Postprint: Study on Characteristics of Xinjiang' s Water-Energy-Carbon Coupled System Based on Ecological Network Analysis

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Abstract

Water resources, energy, and carbon emissions are critical factors that perturb the socio-economic-ecological complex system. Changes in individual elements generate linkage effects, transmit ecological pressure, and influence the sustainable development of regions and industries. Focusing on Xinjiang as the study area and based on Xinjiang' s input-output tables for 2007, 2012, and 2017, this research employs environmental input-output and ecological network analysis models to reveal the coupling characteristics of the "water-energy-carbon" network system. The results indicate: (1) Mixed water is primarily utilized for inter-provincial outflow and household consumption, whereas mixed energy and mixed carbon are mainly directed toward inter-provincial outflow and gross capital formation. (2) The recycling rate of the water network is below 42%, while those of the energy and carbon networks are below 25%, with the overall network system demonstrating a declining trend. (3) The robustness of the water, energy, and carbon network systems leans toward developmental stagnation, exhibiting an overall state of unsustainable development. (4) In Xinjiang' s "water-energy-carbon" coupling system, the correlations among water, energy, and carbon systems across various sectors are weak, control and dependency relationships remain sporadic, and synergistic "water-energy-carbon" relationships have not been established among industries. Elucidating the patterns of Xinjiang' s "water-energy-carbon" coupling system provides empirical support for implementing a low-carbon and efficient integrated resource management model.

Full Text

Characteristics of the “Water-Energy-Carbon” Coupling System in Xinjiang Based on Ecological Network Analysis

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Abstract

Water resources, energy, and carbon emissions constitute critical factors that disturb economic-social-ecological composite systems. Changes in any single element generate linkage effects that transfer ecological pressure and impact regional and industrial sustainable development. Focusing on Xinjiang as the study area and utilizing Xinjiang’ s input-output tables, this study employs environmental input-output and ecological network analysis models to reveal the coupling characteristics of the “water-energy-carbon” network system. The results indicate that: (1) Mixed water is primarily utilized for domestic outflow and household consumption, while mixed energy and mixed carbon are mainly allocated to domestic outflow and total capital formation. (2) The circulation rates of water networks remain below 42%, while those of energy and carbon networks stay below 25%, demonstrating an overall declining trend across the network system. (3) The robustness of water, energy, and carbon networks all tilted toward development stagnation, exhibiting unsustainable development. (4) The water, energy, and carbon systems within Xinjiang’ s “water-energy-carbon” coupling system show weak interconnections among departments, with control and dependency relationships remaining incidental and failing to establish synergistic relationships among water, energy, and carbon between industries. Clarifying the operational patterns of Xinjiang’ s “water-energy-carbon” coupling system provides empirical support for implementing a low-carbon, efficient integrated resource management model.

Key words: ecological network analysis; environmental input-output; “water-energy-carbon” coupling; Xinjiang

With the proposal of carbon peak and carbon neutrality goals, the “dual carbon” target has become an integral component of Xi Jinping’ s ecological civilization philosophy, inevitably triggering systemic transformations in national resource utilization patterns. Water resources, energy, and carbon emissions represent crucial elements affecting economic development, characterized by interdependence and mutual constraint, wherein alterations in a single element induce cascading changes in others. However, in actual resource management practice, water resources, energy, and carbon emissions fall under different administrative jurisdictions, and industrial sectors often remain constrained by their own developmental demands, preventing the water-energy-carbon system from achieving positive synergies and mitigating negative trade-offs during resource utilization.

Investigating how to promote regional resource efficiency and carbon reduction from a multi-element coupling perspective constitutes an urgent issue for regional sustainable development in the new era.

Domestic and international scholars have primarily focused on two-element couplings such as water-energy resources [2-4] and energy consumption-carbon emissions [5-7], with three-element research still in its nascent stage, concentrating mainly on "water-energy-carbon" coupling in typical industries [8-10]. With the high-quality development strategy, research on urban resource consumption low-carbon management [11], resource-environment and economic growth synergy [12], and urban industrial "water-energy-carbon" coupling analysis [13] has gained attention. Research methodologies for "water-energy-carbon" coupling relationships can be categorized into two types: first, life cycle assessment [14] and material flow analysis [15], which evaluate the entire life cycle of research objects. While ensuring quantitative accuracy, these methods require extensive data support and represent "bottom-up" approaches. Later, ecological network analysis was introduced to identify system intrinsic attributes from a holistic perspective [16]. Second, the input-output method establishes product supply-demand equations to forecast economic development prospects, with research regions expanding from single-region to multi-region input-output methods and from static to environmental input-output approaches [17-19], representing "top-down" methods.

In summary, current research on resource element coupling continues to expand in scope with increasingly diversified methodologies. However, three aspects require improvement: first, existing achievements concentrate on single resource domains and single industries, necessitating strengthened research on multi-resource element and multi-industry system management under carbon constraints; second, research areas focus on national or economically developed regions, lacking empirical studies on special regions. Therefore, this paper selects Xinjiang, characterized by resource-rich and ecologically fragile conditions, to calculate implicit water consumption, implicit energy consumption, and implicit carbon emissions across 18 industrial sectors based on the 2007, 2012, and 2017 input-output tables. The study identifies "water-energy-carbon" system coupling attributes from circulation rates and system robustness, and analyzes "water-energy-carbon" ecological network synergistic effects from sector dynamics, aiming to provide decision-making support for achieving collaborative management and efficient resource utilization across regional industries.

1.1 Study Area Overview

Xinjiang, located in northwestern China between 73°40 -96°18 E and 34°25 -48°10 N, covers an area of 1.66 million km^2. The region possesses numerous rivers and glaciers, with coal, petroleum, and natural gas reserves reaching 166.49$\times10^{8}$ tons, 2.19$\times10^{8}$ tons, and 101$\times10^{8}$ m^3 respectively, establishing it as a crucial energy reserve, processing, and export base in China. With annual precipitation of merely 150 mm, Xinjiang exhibits typical characteristics of an ecologically fragile region where production and ecological water use conflicts are increasingly prominent. In 2017, Xinjiang’ s GDP reached 17741.34$×10^{8}$ yuan, with industrial added value of 7271.08$×10^{8}$ yuan. Resource-based industries such as coal mining, petroleum processing, and smelting accounted for 53.90% of industrial added value, forming a resource-based industrial structure with tightening resource constraints and pronounced carbon lock-in effects.

1.2 Theoretical Model

To reveal the coupling attributes and control-dependency relationships of water, energy, and carbon among Xinjiang’ s industries, this study constructs an organic, multi-level, and comprehensive analytical framework comprising “water-energy-carbon”multiple elements (Figure 1). First, direct water, energy, and carbon emissions of industries are accounted for, considering energy-related water consumption (water-for-energy), water-related energy consumption (energy-for-water), and water-related carbon emissions (carbon-for-water). Second, based on input-output analysis, implicit water, implicit energy, and implicit carbon are calculated. Implicit resource consumption and emissions are added to associated implicit resource consumption and emissions to form mixed water, mixed energy, and mixed carbon. Finally, ecological network analysis is applied to quantitatively simulate and analyze the relationships within the coupling system by measuring circulation rates, robustness, and control-dependency degrees.

[Figure 1: see original paper]

1.3 Data Sources and Processing

This study employs the environmental input-output research method, utilizing Xinjiang’ s 2007, 2012, and 2017 input-output tables as primary data sources. Considering statistical scope for resource data, the 42 industrial sectors in the input-output tables were consolidated into 18 sectors (Table 1). To eliminate price index effects across different years, output value data were converted to 2017 constant prices. Direct energy consumption data were obtained from the *Xinjiang Statistical Yearbook* and *China Energy Statistical Yearbook*, while direct water resource consumption data were sourced from the *Xinjiang Water Resources Bulletin* and field investigations by the Xinjiang Water Resources Department. Since Xinjiang does not publish data on water consumption per unit of energy or energy consumption per unit of water, water consumption intensity for energy and energy consumption intensity for water were adopted from research by Jiang Shan [20] and Xiang Xiaozhi et al. [21] respectively.

1.4.1 Environmental Input-Output Model

Following Zhang Jun et al. [22], this study calculates direct water resource consumption, direct energy consumption, and direct carbon emissions for each industrial sector. Water resources include surface water, groundwater, and reclaimed water (3 types), while energy includes coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, natural gas, and electricity (9 types). The consumption of different water resources, energy types, and carbon emissions across sectors are summed to obtain sectoral water consumption (Wi, 10^8 m^3), energy consumption (Ei, 10^8 kWh), and carbon emissions (Ci, 10^8 kg). Associated water consumption from energy use (Cw, 10^8 m^3), associated energy consumption from water use (Ew, 10^8 kWh), and associated carbon emissions from water use (Ccw, 10^8 kg) are calculated as follows:

$$W_i = \sum_k w_k^i$$

$$E_i = \sum_p e_p^i$$

$$C_i = \sum_p c_p^i$$

where w_k^i represents the k-th water resource consumption of sector i (10^8 m^3); c_p^i represents the p-th energy consumption of sector i (10^8 kWh); and e_p^i represents the p-th carbon emission of sector i (10^8 kg).

The Xinjiang regional economy represents a regional development entity formed by the joint action of internal economic development factors and external conditions. Total output of each industrial sector is influenced by intermediate use and final demand, where intermediate demand sectors are affected by total output and final demand sectors are driven by consumption demand [23]. Following Zhang et al. [24], Peng et al. [25], and Sun et al. [26], this study employs the environmental input-output model to calculate implicit water, implicit energy, and implicit carbon. Using water resources calculation as an example:

1) Direct water consumption coefficient for each sector:

$$w_i^d = \frac{W_i}{X_i}$$

where X_i represents the economic output of sector i (10^8 yuan).

2) Intermediate sector implicit water matrix (W_e):

$$W_e = W_d \cdot (I - A)^{-1}$$

where W_d is the direct water consumption coefficient matrix; I is the identity matrix; $A = (a_{ij})$ is the direct consumption coefficient matrix; a_{ij} represents the direct consumption of sector i' s products per unit output of sector j; z_{ij}

represents the direct consumption from sector j to i (10^8 yuan); and X_{diag} is the diagonal matrix of X_i.

3) Final sector implicit water matrix (W_z):

$$W_z = L_{\text{diag}} \cdot (I - A)^{-1}$$

where L_{diag} is the diagonal matrix of value-based demand from final sectors to sector i.

4) Mixed water matrix (W_h):

$$W_h = W_e + W_e'$$

where W_e' is the energy-related implicit water matrix.

Total System Throughput (TST) represents the sum of all flows within the network system:

$$TST_b = \sum_i T_i$$

$$TST_f = \sum_i y_i$$

where T_i is the total mixed water flow through sector i (10^8 m^3); and y_i is the mixed water consumed by final demand from sector i (10^8 m^3).

System robustness (SR) represents the sustainable development capacity of the coupling network by balancing flow efficiency and redundancy:

$$C = TST_b \times \log(TST_b) - \sum_i T_i \times \log(T_i)$$

$$\alpha = \frac{C}{TST_b}$$

$$SR = -\alpha \times \log(\alpha)$$

where C is the ascendency of the water network (10^8 m^3); TST_b is the sum of mixed water flows in intermediate sectors (10^8 m^3); α is the ratio of system ascendency to development capacity; and SR is the robustness index.

Control index (CA) and dependency index (DA) quantify resource flows between economic sectors by calculating the control degree of sector i over j and the dependency degree of sector j on i:

$$g_{ij} = \frac{f_{ij}}{T_i}$$

$$T_i = \sum_j f_{ij}, \quad T_j = \sum_i f_{ij}$$

$$N = G + G^2 + G^3 + \cdots$$

$$c_{ij} = \frac{n_{ij} - n_{ji}}{T_j^{\text{repr}}}$$

$$d_{ij} = \frac{n_{ij} - n_{ji}}{T_i^{\text{repr}}}$$

where f_{ij} is the mixed water flow from sector i to j (10^8 m^3); T_i^{repr} is the n-dimensional square matrix formed by repeating T_i n times by row; T_j^{repr} is the n-dimensional square matrix formed by repeating T_j n times by column; n_{ij} is the cyclic flow from sector i to j after one or more cycles; c_{ij} is the control coefficient of sector i over j; and d_{ij} is the dependency coefficient of sector j on i.

The calculation principles for energy networks, carbon networks, and associated networks are identical to those for water resources, requiring only substitution of relevant coefficients.

1.4.2 Ecological Network Analysis Model

Ecological network analysis employs matrix operation principles to simulate energy flow patterns in ecosystems. Following Zhang Jun et al. [27], this study constructs an ecological network analysis model based on implicit water, implicit energy, and implicit carbon calculated from the environmental input-output model. The Finn Cycling Index (FCI) and system robustness (SR) reveal circulation rates and sustainability among industrial sectors, while control index (CA) and dependency index (DA) characterize sectoral control-dependency relationships. For subsequent calculations, associated networks (containing energy-for-water) and single networks (without energy-for-water) are distinguished. Using water-associated network calculation as an example:

Finn Cycling Index represents the cycling rate of flows within the network, where higher values indicate greater effective utilization efficiency:

$$FCI = \frac{\sum_i \sum_j n_{ij}}{\sum_i T_i}$$

where N is the integral dimensionless flow matrix of metabolic water; n_{ij} is the cyclic flow from sector i to j after one or more cycles; G is the direct dimensionless flow matrix; g_{ij} is the flow intensity from sector i to j; and f_{ij} is the mixed water consumed by intermediate sectors flowing from i to j (10^8 m^3).

The calculation principles for carbon networks are identical to those for water-associated networks, requiring only substitution of relevant coefficients.

2.1 End Consumption Based on Environmental Input-Output Model

In 2007, 2012, and 2017, Xinjiang' s final demand sectors consumed 619.76$×10^{8}$ m^3, 953.39$×10^{8}$ m^3, and 849.18$×10^{8}$ m^3 of mixed water respectively, showing a consumption growth rate of 297.10%. From the perspective of final demand structure, domestic outflow and household consumption accounted for the highest proportion of mixed water consumption, representing 53.90% and 40.34% of total final use respectively. In terms of sectoral distribution, agriculture (sector 1) was the largest mixed water consumer, while domestic outflow accounted for 11.58% of total mixed water volume.

[Figure 2: see original paper]

Mixed energy consumption in Xinjiang' s final demand sectors reached 52941.68$×10^{8}$ kWh, 79898.71$×10^{8}$ kWh, and 112150.72$×10^{8}$ kWh in 2007, 2012, and 2017 respectively. Capital formation accounted for 42.24% of total final mixed energy consumption, while household consumption represented 40.34%. From a sectoral perspective, the chemical industry (sector 11) and non-metallic mineral products industry (sector 6) were the main drivers of capital formation, while petroleum and natural gas extraction (sector 2) and metal smelting and products (sector 8) were the primary outflow sectors.

[Figure 3: see original paper]

Mixed carbon emissions totaled 50650.62$×10^{8}$ kg, 79898.71$×10^{8}$ kg, and 112150.72$×10^{8}$ kg in 2007, 2012, and 2017 respectively, showing an upward trend. In terms of sectoral emission structure, metal smelting and products (sector 8) and electricity production and supply (sector 13) were the main mixed carbon emission sectors, accounting for 49.54% of total final emissions.

[Figure 4: see original paper]

2.2 Coupling Characteristics of the "Water-Energy-Carbon" System Based on Ecological Network Model

2.2.1 System Circulation Rate

The Finn Cycling Index quantifies the intensity of cyclic flows within the network, revealing the impact of water-energy-carbon coupling on network circulation. Comparative analysis of associated networks and single networks for water, energy, and carbon illuminates the resource circulation characteristics of Xinjiang' s industrial "water-energy-carbon" coupling network. Calculations show that the total water network circulation rate decreased from 38.46% in 2007 to 21.23% in 2012 and 21.31% in 2017. The water-associated network' s total circulation rate was 38.44%, indicating that water flows related to energy consumption reduce the flow rate of mixed water. In the water network, agriculture (sector 1) exhibited the highest circulation rate, with its water consumption accounting for 93.66% of total mixed water, while the circulation rate of the water-associated network was 38.98%, suggesting that agriculture reduced the overall system circulation rate.

Energy network and energy-associated network Finn Cycling Indices were 41.25% and 24.34% respectively in 2007, decreasing to 23.56% and 21.66% in 2017. The energy-associated network' s metal smelting and products (sector 8) and chemical industry (sector 11) consumed 49.49% of mixed energy, but weak inter-sectoral linkages among major consuming sectors led to declining energy circulation rates. Carbon emission-associated network circulation rate was 21.66%, 11.13 percentage points higher than the carbon network, with metal smelting and products (sector 8) and chemical industry (sector 11) contributing only 36.82% to cycling despite accounting for 49.54% of mixed carbon emissions.

[Figure 5: see original paper]

2.2.2 System Robustness

Ecological network circulation efficiency is not necessarily better when higher; systems must maintain stable operational reserves when facing disturbances. System robustness index (SR) reveals coupling network sustainability by balancing flow efficiency and redundancy. When the ratio of system ascendency to development capacity (α) approaches $1/e$, the system demonstrates optimal sustainable development capacity. When α approaches 0, the system exhibits higher efficiency; when α approaches 1, the system shows greater elasticity. Analysis of Xinjiang' s ecological network SR curve shows that the mean water network (including water-associated and water networks) robustness index was 0.124–0.128, remaining on the left side of the curve with gradually increasing robustness but failing to break through the inflection point toward sustainable development. Energy network and carbon network robustness means were also located within the 0.124–0.128 interval on the left side of the curve, indicating that although robustness shows an upward trend, no substantive breakthrough in sustainable development capacity has been achieved, with the overall system remaining in an unsustainable state.

[Figure 6: see original paper]

2.2.3 Changes in System Control and Dependency

"Water-energy-carbon" coupling influences sectoral control-dependency relationships, altering internal system relationships. Control and dependency indices reveal the impact of "water-energy-carbon" coupling on inter-sectoral linkages from input and consumption perspectives.

Regarding control changes, the 2007–2017 water system [Figure 7: see original paper] showed that non-metallic mineral products (sector 6) to construction (sector 15) had a control change rate of 28.54%, while metal mining (sector 3) to metal smelting and products (sector 8) was 12.46%, with other sectors below 10%. Energy system [Figure 7: see original paper] showed metal mining (sector 3) to metal smelting and products (sector 8), agriculture (sector 1) to food and tobacco processing (sector 10), and metal smelting and products (sector 8) to metal mining (sector 3) with control change rates of 13.14%, 9.66%, and 9.51% respectively. Carbon system control relationship changes resembled those of the energy network.

Regarding dependency changes, the 2007–2017 water system [Figure 8: see original paper] showed construction (sector 15) dependency on non-metallic mineral products (sector 6) at 10.05%, with most sector dependencies below 10%. Energy system [Figure 8: see original paper] showed petroleum processing (sector 5), petroleum and gas extraction (sector 2), and metal smelting and products (sector 8) dependency on metal mining (sector 3) at 8.28%, 7.54%, and 7.14% respectively. Carbon system [Figure 8: see original paper] showed construction (sector 15) dependency on non-metallic mineral products (sector 6) and metal smelting and products (sector 8) at 9.54% and 9.77% respectively.

Overall, most sectoral control and dependency indices in water, energy, and carbon networks range within 0–0.1 and 0–0.2 respectively, indicating weak "water-energy-carbon" coupling system correlations, incidental control-dependency relationships, and failure to form synergistic effects in resource utilization management.

[Figure 7: see original paper]
[Figure 8: see original paper]

3 Discussion

Compared with existing research, this study extends from two-element coupling [23,27,29] to three-element "water-energy-carbon" analysis, and expands the study area from economically developed regions [24,30] to energy-rich regions. In terms of system circulation rates, Fujian [31] and Hubei [32] show higher water network Finn Cycling Indices than energy networks, consistent with this study' s results, primarily because agriculture accounts for high proportions of total water use in these provinces while having high allocation coefficients, reducing water flow path options and enabling faster water circulation than energy.

Regarding system robustness, Anhui [33] and Hubei [32] ecological networks are closest to the equilibrium point, followed by Fujian [31], while Xinjiang' s ecological network remains in development stagnation due to water resources being primarily used in agriculture and energy mainly consumed by metal smelting and chemical industries, creating a single industrial structure unfavorable for overall system sustainability. Regarding control-dependency changes, Xinjiang' s sectoral control and dependency levels remain incidental compared with other provinces [23,27,29], failing to form synergistic effects due to weak inter-sectoral linkages that prevent efficient water and energy utilization.

In reality, Xinjiang' s management of water resources, energy, and carbon emissions has long remained fragmented, with the "water-energy-carbon"system characterized by high resource consumption and emissions, single industrial structure, declining circulation rates, development stagnation, and risk of coupling coordination dysfunction. Therefore, from a multi-element coupling perspective, collaborative management of the "water-energy-carbon" coupling system that identifies major consumption and pollution sources, considers resource linkage impacts comprehensively, optimizes element flow paths, achieves effective technology-resource integration, establishes two-way supply-demand feedback, and promotes coordinated element development will facilitate regional resource efficiency and carbon reduction, enabling positive synergies and reducing negative trade-offs.

4 Conclusions

This study on Xinjiang' s "water-energy-carbon" coupling system characteristics based on ecological network analysis yields the following conclusions:

1) From 2007 to 2017, Xinjiang' s industrial mixed water, mixed energy, and mixed carbon emissions showed overall upward trends, with mixed water primarily used for outflow and household consumption, while mixed energy and mixed carbon were mainly allocated to outflow and capital formation. Agriculture represents the primary mixed water consumption sector, while metal smelting and products and chemical industry are the main mixed energy consumption and mixed carbon emission sectors.

2) From 2007 to 2017, the water-associated network circulation rate decreased from 38.46% to 21.31%; the energy-associated network circulation rate decreased from 41.25% to 21.66%; and the carbon emission-associated network circulation rate decreased from 38.46% to 23.56%. The overall "water-energy-carbon" coupling system demonstrates a declining trend.

3) The water-associated network robustness remained within 0.124–0.128, while energy-associated and carbon-associated network robustness stayed within 0.124–0.128, with the "water-energy-carbon" coupling system in an unsustainable development state.

4) Interconnections among water, energy, and carbon systems across Xin-

jiang’ s industrial sectors remain weak, with control and dependency relationships in an incidental state, failing to form synergistic effects.

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Note: Figure translations are in progress. See original paper for figures.