;
Industrial investment	GDP growth rate	
Smart energy construction	Remaining available energy reserves	
Pollution control investment	Pollution stock	
Smart business environment construction	Total capital inflow	
Livelihood construction	Total population	

3. Simulation Result Analysis

3.1. Selection of Study Region

This study focuses on Daqing City, located in northeastern China. Daqing is a “mature” resource-based city that has thrived due to oil. The city has been engaged in crude oil development for over 60 years. Daqing Oilfield used to be the largest crude oil production base in China, with a cumulative crude oil production of 2.5 billion tons by 2023. But its output was gradually surpassed. Due to its heavy reliance on resource-based industries, Daqing faces challenges in high-quality transformation.

Firstly, regional economic growth has weakened. Daqing’s GDP increased steadily from CNY 102.935 billion in 2000 to CNY 410.005 billion in 2013. However, it began to decline after 2014, reaching CNY 230.107 billion in 2020—a decrease of 43.88% compared to 2013. The rate of the oil and gas industry’s contribution to GDP has dropped below 50%.

Secondly, oil production is declining. Daqing Oilfield is in the late stage of oil and gas extraction, with the main old oilfields having a comprehensive water cut rate exceeding 95%. Although the expansion of shale oil extraction may alleviate this situation, the high extraction costs limit further development.

Thirdly, there has been a continuous outflow of residents and labor. Since 2014, declining oil prices and reduced production, coupled with harsh winter conditions, have led to population decline and labor outflow. Compared to 2010, Daqing’s total population decreased by 122,970 people in 2020, a decline of 4.23%. The proportion of population aged 15–59 also decreased by 7.82%.

3.2. Data Sources and Processing

In this study, data for Daqing from 2011 to 2021 were selected, adhering to principles of completeness, availability, comparability, and consistency. Data sources included the Daqing Statistical Yearbook, Daqing City National Economic and Social Development Statistical Bulletin, Heilongjiang Province Statistical Yearbook, Heilongjiang Province Environmental Conditions Bulletin, Heilongjiang Province Science and Technology Expenditure Statistical

Bulletin, China City Statistical Yearbook, China Science and Technology Statistical Yearbook, China Energy Statistical Yearbook, and China Environmental Statistical Yearbook.

Data calculations were primarily based on regional historical statistics. For missing data, values were derived using methods such as arithmetic mean calculation, regression analysis, and trend extrapolation.

3.3. Parameter Setting and Validation

Based on China's "Smart City" vision in 2010, the "High-Quality Development" concept in 2017, and Daqing's designation as a "Dual Pilot City for Smart City Construction", this study integrated investment factors related to Smart Daqing into the model. The initial values were set for 2011, with historical data ranging from 2011 to 2021 and a forecast period from 2022 to 2030. Input variable initial values were assigned using the mean method, as shown in Table 2.

Table 2. Initial values of input variables.

Indicator	Calculation Method	Initial Parameter
Science and technology resource investment coefficient	=R&D expenditure/GDP (including the regional government and enterprise R&D investments in science and technology)	23.81%
Industrial investment structure	=investment in the primary, secondary, and tertiary industries/the total fixed asset investment	7.53%; 57.88%; 34.59%;
Smart energy investment coefficient	=smart energy investment/investment of the secondary industry	23.91%
Smart environmental protection investment coefficient	=environmental pollution control investment/fiscal expenditure	23.45%
Smart business environment construction coefficient	=smart governance investment/fiscal expenditure	12.00%
Smart livelihood construction coefficient	=smart city investment/fixed asset investment	23.91%

The model structure and equations were validated against historical data, with a simulation time from 2011 to 2021 and a step length of 1 year. The results showed average error rates of 6.09% for patent applications, 4.49% for total capital inflow, and 0.55% for total population. The simulated values closely matched actual values, passing validation and confirming the model's reasonableness for prediction and simulation.

3.4. Simulation Scenario Design

This paper selected six policy-related input variables to observe the effects under different scenarios by transformation policy, as shown in Table 3. Meanwhile, six output variables were also chosen, with transformation effects that will be analyzed through changes in these output variables.

Current: This was the natural scenario based on historical average values of input variables without adjusting policy coefficients.

C1-1 and C1-2: These scenarios examined the impact on output variables when the coefficient of science and technology investment was increased or decreased by 20%, respectively, while other policy coefficients remained unchanged.

C2-1 and C2-2: These scenarios assessed the impact when the industrial investment structure coefficient was increased or decreased by 20%, with other coefficients held constant.

C3-1 and C3-2: These scenarios evaluated the impact when the smart energy investment coefficient was increased or decreased by 20%, while other coefficients remained unchanged.

C4-1 and C4-2: Analyzed the impact when the smart environmental protection investment coefficient was increased or decreased by 20%, with other coefficients unchanged.

C5-1 and C5-2: These scenarios explored the impact when the smart business environment construction coefficient was increased or decreased by 20%, while other coefficients remained constant.

C6-1 and C6-2: These scenarios examined the impact when the smart livelihood construction coefficient was increased or decreased by 20%, with other coefficients unchanged.

C7: This scenario assessed the combined impact when all six input variables were increased by 20%, focusing on the integrated policy effects on transformation outcomes.

Table 3. Policy scenario variation plan for high-quality transformation of Daqing driven by smart eco-innovation.

Policy Scenario	Science and Technology Resource Investment Coefficient	Industrial Investment Structure	Smart Energy Investment Coefficient	Smart Environmental Protection Investment Coefficient	Smart Business Environment Construction Coefficient	Smart Livelihood Construction Coefficient
Current	0.2381	0.0753:0.5788:0.3459	0.2391	0.2345	0.1200	0.2391
C1-1 (+20%)	0.2857					
C1-2 (−20%)	0.1905					
C2-1 (+20%)		0.0753:0.4630:0.4617				
C2-2 (−20%)		0.0753:0.6946:0.2301				
C3-1 (+20%)			0.2869			
C3-2 (−20%)			0.1913			
C4-1 (+20%)				0.2814		
C4-2 (−20%)				0.1876		
C5-1 (+20%)					0.1440	
C5-2 (−20%)					0.0960	
C6-1 (+20%)						0.2869
C6-2 (−20%)						0.1913
C7 (+20%)	0.2857	0.0753:0.4630:0.4617	0.2869	0.2814	0.1440	0.2869

3.5. Result

The simulation period was set from 2011 to 2030 with a step length of 1 year. The results for the six output variables under the 14 policy scenarios were obtained, as shown in Figure 5.

This study combined simulation results with the effects of policy scenario changes for ranking and statistical analysis (as shown in Figure 6). Comparing the results of Current, C1-1, C1-2, and other scenarios revealed distinct effects of different policy variations, as detailed below.

(1) Increasing investment in science and technology resources effectively boosts scientific research output. In Figure 6a, the simulation result of C1-1 is ranked 2, which indicates that investment in science and technology resources can enhance technological innovation capabilities and build a smart innovation ecosystem. The ranking results in Figure 6b–d also indicate that it also drives regional economic growth and reduces industrial energy consumption and pollution stock. However, it has a limited impact on retaining Daqing’s population and slowing population outflow, as shown in Figure 6, due to the labor displacement effect from improved oil and gas technologies.

(2) Adjusting the industrial investment structure significantly promotes economic growth. In Figure 6b, the ranking of C2-1 is 2, indicating that the GDP growth rate is second only to C7. As the tertiary sector develops, industrial energy consumption decreases, pollution accumulation slows, and population outflow declines. This validates the conclusion that industrial structure upgrading promotes the economic transformation of resource-based cities [62]. However, in Figure 6e, the ranking of C2-1 is 8, which indicates that reduced investment in the secondary industry is not conducive to attracting capital inflows.

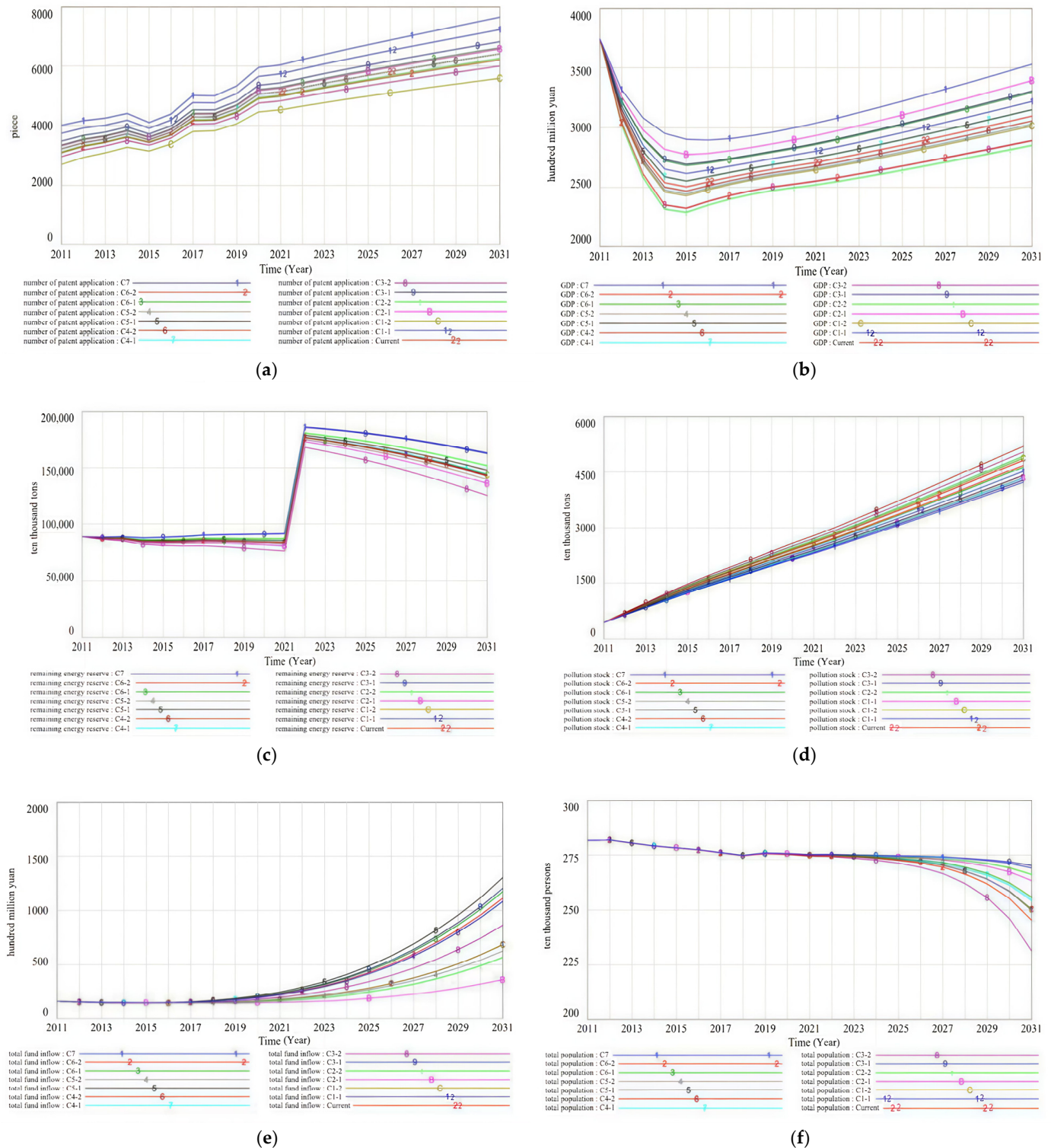


Figure 5. Policy simulation results. (a) Patent applications; (b) GDP growth rate; (c) remaining available energy reserves; (d) pollution stock; (e) total capital inflow; (f) total population.

(3) Smart energy construction has a comprehensive impact. Apart from Figure 6d, the ranking results of C3-1 are all in the top three. An intelligent oilfield drives technological progress, promotes environmentally friendly oil and gas extraction, and increases clean energy use. This reduces industrial and residential energy consumption, lowers pollution, and improves livability, resulting in less population decline compared to other scenarios. Previous studies have also demonstrated that smart energy, through highly intelligent coordi-

nation, enhances energy efficiency and cleanliness, thereby achieving sustainable development goals [63,64]. Moreover, it also has the lowest population outflow among all scenarios.

(4) Smart environmental protection policies create a green environment. In the various ranking results in Figure 6, the ranking of C4-1 in Figure 6d is favorable. Increased government investment in smart environmental protection has improved compliance rates for industrial “three wastes”, reduced emissions of these pollutants, and slowed the accumulation of pollution, leading to better regional ecology.

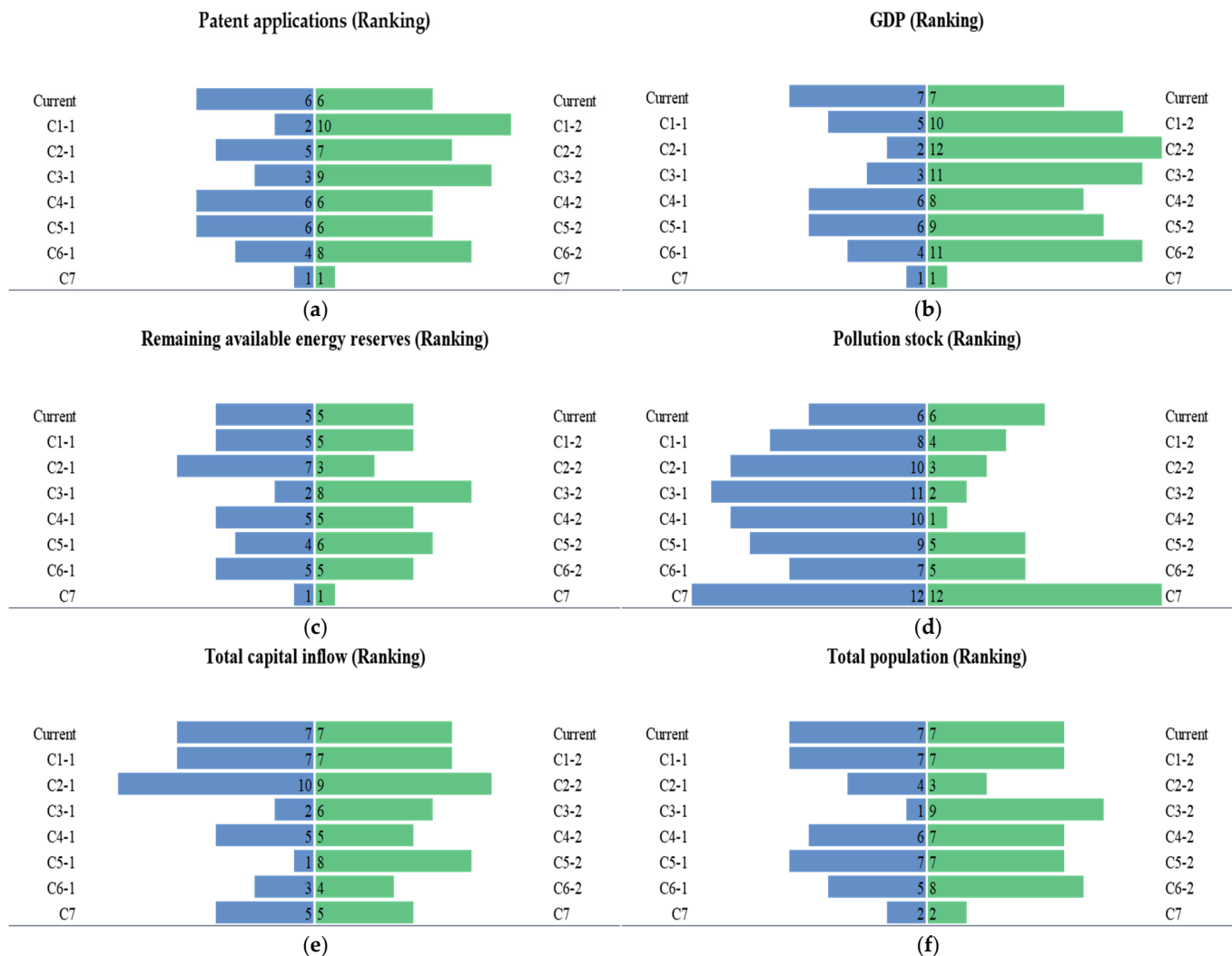


Figure 6. Ranking and statistical analysis of scenario simulation results. (a) Patent applications ranking; (b) GDP growth rate ranking; (c) remaining available energy reserves ranking; (d) pollution stock ranking; (e) total capital inflow ranking; (f) total population ranking. The lengths of the blue and green bars indicate the rank. In Figure 5, smaller numbers indicate higher-ranked lines, while larger numbers indicate lower-ranked lines. For example, number 1 represents the topmost line. Identical numbers for multiple policy scenarios indicate overlapping lines that cannot be distinguished in ranking. For instance, in the patent application ranking, five policy scenarios share the number 6, indicating their effects are indistinguishable at rank 6.

(5) Smart business environment construction significantly attracts investment. C5-1 ranks 1 in Figure 6e, which indicates that the construction of a smart business environment can promote capital inflow. Over the past decade, Daqing’s government has optimized the regional business environment through digital transformation and smart governance. The

development of shale oil and large-scale “oil-to-chemicals” projects has led to substantial capital inflows, providing continuous funding.

(6) Smart city construction provides a fundamental guarantee for high-quality transformation. Under the six scenarios in Figure 6, the ranking range of C6-1 is 3 to 7. Developing smart infrastructure in regions enhances innovation, optimizes the business environment, reduces pollutant emissions, and increases GDP output. This is consistent with the conclusion that the construction of smart cities in China promotes technological innovation, energy efficiency, and green production and growth in cities [65,66].

(7) The comprehensive policy scenario C7 yields the best simulation results, indicating that combined effects of smart eco-innovation policies are the most significant. For resource-based regions, pursuing a smart eco-innovation transformation path will gradually lead to a new pattern of high-quality development.

4. Discussion

This study integrates smart eco-innovation with high-quality transformation, exploring how it drives the transformation of resource-based regions. Specifically, smart eco-innovation creates an innovative, coordinated, green, open, and shared environment. It guides production factor flows to resource-based regions, promotes industry and market integration, and adjusts regional industrial structures. Additionally, smart technologies can form standalone industries or integrate with others, driving innovations in industrial forms and models. Digitalization of industries and industrialization of digital technologies are the outcomes of smart technologies. Building digital mines and smart oil fields can significantly transform the industrial forms of resource-based regions [67–69].

Based on these insights, we developed a high-quality transformation system model for Daqing City and designed simulation scenarios. The model is applicable not only to Daqing but also to other resource-based regions in China. Although adjustments may be needed based on data availability and regional conditions, the model is also adaptable. China has 116 resource-based regions [70], most of which face common challenges such as single industrial structures, environmental pollution, and ecological destruction due to rapid economic development and population growth.

Moreover, the SDM model used in this study can be integrated with other models to analyze ecological and economic issues. For example, Uehara et al. (2018) developed a fully dynamic input–output/SDM to analyze the dynamic relationships within and between ecological and economic systems [71]. Additionally, the SDM model can be used to analyze urban resilience across economic, social, environmental, and infrastructural dimensions [72]. This suggests that the model has broader potential for extended applications beyond resource-based region development research.

5. Conclusions and Implications

5.1. Conclusions

Based on data of Daqing City, China, from 2011 to 2021, this paper constructs a smart ecological dynamic model for the high-quality transformation of resource-based regions. It includes the driving system, the dynamic system, and the effect system. This paper conducts a simulation analysis of a high-quality transformation dynamic system. Fourteen scenarios are designed to simulate and analyze the effects on patent applications, GDP, remaining available energy reserves, pollution stock, total capital inflow, and total population.

The results show that implementing smart eco-innovation as a fundamental driving force for high-quality transformation can achieve multiple goals. Strengthening investment in the tertiary sector, smart energy, and smart cities [73], increasing investment in science and technology resources and smart environmental protection, and optimizing the smart

business environment can create a foundation for regional innovation and development. For example, increased investment in smart energy attracted significant capital to Daqing, boosting oil and gas exploration. In 2021, Daqing Oilfield added 1.268 billion tons of shale oil reserves. This increased available energy reserves, ensured sustainable exploitation, and provided a buffer period for Daqing's transformation. These measures can increase the technological content of industrial output, ensure the rational development and utilization of resources, promote the digital and intelligent transformation of resource-based industries, and cultivate new forms of regional smart economy [74]. At the same time, they can reduce energy consumption, manage environmental pollution, create a livable environment, optimize the business environment [75,76], and control the decline in the total regional population.

5.2. Implications

Based on the conclusions above, this paper draws the following implications:

First, establish a smart eco-innovation system to empower the upgrading of traditional resource-based industries [77]. Resource-dominant enterprises should lead the creation of a favorable environment for smart eco-innovation. Governments in resource-based regions can establish smart innovation platforms, such as resource industrialization labs, enterprise R&D centers, and experimental bases. These platforms can foster collaboration among businesses, universities, and research institutions. Innovation resources should be integrated into enterprises. Diversified investment and financing mechanisms for smart eco-innovation could be developed. Tax relief policies should be implemented. Green transformation of industries can be guided through catalogs. These measures can stimulate market vitality in smart eco-innovation and promote smart ecological industry development [9].

Second, extend the industrial chain and upgrade resource-based industries with smart technologies. Regions should leverage their resource endowments and leading industries to extend the industrial chain from processing and manufacturing to high-end areas such as product design and R&D [62]. They can deploy smart technologies, including cloud computing, intelligent sensing, and satellite positioning, to develop new industries like smart environmental protection and technology experimental bases. They can also develop sectors such as new energy, new materials, and tourism. Using smart eco-innovation to create green industries and cultivating smart energy-saving and environmental protection industries can optimize the integration of resource-based and non-resource-based industries. This can promote the development of green finance, green smart logistics, and green smart consumption.

Third, build regional smart ecology and use smart technologies to create the software and hardware environment for regions. On the one hand, regions should strengthen the intelligent construction of mines and oilfields, integrating data to enhance production, safety, and logistics support systems for resources. In addition, the construction of smart cities needs to be carried out in collaboration with multiple fields [78]. Regions can improve inter-city transportation information, road networks, and livelihood infrastructure (e.g., smart education and healthcare) to create hardware facilities for smart construction in resource-based regions [49]. On the other hand, enhancing government services and establishing a scientific social governance mechanism could achieve coordinated public value ecology involving the government, market, and society [79]. Regions can fully leverage government leadership to build a smart public supervision system and optimize the allocation of public service resources [80,81].

6. Limitations and Future Recommendations

This study provides preliminary evidence for the “smart eco-style” transformation of resource-based regions, yet it also has certain limitations that could be further explored as future research topics.

First, this paper conducts the system dynamics analysis of the high-quality transformation of resource-based regions driven by smart eco-innovation, but it does not quantify the “smart eco-style” transformation. Future research could evaluate the value effects of smart ecology and measure its impact on regional development. For example, using intelligent energy management and ecological monitoring as practiced in smart parks can quantify the effects of “smart eco-style” transformation.

Second, this paper introduces how smart eco-innovation promotes regional high-quality transformation in the Introduction section briefly. However, the mechanism is complex and could be analyzed in detail in future research. Smart eco-innovation includes both technological upgrades and the synergistic effects of managerial innovation, policy support, and social participation. Future research can delve into the interactions among these factors and explore how to achieve coordinated regional development in economic, social, and environmental aspects through such innovation.

Finally, due to data limitations, this paper does not investigate the spatial differentiation model of smart ecological economic zones. Instead, future research could analyze this model and propose specific implementation suggestions for different regions. For example, we can design tailored plans for smart ecological economic zones based on local resources, industries, and ecology. Also, integrating the SDM can help analyze the impacts of “smart eco-style” on regional economic structure and layout, thus supporting evidence-based policy-making.

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Abbreviations

The following abbreviations are used in this manuscript:

eco-innovation	Ecological innovation
IT	Information technology
ICT	Information and communication technology
AI	Artificial intelligence
SDM	System dynamics modeling
tce	Ton of standard coal equivalent
three wastes	Waste water, waste gas, solid waste

Appendix A

Table A1. Key indicator variables and attributes of the subsystems.

Primary Indicator	Secondary Indicator	Unit	Indicator Attribute	Secondary Indicator	Unit	Indicator Attribute
Scientific and technological innovation subsystem	Science and technology human resources (number of R&D personnel)	ten thousand people	state variable	R&D investment	hundred million yuan	auxiliary variable
	Increase in science and technology human resources	ten thousand people	rate variable	Education investment	hundred million yuan	auxiliary variable
	Decrease in science and technology human resources	ten thousand people	rate variable	R&D investment coefficient	/	constant
	Number of postgraduate graduates	people	auxiliary variable	Education investment coefficient	/	constant
	Science and technology resource investment	hundred million yuan	auxiliary variable	Number of patent applications	piece	auxiliary variable
	Science and technology resource investment coefficient	/	constant			
Economic coordination subsystem	GDP	hundred million yuan	state variable	Smart agriculture investment	hundred million yuan	auxiliary variable
	GDP increase	hundred million yuan	rate variable	Smart agriculture investment coefficient	/	constant
	GDP growth rate	%	auxiliary variable	Value added of the primary industry	hundred million yuan	auxiliary variable
	Fiscal expenditure	hundred million yuan	auxiliary variable	Value added of the secondary industry	hundred million yuan	auxiliary variable
	Fiscal expenditure coefficient	/	constant	Value added of industry	hundred million yuan	auxiliary variable
	Fixed asset investment	hundred million yuan	auxiliary variable	Value added of the tertiary industry	hundred million yuan	auxiliary variable
	Fixed asset investment coefficient	/	constant	Energy consumption of the primary industry value added	ten thousand tce	auxiliary variable
	Investment in the primary industry	hundred million yuan	auxiliary variable	Energy consumption of the secondary industry value added	ten thousand tce	auxiliary variable
	Investment in the secondary industry	hundred million yuan	auxiliary variable	Energy consumption of the tertiary industry value added	ten thousand tce	auxiliary variable
	Investment in the tertiary industry	hundred million yuan	auxiliary variable	Energy consumption coefficient for value added of the three industries	/	constant
	Investment coefficient of the three industries	/	constant	Industrial coordination	/	state variable
	Smart city investment	hundred million yuan	auxiliary variable	Industrial coordination change rate	%	rate variable
	Smart city investment coefficient	/	constant	Urban–rural coordination	/	state variable
	Smart energy investment	hundred million yuan	auxiliary variable	Urban–rural coordination change rate	%	rate variable
	Smart energy investment coefficient	/	constant			

Table A1. Cont.

Primary Indicator	Secondary Indicator	Unit	Indicator Attribute	Secondary Indicator	Unit	Indicator Attribute
Green energy subsystem	Remaining available energy reserves	ten thousand tce	state variable	Production of the three wastes	ten thousand tons	auxiliary variable
	Energy production	ten thousand tce	rate variable	Non-compliant amount of the three wastes	ten thousand tons	auxiliary variable
	Energy consumption	ten thousand tce	rate variable	Compliance rate of the three wastes	%	auxiliary variable
	Sectoral energy consumption	ten thousand tce	auxiliary variable	Economic loss due to pollution	hundred million yuan	auxiliary variable
	Industrial energy consumption	ten thousand tce	auxiliary variable	Environmental capacity	/	state variable
	Residential energy consumption	ten thousand tce	auxiliary variable	Rate of change in environmental capacity	%	rate variable
	Smart energy investment	hundred million yuan	auxiliary variable	Environmental pollution carrying capacity	/	auxiliary variable
	Smart energy investment coefficient	/	constant	Smart environmental protection investment	hundred million yuan	state variable
	Economic loss due to energy shortage	hundred million yuan	auxiliary variable	Annual smart environmental protection investment	hundred million yuan	rate variable
	Existing pollution quantity	ten thousand tons	state variable	Smart environmental protection investment coefficient	/	constant
Open development subsystem	Increase in pollutant quantity	ten thousand tons	rate variable			
	Regional openness	/	state variable	Total commodity flow value	hundred million yuan	auxiliary variable
	Change in regional openness	/	rate variable	Commodity import and export value	hundred million dollars	auxiliary variable
	Total capital inflow	hundred million yuan	auxiliary variable	Domestic commodity flow value	hundred million yuan	auxiliary variable
	Actual foreign capital utilized	hundred million dollars	auxiliary variable	Smart business environment construction	hundred million yuan	auxiliary variable
People's livelihood subsystem	Actual domestic capital utilized	hundred million yuan	auxiliary variable	Smart business environment construction coefficient	/	constant
	Total population	ten thousand people	state variable	Population outflow volume	ten thousand people	auxiliary variable
	Net population growth	ten thousand people	rate variable	Environmental pollution coefficient	/	auxiliary variable
	Volume of growth of natural population	ten thousand people	auxiliary variable	Living standard (per capita GDP)	ten thousand yuan	auxiliary variable
	Net population inflow volume	ten thousand people	auxiliary variable	Smart livelihood construction	hundred million yuan	auxiliary variable
	Population inflow volume	ten thousand people	auxiliary variable	Smart livelihood construction coefficient	/	constant

Table A2. Explanations of technical terms.

Terms	Meaning
Smart ecology construction:	Achieving urban sustainability by promoting harmonious coexistence between humans and nature, optimizing resource utilization, reducing pollution emissions, and enhancing residents' quality of life through technological innovation and urban planning.
High-quality development:	Development driven by innovation, characterized by coordination, embodied in green practices, pursued through openness, and aimed at sharing, seeks to transform economic growth from mere scale expansion to quality and efficiency enhancement, thereby fulfilling people's aspirations for a better life and achieving comprehensive and sustainable development.
New development concept:	A scientific conceptual framework primarily comprising innovation, coordination, green development, openness, and sharing, guiding economic and social development to promote high-quality growth, facilitate comprehensive progress, and achieve sustainability.
Oil-to-chemicals:	A development model that uses petroleum as raw material, extends the industrial chain, and enhances product value added through deep processing in the petrochemical industry, thereby transforming a resource-based economy towards diversification and high-end development.
Urban resilience:	The capacity of an urban system to withstand, adapt to, and rapidly recover from natural disasters, socio-economic shocks, or other uncertainties, while learning from crises to enhance its own sustainable development.

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