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Research Article

Regional Differences Reflected in Resource Flow in China: Multidimensional Analysis Integrating MRIO and Machine Learning Clustering

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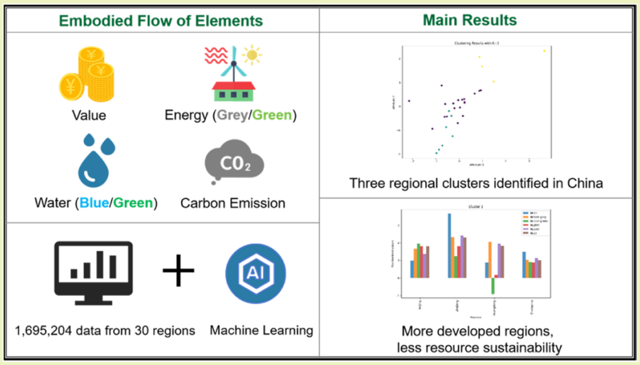

ABSTRACT: In the context of globalization and trade liberalization, the harmonious development of the economy, energy, and ecology has become a critical global issue. The inter-regional flows of energy, water resources, and carbon emissions play an increasingly influential role in economic growth. However, there are significant differences in resource endowment and consumption among different regions of China. To bridge these regional gaps and enable a quantitative understanding of multidimensional resource interactions, this study presents a resources embodied flow framework based on input-output model, quantitatively characterizing resources flows across 30 regions of China from six dimensions: monetary trade, fossil energy and renewable energy, blue water and green water, as well as carbon emissions. Furthermore, it carries out artificial intelligence algorithms to conduct a comprehensive clustering and analysis of resource utilization and environmental disparities across various regions in China, enabling a quantitative assessment of each region's resources sustainability index. The findings identify three distinct regional clusters: the average resources sustainable development evaluation index (*SDI*) of the northern and western resource-intensive areas (Cluster 1) is −0.68, indicating that the resources are mainly in the output state; The average *SDI* of the central and eastern production-oriented regions (Cluster 2) is about 0.10, showing a relatively balanced utilization of resources and preferable regional sustainability; The average *SDI* of the developed region driven by economy and consumption (Cluster 3) is as high as 1.31, presenting serious net import of resources and environmental pressure. This article emphasizes the significant differences in regional resource sustainability and reveals the importance of analyzing energy and ecological resources from a trade perspective to achieve more balanced regional development.

KEYWORDS: *input-output analysis, net embodied flow, cluster analysis, k-means++ algorithm, energy, water, carbon emission*

■ INTRODUCTION

Energy and water resources are crucial elements of industries in modern economies,[1−3] while carbon emissions are an inevitable environmental impact of industrial activities and also a significant factor in inter-regional connections.[4] With the acceleration of economic globalization and trade liberalization, the inter-regional flows of energy, water resources, and carbon emissions play an increasingly important role in economic development, among which the embodied flows are significant aspects of energy and environmental issues.[5,6] As quantitative indicators of energy and environmental system, resources embodied flow could affect regional supply and demand, as well as trade patterns. Moreover, it could reflect the interdependence of energy and environment between regions and the quality of the ecological environment.[7,8]

In recent years, as the world's second-largest economy,[9,10] China's economic development has attracted global attention. Yet this growth has been achieved at the cost of serious energy and environmental challenges.[11,12] As the largest carbon dioxide emitter globally[13,14] and one of the countries with scarce water resources,[15,16] China faces particularly prominent issues in energy consumption, water resource utilization, and carbon emissions, which threaten both regional ecosystems and global climate goals. To address these challenges, China has proposed the "carbon peaking and carbon neutrality goals", aiming to promote low-carbon development actively through specific measures and advocate for the rational use of water

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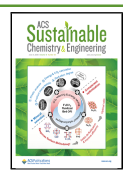

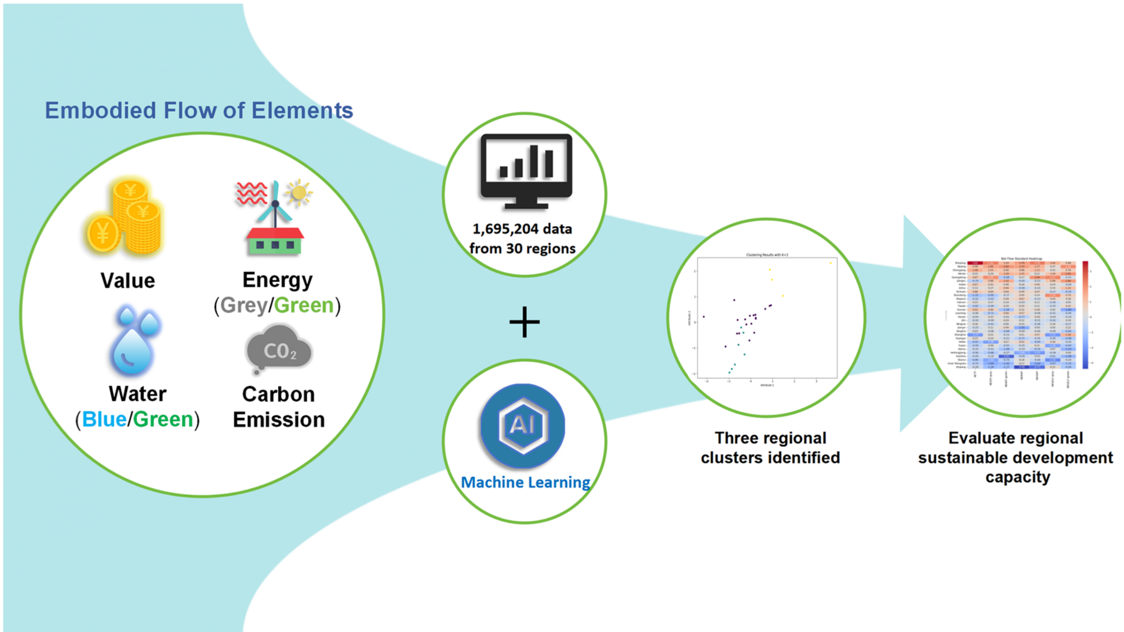

Figure 1. This study investigates the complex patterns of resource flow across China's regions and their implications for economic growth and environmental sustainability by using the IO model and the machine learning k-means++ clustering algorithm.

resources strongly, achieving a win-win situation for economic development and environmental protection.

The disparities in energy structure,[17] resource and environmental carrying capacity,[18] and economic development levels[19] across different regions of China make it urgent to formulate carbon reduction and low-carbon development policies scientifically to achieve sustainable regional economic and environmental development. Therefore, studying the patterns of energy, water resources, and carbon emission flows among different regions in China, and exploring the embodied flows of regional energy/resources brought by trade, is of significant theoretical and practical importance for guiding regional production and consumption patterns, reducing trade barriers, promoting inter-regional economic cooperation, and achieving sustainable ecological and environmental development.

These flows have brought opportunities for economic growth and social development regionally, but they may also cause environmental pressure and social imbalance problems. Therefore, how to achieve a balance between resource flow and sustainable development has become an important topic of current research. Researchers have conducted a series of studies, such as studying the flow and influencing factors of carbon emissions between regions in China.[20−22] Research has been carried out on the spatiotemporal evolution characteristics and influencing factors of energy flow in multiple regions of China, and exploring the dynamic evolution process of energy relations between regions.[23] Based on multiple regions input-output (IO) model of China, it was found that the energy use and flow between different regions exhibit a certain degree of agglomeration and dispersion.[24−26] These studies provide effective evidence to deeply understand the energy, water, and carbon emissions embodied flows among different regions in China, respectively.

Although many studies have explored the flows of energy,[27−29] water,[30−32] and carbon emissions[33,34] between different regions, the studies on various factors are relatively independent, with few focusing on multidimensional embodied flows, especially the comparative analysis of regional impacts brought by the flows of renewable resources and traditional resources. There is a lack of scientific methods to identify the regional impacts generated by the multiple embodied flows. The roles and interaction mechanisms of different regions remain unclear.[35] To address these issues, this paper proposes the concept of Net Embodied Flows (NEF) to describe the differences in energy, water, and carbon emissions flows between products, services, or industries across regions, measured from the perspectives of production and consumption. The concept of NEF encompasses various types, such as Net Embodied Trade Flows (NETF), Net Embodied Energy Flows (NEEF-E), and Net Embodied Environmental Flows (NEEF-Env).

To better compare the embodied flows of resources and carbon emissions in interprovincial trade, NEF models for multiple regions are established and analyzed based on China's multiregional input-output model (MRIO), and further subdivided according to the environmental sustainability of energy, water resources, and carbon emissions, such as NETF, Net Embodied Gray Energy Flow (NEGEF-gray), Net Embodied Green Energy Flow (NEGEF-green), Net Embodied Blue Water Flow (NEBWF), Net Embodied Green Water Flow (NEGWF) and Net Embodied Carbon Emission Flow (NECF). By analyzing the net embodied flows of energy and the environmental elements among different regions, this study aims to reveal the similarities and differences of NEF among regions.

While existing studies predominantly analyze single-dimension flow, this paper sets up a multidimensional framework that uniquely integrates six NEF indicators (NETF, NEGEF-gray/green, NEBWF, NEGWF, NECF) to capture the systemic interplay between trade-driven resource transfers and regional sustainability. This approach addresses a critical gap in understanding how heterogeneous resource dependencies manifest spatially, thereby enabling targeted policy design.

This study uniquely combines a refined MRIO framework with an advanced k-means++ clustering algorithm to derive a multidimensional NEF-based *SDI*, as shown in Figure 1. By bridging energy, water, and carbon emission flows with a comprehensive resource and environmental sustainability assessment, our work offers a novel perspective that informs targeted regional environmental and economic policies.

MATERIALS AND MODELS

Compilation of 30 Regions' NEF MRIO Table. To illustrate the regional networks of virtual resources, we compiled six revised NEF MRIO tables by incorporating regional energy and environmental flows embodied in economic flows. This approach reflects the embodied transfer of *NETF*, *NEGEF-gray*, *NEGEF-green*, *NEBWF*, *NEGWF*, and *NECF* across different regions. It analyzes the energy and environmental resource endowments related to China's inter-regional trade network.

Due to the lack of basic data support in Tibet, Hong Kong, Macao, and Taiwan, this study does not include these areas. Therefore, a new MRIO covering 30 regions across the country has been compiled, simplified as eq 1, where each element represents the interaction between regions.

$$X = (I - A)^{-1}Y = LY \tag{1}$$

where $A = \begin{bmatrix} a^1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & a^{30} \end{bmatrix}$ is a 30 × 30 diagonal matrix of direct consumption coefficient, which reflects the technical level of each region. $X = \begin{bmatrix} x^1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & x^{30} \end{bmatrix}$ represents the total output matrix and $Y = \begin{bmatrix} y^1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & y^{30} \end{bmatrix}$ represents the final demand matrix for each region. eq 1 describes all direct and indirect input-output relationships between different regions. *L* is also well-known as the Leontief Inverse matrix; thus, the monetary input-output model within the research boundary is obtained.

Calculation of the Direct Consumption Coefficient Matrix of Energy and Environmental Input-Output. The direct consumption coefficient matrix for energy and environmental input-output can be achieved by dividing the energy consumption e^s, water consumption w^s, and carbon emission ce^s of each region by the total output X^s of that region. This calculation results in the energy and environmental input-output coefficients, which are represented by eqs 2–4:

$$E^s = \frac{e^s}{X^s} \tag{2}$$

$$W^s = \frac{w^s}{X^s} \tag{3}$$

$$CE^s = \frac{ce^s}{X^s} \tag{4}$$

Each element of the coefficient matrices E^s, W^s, and CE^s represents the quantity of energy or environmental resources that needs to be consumed per unit output in Region *S*, defining the so-called energy or environmental resource consumption density. Additionally, these coefficients provide a measure of how much energy, water, and carbon are relative to the total output, thereby reflecting the environmental impact of regional production activities.

By left-multiplying the diagonal matrices of E^s, W^s, and CE^s by Leontief Inverse Matrix, and further multiplying this result by the final demand matrix, the final multiregional matrices of energy and environmental consumption footprints, *EEF*, *EWF* and *ECEF* are obtained as eq 5, 6, and 7:

$$EEF = E^s \times LY \tag{5}$$

$$EWF = W^s \times LY \tag{6}$$

$$ECEF = CE^s \times LY \tag{7}$$

where $E^s = \begin{bmatrix} e^1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & e^{30} \end{bmatrix}$, $W^s = \begin{bmatrix} w^1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & w^{30} \end{bmatrix}$, and $CE^s = \begin{bmatrix} ce^1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & ce^{30} \end{bmatrix}$ are 30 × 30 diagonal matrices representing the direct consumption coefficients for energy, water, and carbon emissions, respectively, and $Y = \begin{bmatrix} y^1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & y^{30} \end{bmatrix}$ is the diagonal matrix of the final demand of 30 regions.

The underlying assumption is that the products or services obtained by each region from others are entirely utilized within that region, and all production inputs within the region are sourced from local resources to serve its final use. Consequently, this leads to the establishment of a network of energy and environmental resource flows within domestic regions due to trade activities. By analyzing the matrix within the network, the transfer pathways and quantities of embodied energy and environmental resource flows in each region can be identified, thus revealing the actual consumption and transfer of energy and environmental resources at the consumer end in each region.

According to the analysis of balanced trade, the net flow of embodied energy, water, and carbon emissions is calculated as the total inflow minus the total outflow. This calculation is succinctly captured in eqs 8–10

$$NEEF = EEF_{IM} - EEF_{EX} \tag{8}$$

$$NEWF = EWF_{IM} - EWF_{EX} \tag{9}$$

$$NECEF = ECEF_{IM} - ECEF_{EX} \tag{10}$$

where *NEEF*, *NEWF*, and *NECEF* represent the net flow of energy, water, and carbon emissions embodied in trade, respectively. EEF_{EX}, EWF_{EX}, and $ECEF_{EX}$ represent the amount of energy, water, and carbon emissions flowing to the other regions, while EEF_{IM}, EWF_{IM}, and $ECEF_{IM}$ refer to the amount of energy, water, and carbon emissions flowing into the region as the form of products and services. Based on the subdomains of this study, *NEEF* includes two types of embodied energy flows: *NEGEF-gray* and *NEGEF-green*, and *NEWF* includes two types of embodied water flows: *NEBWF* and *NEGWF*. The same principles are applied to calculate the net embodied trade value flow, as demonstrated in eq 11:

$$NETF = ETF_{IM} - ETF_{EX} \tag{11}$$

Hence, we obtained the *NETF*, *NEGEF-gray*, *NEGEF-green*, *NEBWF*, *NEGWF*, and *NECF* transfer networks among 30 regions in China due to trade. This data collection sets the stage for the next step of machine learning clustering work based on six dimensions.

Machine Learning k-Means++ Clustering Algorithm. K-means algorithm, which originated from a vector quantization method in signal processing,[36,37] is now widely popular in the field of machine learning as a clustering analysis method.[38,39] This algorithm divides *n* points into *k* clusters, so that each point belongs to the cluster corresponding to the nearest mean, serving as the cluster center. This criterion forms the basis of the clustering process.

The k-means++ clustering algorithm is an improved method based on the traditional k-means, which enhances performance by selecting better initial centroids.[40,41] In the standard k-means approach, selecting initial centroids randomly may lead to local optima, particularly for high-dimensional data sets. The k-means++ avoids the problem of falling into local optima, common in traditional k-means, by randomly selecting a data point as the first centroid, thereby improving the clustering performance and stability. K-means++ has not only improved the clustering performance but also the convergence rate compared with the traditional k-means. As a result, it is a classic clustering algorithm widely used in data mining and machine learning.

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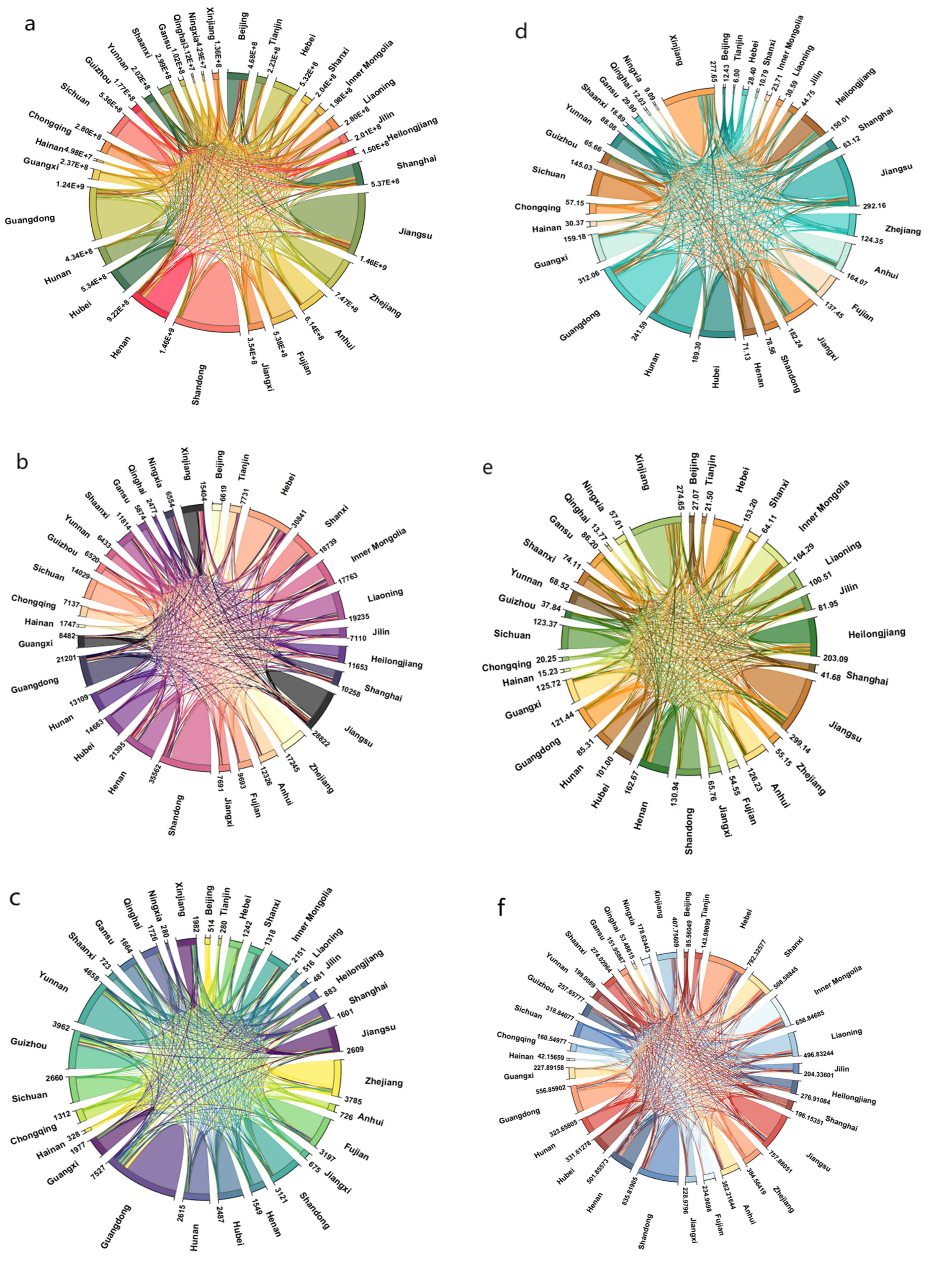

Figure 2. Inter-regional linkage of the total direct and embodied flows of trade (a), gray energy (b), green energy (c), blue water (d), green water (e), and carbon emissions (f) in 30 provincial regions of China.

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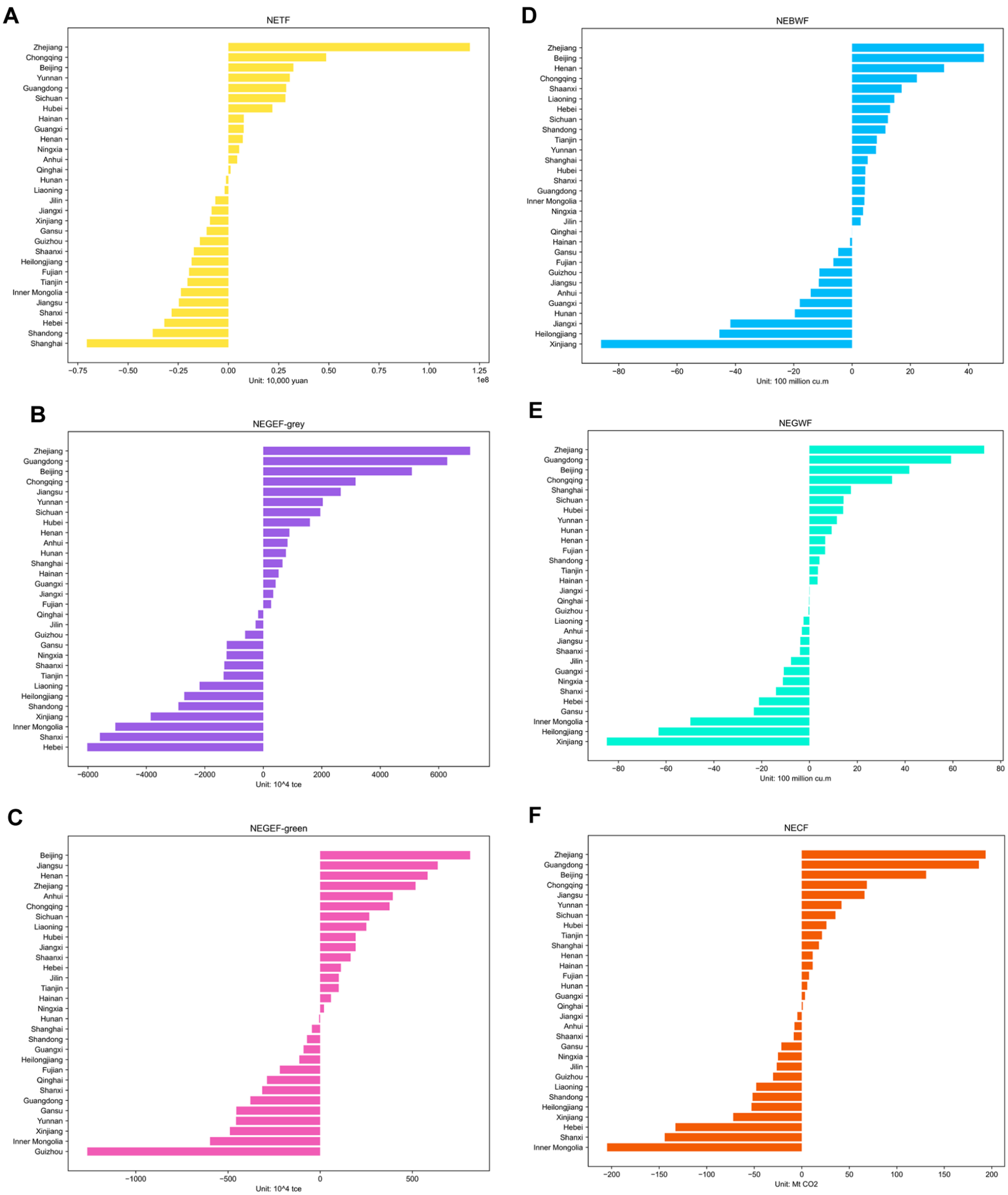

Figure 3. The spatial distribution of six NEF vectors—NETF (A), NEGEF-gray (B), NEGEF-green (C), NEBWF(D), NEGWF(E), and NECF(F) are analyzed. The color bar represents the values of different vectors of 30 regions, respectively.

In this study, the k-means++ clustering algorithm and its components will be utilized to comprehensively cluster regions based on six-dimensional attributes and to form visualized results. By studying different clusters, the typical characteristics of various provincial clusters will be analyzed in depth. Additionally, programming will be implemented by Python to execute k-means++ clustering.

Calculation of *SDI*. In this study, an innovative regional resources sustainable development evaluation model is proposed that comprehensively considers six key dimensions of *NEF* z-score and introduces the *SDI* as the core evaluation index. This model enables

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accurate calculation of the *NEF* value and its summarization into the *SDI*, allowing for a quantitative evaluation of the self-consistency and resources sustainable development level of resource utilization in the region. The expression method is similar to eq 12

$$SDI = \sum w_n z_n \quad (n = 1, 2, \cdots, 6) \tag{12}$$

It is assumed that energy, water, and carbon emissions from different sources and uses have the same impact on regional development; therefore, each NEF has the same w value. This assumption is based on the belief that in regional development, energy, water resources, or carbon emissions, each holds equal importance in resources sustainability assessment.

When the *SDI* value approaches zero, it indicates that the allocation and utilization of resources within the region have reached a high degree of self-consistency, signifying a balance between resource consumption and ecological carrying capacity, which aligns with the concept of resources sustainable development. Conversely, an increase in negative deviation of *SDI* values indicates that the region exhibits characteristics of resource output, whereas an increase in positive deviation reveals an enhanced dependence of the region on external resources.

The absolute value of the *SDI* is directly related to the status of regional resources' sustainable development. A high absolute value indicates that regional resources sustainable development is facing significant challenges. In practical applications, the ideal state is that the regional *SDI* value is close to zero. This study not only provides a quantitative evaluation tool, but also offers strategic support for sustainable resource management between regions.

Data Resources. *Economic Data.* This work refers to the 2017 China Multidepartmental IO Table provided by the National Bureau of Statistics of China[42] and the 2017 China Multiregional and Multidepartmental input-output Table (updated in 2021) provided by China Emission Accounts and Datasets (CEADs)[43] as the foundational research data, which were the most comprehensive and authoritative data sets for China's inter-regional flows when this study was carried out. While the original national IO table includes Tibet, we excluded it along with Hong Kong, Macao, and Taiwan due to incomplete energy, water, and carbon emissions data—a boundary-setting approach consistent with prior studies.[44−46]

Based on these economic data sets, environmental input-output tables, and energy input-output tables within the research boundary are compiled to analyze energy, water, and carbon emissions dynamics, as well as resources sustainable development issues across different regions in China.

Energy Data. The basic energy consumption data of 30 provincial regions in China are sourced from the *China Statistical Yearbook 2018*[47] and *China Energy Statistical Yearbook 2018*,[48] both published by the National Bureau of Statistics of China, as well as relevant data released by local governments and industries.[49−54] In most regions, energy statistics directly provide the consumption ratios of gray and green energy. For regions where the proportion of energy consumption cannot be directly obtained, this study assumes that energy produced within the region first meets local demand, based on the premise that locally products produced primarily satisfy local needs.[55] By calculating energy consumption according to the production proportion, this method determines the consumption of gray and green energy in the region, thereby distinguishing the flows of gray and green energy in regional trade. This approach effectively characterizes the structural features of regional energy consumption and enhances understanding of energy flows and environmental impacts.

Water Data. The total water consumption in this study is defined as the total amount of blue and green water used in China's annual production in 2017. To collect the required water resource data, sources such as the *China Environmental Statistical Yearbook 2018*[56] and *China Water Resources Bulletin 2017*[57] were used to calculate the proportion of blue and green water resources in 30 provincial regions in China. These ratios provide a basis for estimating the consumption of regional blue and green water, thereby distinguishing the flows of blue and green water in regional production and consumption.

Carbon Emission Data. Carbon emissions data used in this study are sourced from CEADs.[58] CEADs provides comprehensive and regionally detailed carbon emissions data, which is crucial for analyzing regional disparities and trends in emissions. To facilitate calculations and ensure consistency, all carbon emissions data in this study were converted into megatons of carbon dioxide ($MtCO_2$) equivalents. This standardization allows for more accurate comparisons and assessments of carbon footprints across different regions.

■ RESULTS

Inter-regional Flow of Resources. The results of the study show that the total direct flows and embodied flows of different resources between provincial regions are presented in Figure 2(a)−(f), respectively, providing a visualization of the structure and connectivity of resource flows in multiple regions. Figure 2 shows that most of the resources between regions prioritize meeting the local production and consumption needs.

Figure 2(a) shows the regional distribution of the inter-regional trade effects for the year 2017. The impact of inter-regional trade is concentrated primarily in Jiangsu, Shandong, and Guangdong regions, with respective proportions of 11.09%, 11.06%, and 9.38%. Figure 2(b) reflects the regional distribution of gray energy, with significant impacts in Shandong (8.93%), Hebei (7.45%), and Jiangsu (7.24%). Figure 2(c) portrays the regional distribution of green energy, with larger flows in Guangdong (12.86%), Yunnan (7.96%), and Guizhou (6.77%). Notably, the inter-regional gray/green energy flows in Hebei, Yunnan, and Guizhou are not coupled with the trade flow results. This phenomenon indirectly suggests that due to inter-regional trade, these developing regions within the country may provide more resources to more developed areas, thereby exacerbating environmental inequality. This situation is closely linked to the imbalance in regional economic development.[59] To address this issue, policymakers could consider adopting administrative regulatory measures to narrow the economic development disparities between regions. Figure 2(d), (e) depict the flows of blue water and green water between regions, while Figure 2(f) reflects the inter-regional connections of carbon emissions flows.

The units are (a) 10^4 yuan, (b) & (c) 10^4 tce, (d) & (e) 10^8 cu.m, (f) mt CO_2.

Net Embodied Trade Flow. NETF refers to the net import and export trade flow of a region, which can be seen as the degree of economic connectivity between the region and other regions. As shown in Figure 3(A), there are significant spatial distribution differences among the 30 regions. The NETF of 13 regions, including Beijing, Zhejiang, Guangdong, Yunnan, and Hainan, are positive, indicating that their economic development is relatively independent and they act as "consumers" in economic development. The goods and services inputted in these regions are greater than those outputted. On the contrary, net embodied trade flows in regions such as Tianjin, Hebei, Shanxi, Inner Mongolia, Shandong, Guizhou, and Xinjiang are negative, indicating these regions are relatively dependent on the external economy and play the role of ″producers″ in economic development, with inputs of goods and services being less than exports of goods and services.

Zhejiang, Chongqing, and Beijing have the highest NETF values of 1202.6 billion yuan, 486.5 billion yuan, and 323.6

billion yuan, respectively. These three regions have the largest trade surplus. The trade deficit regions represented by Shanghai, Shandong, and Hebei have smaller NETF values of −704.4 billion yuan, −377.1 billion yuan, and −318.8 billion yuan, respectively.

Net Embodied Gray Energy Flow. NEGEF-gray refers to the flow value of energy from traditional energy sources (e.g., fossil fuels) in trade, which reflects carbon emissions level of a region. It can be seen that there are 14 regions with negative NEGEF-gray values in Figure 3(B). Hebei, Shanxi, Inner Mongolia, and Xinjiang exhibit large negative NEGEF-gray values, which are respectively −60.2 mtce, −55.9 mtce, −50.6 mtce, and −38.5 mtce, indicating that these regions are net exporters of traditional energy in inter-regional trade. This implies that these regions rely heavily on fossil fuels in energy production and consumption, thereby directly generating substantial pollution and greenhouse gas emissions, which significantly impact the environment.

Zhejiang (70.8 mtce), Guangdong (62.9 mtce), and Beijing (50.8 mtce) are net importers of traditional energy, consuming substantial gray energy provided by other regions, and emitting less direct carbon locally. The NEGEF-gray values in some regions are relatively low, such as Qinghai, Jilin, and Fujian, indicating that their energy consumption and production scales are relatively balanced.

Net Embodied Green Energy Flow. NEGEF-green refers to the flow value implied in trade of energy from renewable energy, such as solar, wind, hydropower, geothermal, etc. It can be seen as the utilization degree of renewable energy in a region. A positive value indicates the region imports renewable energy from others, while a negative value indicates its renewable energy is indirectly used by other regions. From Figure 3(C), it can be seen that the NEGEF-green in regions such as Beijing (8.1 mtce), Jiangsu (6.4 mtce), Henan (5.8 mtce), and Zhejiang (5.2 mtce) is positive, indicating that these regions are net importers of renewable energy. On the contrary, Guizhou (−12.6 mtce), Inner Mongolia (−6.0 mtce), Xinjiang (−4.9 mtce), and Yunnan (−4.6 mtce) show negative NEGEF-green values, indicating they are net renewable energy exporters and supply green energy to NEGEF-green positive regions via trade.

It is worth noting that the NEGEF-green data in certain regions approximate zero, such as Hainan (0.59 mtce), Ningxia (0.2 mtce), Hunan (−0.1 mtce), and Shanghai (−0.45 mtce). This result indicates that these regions have a relatively balanced import and export of green energy.

Net Embodied Blue Water Flow. The use of blue water is typically related to the extraction, transfer, and treatment of water resource. NEBWF refers to the virtual net flow value of blue water resources implied in trade, which can be seen as the utilization degree of freshwater resources in a region from surface and underground natural sources such as precipitation, rivers, and groundwater. Among the 30 regions in Figure 3(D), Zhejiang, Beijing, and Henan have relatively large positive NEBWF, with 4.5 billion cu.m, 4.5 billion cu.m, and 3.2 billion cu.m, respectively. This is related to the economic structure and geographical conditions of the region, reflecting the high demand for indirect blue water resources by the industrial structure and production patterns of these regions, making them overflow areas for embodied blue water. The consumption of blue water resources in 18 positive regions is relatively high in economic development, and it is necessary to introduce water resources from other negative regions to meet production and consumption demands.

A negative NEBWF indicates that the region exports blue water resources to other regions. Among the 12 regions with negative values, Xinjiang, Heilongjiang, and Jiangxi have relatively large negative NEBWF, with −8.6 billion cu.m, −4.6 billion cu.m, and −4.2 billion cu.m, respectively. This indicates that these regions consume less water resources, and the blue water resources required for the goods they produce exceed the blue water resources they consume. Thus, these regions can export blue water resources to other regions via trade in exchange for economic output and commodities.

Net Embodied Green Water Flow. Green water is associated with regional soil resource protection and the coverage of green plants. NEGWF refers to the net flow of green water resources embodied in trade, which can be regarded as an indicator related to natural soil and water resource conditions. Specifically, in Figure 3(E), among the regions with a positive NEGWF, Zhejiang has the highest value, reaching 7.3 billion cu.m, followed by Guangdong (5.9 billion cu.m) and Beijing (4.2 billion cu.m). This indicates that these regions rely heavily on green water resources from other areas via trade.

Xinjiang has the lowest NEGWF among the regions with negative value, reaching −8.5 billion cu.m, followed by Heilongjiang (−6.3 billion cu.m) and Inner Mongolia (−5.0 billion cu.m), indicating regions with negative NEGWF export green water to those with positive values.

From the overall distribution of NEGWF, the number of regions with a negative NEGWF equals that with positive NEGWF, indicating China's various regions maintain relatively balanced in terms of consumption and supply of green water resource.

Net Embodied Carbon Emissions Flow. NECF refers to the net flow of carbon emissions embodied in inter-regional trade, reflecting the carbon footprint associated with the production and consumption activities in different regions. As shown in Figure 3(F), there are significant spatial distribution differences among the 30 regions.

Beijing (158.6 mt CO_2), Zhejiang (202.4 mt CO_2), and Guangdong (160.7 mt CO_2) exhibit the highest NECF values, indicating that these regions are net importers of carbon emissions, consuming products and services produced using carbon-intensive processes in other regions. Conversely, Hebei (−149.6 mt CO_2), Shanxi (−153.3 mt CO_2), and Inner Mongolia (−208.7 mt CO_2) exhibit significantly negative NECF, indicating they are net exporters of carbon emissions, producing goods and services for other regions and bearing the environmental costs.

Some regions have relatively balanced NECF values, such as Jiangxi (−0.9 mt CO_2), Anhui (2.9 mt CO_2), and Fujian (9.6 mt CO_2), reflecting a more self-sufficient economic structure concerning carbon emissions. The analysis of NECF highlights carbon emissions disparities from inter-regional trade in China and underscores the need for coordinated policies to achieve a balanced and sustainable approach to carbon emissions management.

6-dimensional Vector Clustering.

NETF represents the net trade flow between regions. If the value is positive, it indicates that the region has imported products and services from other regions to meet its own production and consumption demand. On the contrary, it

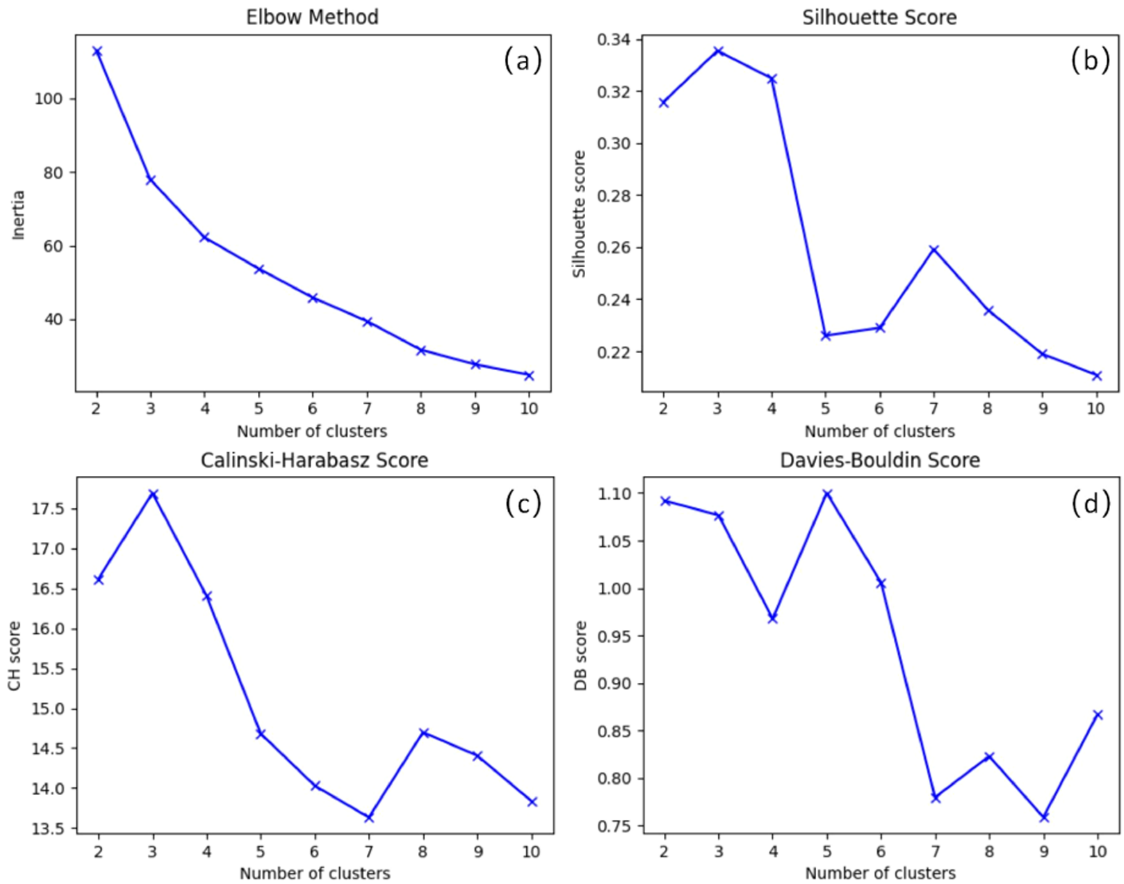

Figure 4. K-value evaluation index: Panel a is the diagram of the elbow method, Panel b represents the Silhouette Coefficient score, Panel c represents the Calinski-Harabasz index, and Panel d represents the DB index.

indicates that the region has exported economic resources to other regions.

NEGEF-gray and NEGEF-green respectively represent non-economic transfers between regions - i.e., the net flow of embodied gray and green energy.

NEBWF and NEGWF represent inter-regional transfers of natural water sources such as surface water, groundwater flows, and rainfall stored in agricultural soils, respectively. These indicators can reflect the allocation of inter-regional water resources.

NECF represents the net flow of carbon emissions embodied in inter-regional trade, reflecting the carbon footprint associated with the production and consumption activities in different regions. If the value is positive, it indicates that the region is a net importer of carbon emissions, consuming products and services produced using carbon-intensive processes in other regions. Conversely, a negative value indicates that the region is a net exporter of carbon emissions, producing goods and services for other regions and incurring the environmental costs. This indicator highlights carbon emissions disparities from inter-regional trade.

Based on the six vectors mentioned above as variables, 30 regions were clustered by the machine learning k-means++ algorithm. As shown in Figure 4, the Elbow Method reveals a gradual deceleration in the decline rate of the sum of squared errors (SSE) as the number of clusters k increases. Notably, a subtle flattening of the SSE reduction trend occurs at k = 3, indicating a potential optimal number of clusters. This finding is further supported by a significant increase in the Silhouette Coefficient (Silhouette Coefficient score = 0.34) and the Calinski-Harabasz index (Calinski-Harabasz index = 17.8). These metrics confirm k = 3 as the optimal clustering choice, balancing intracluster cohesion with intercluster separation.

However, it is worth noting that while $k = 3$ achieves higher Silhouette Coefficient and Calinski-Harabasz index, the Davies-Bouldin index (Davies-Bouldin index = 1.08) remains relatively high. This suggests that, although smaller numbers of clusters generally result in better overall cohesion and separation, certain clusters may exhibit less compactness and distinct boundaries. Consequently, intracluster similarity increases, and intercluster differentiation diminishes. After considering the silhouette coefficient, CH index, and DB index in combination, $k = 3$ was identified as the optimal number of clusters. This choice allows the macro-level patterns of multidimensional resource flows in inter-regional trade to be effectively revealed through three distinct categories.

By the k-means++ clustering algorithm, 30 regions in China were clustered into three clusters, each characterized by similar patterns of embodied resource flows. The clustering results are presented in Table 1.

Cluster analysis has revealed that distinct clusters represent various types of regions. The delineation of these clusters is predicated upon their similarities in energy acquisition methods, resource consumption, environmental pressures, and sustainability aspects.

Resource-Based or Production-Oriented Regions. Cluster 1 encompasses multiple regions in the northern and western parts of China. These areas exhibit distinct character-

Table 1. K-means++ Clustering Results

clusters	regions
1	Hebei, Shanxi, Inner Mongolia, Heilongjiang, Guizhou, Gansu, Xinjiang
2	Tianjin, Liaoning, Jilin, Shanghai, Jiangsu, Anhui, Fujian, Jiangxi, Shandong, Henan, Hubei, Hunan, Guangxi, Hainan, Sichuan, Yunnan, Shaanxi, Qinghai, Ningxia
3	Beijing, Zhejiang, Guangdong, Chongqing

istics of resource output or production orientation due to their abundant natural resources, such as minerals, forests, and water resources, or relatively developed industrial production bases. As shown in Figure 5, these regions demonstrate specific outward-oriented economic patterns in embodied resources flow.

In terms of economic development characteristics, most regions in Cluster 1 exhibit negative NETF values, indicating their economic growth relies on exporting resources to external regions in exchange for economic benefits. These regions primarily depend on the extracting and exporting of energy resources such as coal, oil, and natural gas. Despite the net trade outflow, their economic development remains relatively stable due to their abundant natural resources.

From an energy structure perspective, most regions in Cluster 1 exhibit significantly negative NEGEF-gray values, implying heavy reliance on the output of fossil energy in their economic activities. Notably, traditional energy-producing regions like Shanxi, Inner Mongolia, and Heilongjiang, as key fossil energy hubs in China, exhibit particularly significant fossil energy outflows. Specifically, in terms of NEGEF-green, most regions in Cluster 1 also exhibit negative values, indicating that the net production of nonfossil energy in these regions exceeds the net consumption. For instance, Inner Mongolia, Guizhou, Yunnan, and Gansu show particularly significant net embodied green energy flows, indicating outstanding performance in the development of nonfossil energy industries and the establishment of a good production scale for clean energy industries. However, Guangxi and Heilongjiang have relatively limited supply of nonfossil energy, resulting in weaker performance in green energy production flows.

The average NEBWF is relatively low, indicating limited net blue water in their economic activities. This observation aligns with their dominant industrial structure focused on agriculture and heavy industry, which have high demand for direct blue water in production and consumption processes. The NEGWF in Cluster 1 generally shows negative values, indicating net embodied green water exports to other regions. This trend is closely linked to the climate, land use, and ecosystem conditions in these cluster's areas. Rich ecosystems such as grasslands and wetlands, along with extensive agricultural production activities, effectively utilize green water resources via the export of agricultural products.

In this cluster, regions such as Shanxi, Inner Mongolia, Heilongjiang, and Xinjiang exhibit significantly negative NECF values, indicating that these regions are net exporters of carbon emissions. The industrial and energy production activities in these regions are highly dependent on fossil fuels, resulting in substantial carbon emissions being transferred to other regions. Additionally, these regions face considerable environmental pressure and resources sustainable development challenges, necessitating policy interventions and technological innovations to reduce direct carbon emissions.

Based on the analysis above, it is evident that regions in Cluster 1 exhibit distinct characteristics in terms of resource output and production orientation while also facing challenges in economic transformation and resources sustainable development.

Industrial and Commercial Development-Oriented Regions. Cluster 2 primarily encompasses regions in the central and eastern parts of China. The data reveals that this cluster faces dual pressures from development opportunities and challenges. Figure 6 depicts the specific fluctuations in these data.

Regions in this cluster, such as Hebei, Liaoning, Jiangsu, and Shandong, are predominantly industrial centers. The economic growth in these areas relies heavily on manufacturing and industrial production, which leads to the export of products to

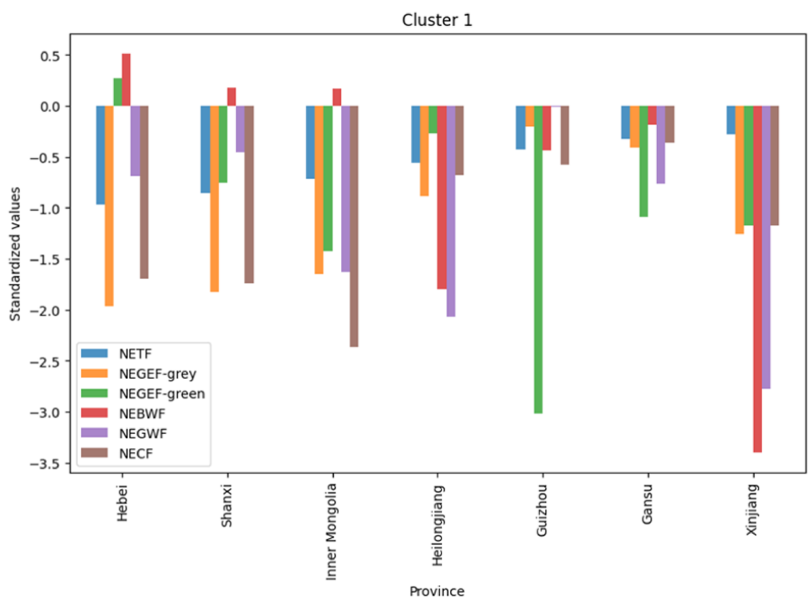

Figure 5. Six-dimensional vectors standardization histogram of Cluster 1.

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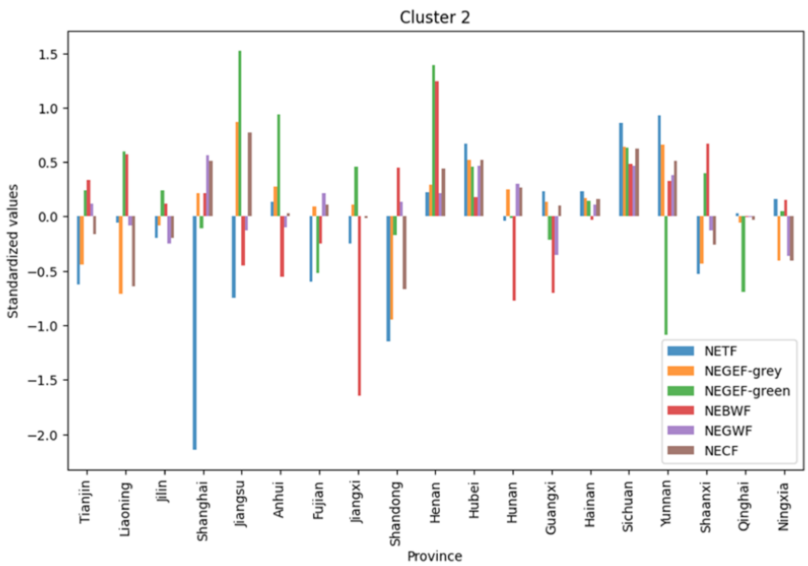

Figure 6. Six-dimensional vectors standardization histogram of Cluster 2.

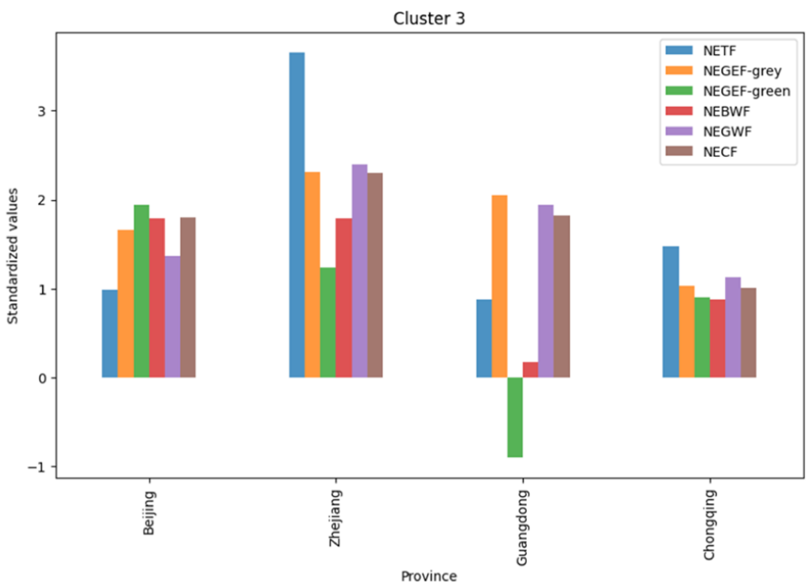

Figure 7. Six-dimensional vectors standardization histogram of Cluster 3.

external markets. The average NETF is significantly negative, reflecting the export-oriented economic characteristics of this cluster.

Cluster 2 exhibits superior performance in NEGEF-gray, with values significantly lower than the traditional energy consumption of Cluster 1, indicating that nonfossil energy has gradually gained traction in Cluster 2, effectively replacing traditional energy sources. This aligns with the higher maturity of manufacturing and service industries in coastal regions, where production technologies impose stricter environmental protection and energy-saving standards. Moreover, NEGEF-green generally shows positive values, revealing the increasing demand for nonfossil energy in these regions as they align with the national strategy of promoting green and low-carbon development.

In terms of water resource consumption, NEBWF values in Cluster 2 exhibit significant fluctuations, reflecting differences in the demand for blue water resources in different regions. The geographical differences in resource endowment have led to a distinct north−south distribution of blue water. Northern regions and cities such as Tianjin, Hebei, Liaoning, and Jilin face water scarcity and rely heavily on imported blue water resources. In contrast, southern regions such as Jiangxi, Anhui, Jiangsu, and Hunan rely on abundant precipitation and natural runoff, making them blue water exporting regions.

In this cluster, regions such as Tianjin, Liaoning, Jilin, Shanghai, Jiangsu, Anhui, Fujian, Jiangxi, Shandong, Henan, Hubei, Hunan, Guangxi, Hainan, Sichuan, Yunnan, Shaanxi, Qinghai, and Ningxia mostly exhibit positive NECF values, indicating that these regions are net importers of carbon emissions. These regions indirectly reduce their local carbon emissions burden by importing carbon-intensive products and services from other regions. Although reliant on external resources for economic development, regions in Cluster 2 exhibit smaller NECF values within the cluster. This characteristic endows them with greater potential and flexibility in carbon emission management and resources sustainable development.

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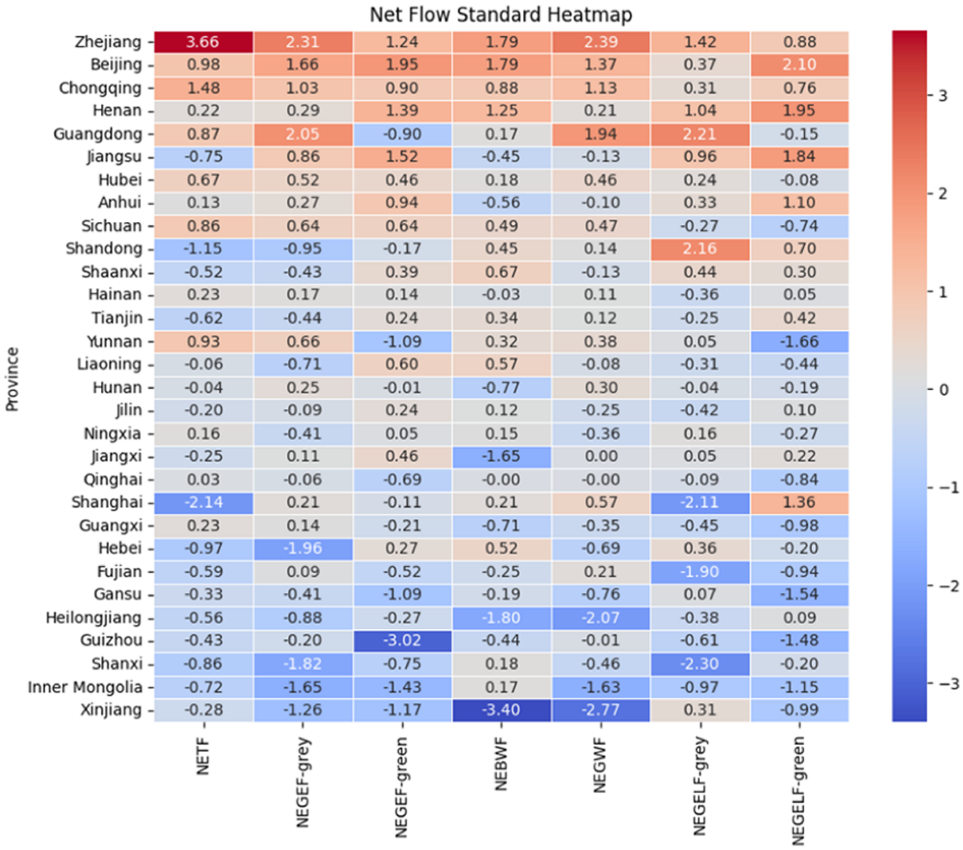

Figure 8. *SDI* of 30 Regions in China.

In conclusion, the regions in Cluster 2 actively adjust their energy structure while balancing resource consumption and environmental burdens through external trade. This strategy not only promotes local economic development but also aligns with the country's overall strategy for resources sustainable development.

Economically and Consumption-Driven Regions. Cluster 3 comprises Beijing, Zhejiang, Guangdong, and Chongqing, four economically developed regions with highly concentrated economic activity and significant consumption levels, demonstrating substantial demand for resources. Their NETF values are all positive, indicating that this cluster relies on products and services provided by other regions for consumption. The economic growth pattern and resource flow characteristics of this cluster are reflected in Figure 7.

Most of the regions in this cluster are well-developed in the service industry. In terms of NEGEF-gray performance, the net embodied gray energy flows in Cluster 3 are all positive and relatively large, indicating that these regions have consumed and transferred a large amount of inter-regional embodied gray energy through value-driven economic development. This is related to the industrial structure and economic development direction of the regions in Cluster 3. For example, Guangdong and Zhejiang are among the most developed regions in China, with a relatively diversified industrial structure and a lower direct reliance on fossil energy.

The majority of NEGEF-green values in the cluster are positive, indicating that these regions import embodied green energy through trade to meet regional consumption needs, consistent with their well-developed service industry and higher proportion of high-tech industries.

From the analysis of water resource flow, Cluster 3 exhibits a relatively high NEBWF, reflecting its extensive use of water resources in economic activities. The well-developed service industry and high-tech industries in this cluster have a significant ″continuous consumption″ of blue water, while the high population density and degree of urbanization result in strong demand for residential and industrial water use. At the same time, the NEGWF of Cluster 3 is also relatively high, indicating that these regions obtain embodied green water resources from other regions through imports of agricultural products to meet local production and consumption needs due to relatively limited agricultural development.

Regions of Cluster 3 exhibit significantly positive NECF values, indicating that these regions are net importers of carbon emissions, acting as net consumers of products and services imported from other regions. The economic activities in these regions are primarily concentrated in high value-added industries, resulting in their local consumption relying mainly on production processes in other regions. However, this also implies that these regions need to depend more on external supply chains for carbon emission management and resources sustainable development.

The results demonstrate that China's regional economic development faces the challenge of balancing economic growth and resources sustainable development. The regions in Cluster 3, due to their high level of economic development, have generated significant demand for resource inputs due to consumption in both daily life and production, while regions in Cluster 1 and Cluster 2 have, to some extent, met these demands. It can be observed that regions with higher levels of

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economic development tend to become net consumers of resources.

Regional SDI. The NEF serves as a framework for characterizing the interconnected economic and environmental flows within complex social economies. Identifying the linkages between energy and environmental resource consumption and economic activities is crucial for balancing resources sustainable development of people and nature. Understanding the NEF between different regional resources will help to explore regional resources sustainable development potentials and directions, and to avoid excessive transfer of resource and environmental pressures, including regional carbon reduction, from one region to another. As shown in Figure 8, an analysis of the regional SDI of different clusters was conducted to quantify the differences in resources sustainability.

The research results show that different regions obtained through clustering algorithms exhibit different resources sustainable development characteristics. Specifically, the average *SDI* of the Cluster 1 region group is −0.68, showing a clear trend of resource output. This indicates that these regions face significant challenges in resource utilization and may face the problem of excessive resource consumption.

In contrast, the average *SDI* of the Cluster 2 region group is 0.10, indicating that the resources within this group of regions are more consistent and exhibit the characteristics of long-term sustainable development. This consistency indicates that these regions are relatively balanced in resource utilization and have exhibited positive performance in resources sustainable development.

On the other hand, although Cluster 3 comprises the four most developed regions in China's economy, it performs the poorest in regional resources sustainable development, with an average *SDI* of 1.31. This result indicates that despite significant achievements in economic development, these regions still face severe challenges in resource utilization and sustainability.

Warm colors represent that the corresponding attribute resources in the region are in a net inflow state, while cool colors represent that the corresponding attribute resources in the region are in a net outflow state. The darker the color, the greater the inflow/outflow volume. If the color tends toward neutrality, it indicates a small flow rate of the corresponding resource flow.

DISCUSSION

China is currently in the vigorous stage of its energy revolution, characterized by the continuous optimization and upgrading of its energy structure.[60] However, this process is challenged by substantial regional disparities in resource distribution, leading to significant differences in economic growth rates and development levels across the country. Some regions' economies are relatively lagging and still face the challenge of insufficient development sustainability. This study analyzes the correlation between trade flows and resource flows by comparing traditional/renewable energy and blue/green water. The results indicate that with the inter-regional flow of trade, developing regions provide more resources for the development needs of developed regions, thereby exacerbating environmental inequality. This study further explores the NEF performance of different clusters.

Compared to traditional regional sustainability evaluation methods, the k-means++ clustering algorithm exhibited superior performance in capturing the spatial heterogeneity of resource flows. For instance, while the *SDI* results were partly consistent with those of Wang et al.,[61] our approach offers greater granularity by incorporating six-dimensional NEF vectors. This refinement enables the clustering of regions with similar sustainability profiles, thereby revealing nuanced inter-regional dependencies.

Cluster 1 (resource exporters) should focus on sustainable resource extraction and stringent emission controls, and its policies should prioritize (i) renewable energy subsidies to reduce gray energy dependence (e.g., Inner Mongolia's wind power potential in 2023:150 million kilowatts[62]) and (ii) water-efficient agriculture to curb blue water overuse (8.6 billion m^3 embodied blue water flows out in Xinjiang). As industrial hubs, Cluster 2 regions like Jiangsu should leverage their balanced SDI (0.10) to pilot circular economy hubs, integrating industrial symbiosis networks to reduce embodied flows. Consumption-driven regions of Cluster 3 need to reduce dependence on external resources by bolstering local green infrastructure.

Our analysis reveals an imbalance in the economic environment, with Cluster 3 thriving at the expense of Cluster 1. For instance, Shanxi plays a role as one of the energy producers for Beijing. The consumption of gray energy provided by Shanxi to Beijing is 14.59 times greater than Beijing's output to Shanxi; that of green energy is 13.22 times greater, that of blue water is 4.47 times greater, that of green water is 12.2 times greater, and that of carbon emissions is 30.6 times greater. Economic benefits are also exported from Shanxi to Beijing, and the trade flow from Beijing to Shanxi accounts for 80% of the flow from Shanxi to Beijing (Figure 9). The

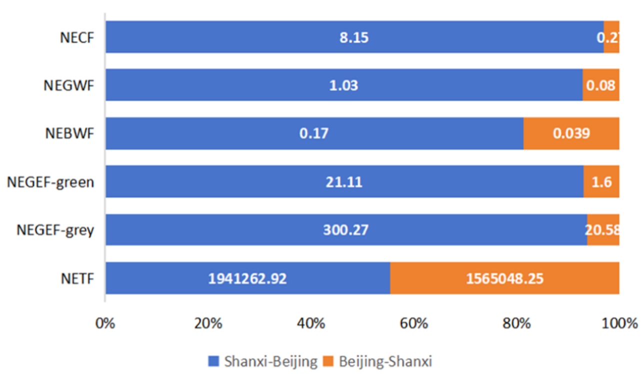

Figure 9. Differences in the multidimensional NEF between Shanxi and Beijing.

results show that the energy, water resources and carbon emissions produced in a single region are unevenly redistributed among other regions in China through the flow of trade.[63−65]

The most direct resource conservation policies implemented by local governments mainly focus on resource production and utilization. Based on local resource endowments and climatic conditions, these governments implement relevant policies and measures such as actively and continuously promoting the large-scale construction of renewable energy industries in the southwest and northwest regions,[66] and improving the efficiency of clean energy and green water use.

In order to establish a resources sustainable development model, it is necessary to understand the complementary resource advantages that consider both energy and environmental ecological benefits. Water, energy, and carbon are

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significant factors in regional resources sustainable development.[67] The sustainable development of resources in a region should be determined by comprehensive environmental sustainability indicators. For example, although Qinghai has a weak regional economic development, it is rich in renewable energy such as solar and wind energy,[68,69] and has obvious advantages in the use of renewable energy and the development of the power industry. The industrial policy in this region should focus on improving industrial efficiency and promoting industrial upgrading. In contrast, although Zhejiang has abundant products, it faces limitations in energy and water resources, and its consumption of energy and water resources is limited by the supply regions. Consequently, Zhejiang should emphasize the importance of effective utilization of resources and environment to make up for its shortcomings. Thus, Zhejiang's policies should tend to maximize the efficiency of energy and environmental resource utilization.

Emphasis should also be placed on inter-regional cooperation policies based on regional advantages. Regions function either as resource consumers (resource input regions) or producers (resource output regions). Consumer regions, such as Beijing, Zhejiang, Guangdong, and Chongqing, should bear a significant share of the consumer responsibility. As these consumers are predominantly located in highly developed areas, they are well-positioned to provide more economic and technological support for their own and other regions' economic development. Producers in Shanxi, Inner Mongolia, Heilongjiang, and other regions should bear more responsibility for production due to their abundant resources. Efforts here should concentrate on improving industrial production technology and resource utilization efficiency. However, some resource-poor and underdeveloped producers, such as Hebei, Liaoning, Sichuan, Henan, etc., should consider relocating some energy/water-intensive industries to resource areas to avoid economic development at the expense of the environment. These results can serve as a reference for policy makers to formulate more targeted and effective environmental policies and promote resources sustainable development in China.

This study quantifies energy, water resources use, and carbon emissions based on China's MRIO of 30 regions. It comprehensively considers 6-dimensional vectors of each region, and the cluster research results are expected to promote comprehensive energy policy decisions to meet China's growing energy and environmental demands. The specific energy consumption and water resources utilization can be seen as complementary indicators to track the main resource pressures of regional development; they are highly beneficial for in understanding the diversity of natural resource pressures on production in related industries, as well as the nature of the relationship between economic activities and natural endowments. The k-means++ clustering based on six-dimensional NEF vectors reveals differential regional roles (e.g., resources exporters vs consumers) that traditional single-dimensional analyses overlook. For instance, Cluster 3′s high SDI (1.31) reflects not merely carbon leakage but over-reliance on external water and energy, a finding unattainable through sector-specific or single-dimensional studies.

Although a six-dimensional energy/environmental extended MRIO table has been constructed, there are some limitations in the compilation process. Due to the lack of observed regional energy, water resources, and carbon emissions data, the parameters used in the IO model are estimated through regional trade flows, assuming uniform trade patterns and technological levels across regions. This may not be accurate as there is regional heterogeneity at the regional level. Consequently, there are some uncertainties in the construction process of the MRIO table. For example, RAS technology is applied to optimize matrices, as conflicting data in construction often leads to imbalanced MRIO tables. However, this optimization technique may adjust data and introduce uncertainty to some extent. The assumption of uniform intensity across regions can be considered more or less plausible, but it still needs to be verified when data becomes available in the future.

These research findings have important policy implications for promoting regional resources sustainable development in China and other countries facing similar challenges. Future research can further explore the causal mechanisms and interactions between economic development, resource utilization, and environmental pressures in different regions of China by leveraging AI technology, to better understand how these factors influence each other. Furthermore, a broader range of resource and environmental factors could also be incorporated, such as pollutants, to provide a more comprehensive assessment of sustainability impacts and enhance the applicability of resource management strategies.

■ CONCLUSIONS

In summary, we present a resources embodied flow framework based on IO modeling to quantify multidimensional resource interactions across 30 regions of China, integrating machine learning algorithms for regional clustering and resources sustainable development evaluation. The findings reveal three distinct resources sustainability clusters: resource-intensive regions in the north and west (Cluster 1) exhibit an average *SDI* of −0.68, characterized by net resource output; central and eastern production-oriented areas (Cluster 2) show a balanced *SDI* of 0.10 with preferable sustainability; and developed economic consumption driven regions (Cluster 3) have a high *SDI* of 1.31, facing severe resource import dependency and environmental pressures. Together, all of the above clusters highlight the need for targeted policies for different regions to optimize inter-regional resource allocation and foster balanced sustainable development by aligning regional characteristics with resource flow patterns.

■ ASSOCIATED CONTENT

Data Availability Statement

The data used to support the findings of this study are available from the corresponding author upon request.

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D.L.: conceptualization, methodology, investigation, data curation, software, visualization, writing original draft, and writing—review and editing. J.L.: validation, formal analysis, and writing—review and editing; J.Z.: software and validation; S.X.: investigation, validation, and writing—review and editing; M.Y.: conceptualization, project administration, funding acquisition, supervision, and writing—review and editing. Z.L.: supervision and writing—review.

Notes

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■ NOMENCLATURE

IO	input-output
NEF	net embodied flows
NEEF-E	net embodied energy flows
NEEF-Env	net embodied environmental flows
MRIO	multi-regional input-output model
NEGEF-gray	net embodied gray energy flow
NEGEF-green	net embodied green energy flow
NEBWF	net embodied blue water flow
NEGWF	net embodied green water flow
NECF	net embodied carbon emissions flow
SDI	resources sustainable development evaluation index
SSE	sum of squared errors
CEADs	China emission accounts and data sets
$MtCO_2$	megatons of carbon dioxide

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