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Research Article

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Analysis of the evolutionary characteristics of indirect energy flow and dependence among Chinese industrial sectors

Yanjing Jia¹ and Zhiliang Dong*²

Abstract

Background: The diversification of product production and consumption generates closer links between industrial sectors and increases the complexity of indirect energy flows between industrial sectors and interdepartmental interdependence.

Methods: We calculated the indirect energy flows between various industrial sectors in 2002, 2007, 2012 and 2017. Then, we have built four indirect energy flow networks and explored the characteristics and the interdependence of indirect energy consumption between sectors. Finally, a quadratic assignment procedure correlation analysis was performed to clarify the relationship between the indirect energy flow relationship and the dependence relationship between industrial sectors.

Results: Different industrial sectors play different roles in the process of indirect energy consumption, with a more concentrated indirect energy supply among industrial sectors compared with consumption and a gradual shift in the indirect energy supply from the chemical industry to the service industry. Higher and more stable flow paths that carry indirect energy flows and clearer interdepartmental dependencies are reflected in the upstream and downstream links of the industrial chain. The correlation

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between indirect energy flows and interdepartmental dependencies is gradually increasing but requires improvements to further optimize China’s industrial structure and reduce energy consumption.

**Conclusions:** Efforts should be made to reduce the energy supply in the chemical sector, optimize the quality of the energy supply in the service sector, and reduce energy consumption. Appropriate attention should be focused on the indirect energy flow relationship between the upstream and downstream industries of the industrial chain, and the integrity of the domestic industrial chain can be improved to reduce the total energy consumption.

**Keywords:** Indirect energy flow, Input-output, Complex network, Dependence, Correlation analysis

**Background**

It has been six years since China's "dual control" action on total energy consumption and intensity was proposed on October 26, 2015. This action controls the total amount and intensity of energy consumption at the regional level, but the current control of total energy consumption is still severe in some regions. Energy is one of the foremost elements of human economic activities, and it is consumed directly or indirectly by the main body of economic activities [1, 2]. Direct energy consumption methods include the consumption of products, such as oil, coal, natural gas, and minerals. The indirect method refers to the indirect consumption of resources through the consumption of economically produced final products or intermediate products[3].
Analyzing energy consumption based on energy consumption categories has provided many key ideas for controlling total energy consumption.

Past studies have found that reducing direct energy consumption plays a pivotal role in achieving total energy control and reducing total carbon and pollutant emissions[4]. As the division of labor continues to be refined, strong economic ties are observed between sectors. Products are often produced by the integration of multiple sectors, and the consumption links are gradually diversified[5]. Therefore, it is necessary to distinguish between the direct energy consumption of a product or industry and the indirect energy consumption, which includes intermediate production and consumption. At the same time, it is also necessary to analyze energy consumption, that is, the energy flow between sectors. Embodied energy consumption not only considers direct energy consumption but also considers indirect energy consumption, which has been less studied in previous research. Therefore, scholars have conducted relevant research on calculating and identifying the influencing factors of embodied energy and the flow of embodied energy in the trade process[6, 7].

Although research on direct energy consumption and embodied energy consumption has gradually matured, only a few scholars have analyzed indirect energy consumption. In reality, however, almost the production and service provision of almost any commodity will indirectly consume energy; therefore, indirect energy consumption has a huge impact on total energy consumption and emission control. Therefore, it is necessary to analyze indirect energy consumption separately as a research object to more effectively improve current energy consumption and reduce total energy
consumption. Previously, scholars mainly conducted research on the influencing factors and consumption structure of residents' indirect energy consumption[8-10]. Because energy is consumed in all aspects of social production and life, some scholars have also conducted research on indirect energy consumption from the perspective of various industrial sectors. Harun M quantified the total, direct and indirect energy intensity of the industrial sector in Malaysia and identified the sectors that led to increased energy consumption[11]. Yuan Y analyzed the indirect energy consumption of China's tourism industry[12]. Wang B analyzed the energy flow network between Chinese industrial sectors and found that general equipment manufacturing and electrical equipment manufacturing are the key sectors of indirect energy consumption[13]. However, the situation of indirect energy flow between industrial sectors is complicated, and limited research has focused on the indirect energy flow between industrial sectors and the dependence control relationship between industrial sectors; therefore, a relevant analysis has been performed on this issue.

First, we need to measure indirect energy consumption. The existing energy consumption measurement methods are mainly divided into measurement methods based on the consumption life cycle and measurement methods based on an input–output table. The measurement method based on the consumption life cycle is mainly used to measure the indirect energy consumption of residents. Moreover, the calculation method needs to clarify the data throughout the whole life cycle of a product from raw material acquisition to final consumption, although the operability is relatively low. Input–output analysis is an economic quantitative analysis method proposed by Leotief.
W in the 1930s, and it has been widely used in the field of energy consumption measurement. Han analyzed the impact of changes in Japan’s economic structure on energy consumption intensity based on the input–output table[14]. Bekhet HA evaluated the impact of the global financial crisis on Malaysia's energy consumption[15]. Some scholars have performed relevant analyses on China's energy consumption based on this method. Zhang L conducted research on the energy flow of the entire city of Beijing and its 30 economic sectors[16]. Indirect energy consumption is the energy consumed indirectly through the input of intermediate products in the production process[17]. The indirect energy flow between industrial sectors can be obtained based on the input and output of intermediate products in various sectors. Therefore, the indirect energy flow between the two industries can be measured based on the input–output table. In this way, the indirect energy flow between industrial sectors could be clarified.

Industrial sectors form a complex system through the supply and consumption of indirect energy. This complex system could be understood through a complex network. Network analysis methods have important contributions in the energy field. Building a complex network could more clearly reflect the indirect energy flow between industrial sectors and the overall characteristics. Research on ecological network analysis methods combined with input–output models has gradually deepened. It is often used to analyze the interaction control and dependence relationship between various subjects. For example, Xu W explored the complex relationship among water resource utilization, energy consumption, and carbon ecological networks in combination with ecological
networks[18]. Zhang G analyzed the water consumption structure of various sectors and their interaction control relationships in Guangdong Province, China[19]. To clarify the stability of indirect energy flows between industrial sectors and the interdepartmental interdependence, we introduced the dependence index of ecological network control analysis to explore the interdependence between industrial sectors and clarify the main indirect energy consumption relationship between industrial sectors.

Indirect energy consumption is an important part of the energy consumption process. The complex structure of the industrial sector is closely related to the whole system. A systematic analysis of indirect energy consumption at the sectoral level can provide new insights for solving energy problems.

In summary, we estimated the indirect energy flows between various industrial sectors in 2002, 2007, 2012 and 2017 based on the input–output table. Taking sectors as nodes, indirect energy flows between sectors as edges, and indirect energy flows as weights, we constructed indirect energy flow networks between industrial sectors in each year. The overall characteristics of the indirect energy flow network and the key sectors in the flow process, the structure of the community, the key flow paths, and the dependencies between the industrial sectors were identified. We performed a quadratic assignment procedure (QAP) correlation analysis to clarify the relationship between indirect energy flow and inter-industry dependence, to develop a more comprehensive understanding of the indirect energy flow between industrial sectors and interdepartmental dependence and to provide a reference for the formulation of policies related to reducing energy consumption.
Data and methods

Data source and preprocessing

The basic input–output table is published every 5 years in China. We selected the basic I-0 tables of the 2002, 2007, 2012 and 2017 editions to measure the indirect energy flows in these four years. The basic I-0 table and original energy data used in this study are from the China Statistical Yearbook and the China Energy Statistical Yearbook. Due to the inconsistency between the industrial sector classification in the "China Input–Output Table" and the industrial sector classification in the "China Energy Statistical Yearbook". To ensure the accuracy of the calculation, Jiang’s method was used and the number of industry sectors was merged into 30 to ensure consistency with the energy consumption table by industry in the "China Input–Output Table" and "China Energy Statistical Yearbook"[20]. The merged industry sector classification is shown in Table 1

Table 1 Industrial sector classification

| number | sector                                      | number | sector                                      | number | sector                                      |
|--------|---------------------------------------------|--------|---------------------------------------------|--------|---------------------------------------------|
| 1      | Agriculture, forestry, animal husbandry and fishery industry (AFAHF) | 11     | Petroleum processing and coking industry (PPC) | 21     | Instrumentation and cultural office         |
| 2      | Coal mining and washing industry (CMW)      | 12     | Chemical industry (CMI)                     | 22     | manufacturing industry (ICOMM)              |
| 3      | Oil and gas extraction industry (OGE)       | 13     | Non-metallic mineral products industry (NMMP) | 23     | Handicrafts and other manufacturing industry (HOM) |
|        |                                             |        |                                             |        | Scrap industry (SRI)                        |
Methods

Calculation of indirect energy flow

After obtaining the data, the direct consumption coefficient $A$ between various industrial sectors could be calculated according to the input–output table, as shown in Formula (1).

$$a_{ij} = \frac{x_{ij}}{x_j}$$

Note: The name of the sector in the article is indicated by the code in brackets in the above table.
where $x_{ij}$ represents the number of products or services of sector $i$ directly consumed in the production process of the product and operation of sector $j$; $x_j$ is the total input of sector $j$; and $a_{ij}$ is the quantity of products or services of sector $i$ directly consumed by the unit's total output of sector $j$ in the production and operation process. The matrix $A$ formed by $a_{ij}$ is the direct consumption coefficient matrix.

The complete consumption coefficient matrix can be calculated on the basis of the direct consumption coefficient matrix, as shown in Formula (2), where $(I - A)^{-1}$ is the Leontief inverse matrix and $I$ is the identity matrix.

$$B = (I - A)^{-1} - I$$  \hspace{1cm} (2)

The complete consumption factor is the sum of all direct consumption factors and all indirect consumption factors. Through Formula (3), the indirect consumption coefficient matrix $C$ can be calculated. The data $c_{ij}$ contained therein represent the number of products or services of sector $i$ that are indirectly consumed in the production and operation of a unit of product in sector $j$.

$$C = B - A$$  \hspace{1cm} (3)

This paper selects the total energy consumption and the indirect consumption coefficient of each industrial sector to calculate the indirect energy consumption among various industrial sectors. The total energy consumption is the sum of various energies consumed by the material and nonmaterial production sectors of the country in a certain period of time. It is divided into three parts: terminal energy consumption, energy
processing conversion loss and energy loss, which includes direct energy consumption and indirect energy consumption. The indirect consumption coefficient reflects the indirect technical and economic links between various sectors of the national economy. Therefore, it is reasonable to use Formula (4) to calculate the indirect energy flow.

\[
E = \begin{pmatrix}
\varepsilon_{11} & \cdots & \varepsilon_{1n} \\
\vdots & \ddots & \vdots \\
\varepsilon_{n1} & \cdots & \varepsilon_{nn}
\end{pmatrix} (i, j = 1,2,\ldots,n); \quad \varepsilon_{ij} = d_i \times c_{ij} \tag{4}
\]

where \(d_i\) represents the total energy consumption of industry sector \(i\) and \(c_{ij}\) represents the energy consumption of sector \(i\) indirectly consumed by sector \(j\).

**Construction of complex network**

A complex network requires two basic elements, nodes and edges, to build a model \(G = (N,E)\), where \(N\) represents a node in the network and \(E\) represents an edge in the network. The nodes in the text represent each sector. The indirect energy flow relationship between sectors is the edge, and the nodes in the text represent each sector.

The indirect energy flow relationship between sectors is the edge, and the indirect energy flow \(\varepsilon_{ij}\) from sector \(i\) to sector \(j\) is the weight of the edge. The flow from sector \(i\) to sector \(j\) is the weight of the edge.

We constructed indirect energy flow networks in 2002, 2007, 2012, and 2017. In the following text, IEFN-1, IEFN-2, IEFN-3 and IEFN-4 are used to represent the networks of these four years. Because the data on the SRI sector in the input–output table in 2002 are all 0, the number of nodes in 2002 is 29, and each of the remaining networks contains 30 nodes. On the one hand, we consider the large magnitude difference between the maximum flow of indirect energy. On the other hand, the
The purpose of this article is to identify the key sectors and key relationships in the process of indirect energy consumption. We use a smaller magnitude of 100 as the threshold point to eliminate the edges with smaller indirect energy flows, and each network contains 306, 539, 572, and 562 edges.

**Topological structure of the network**

(1) Point intensity. The point intensity $D(i)$ represents the total amount of indirect energy flowing into and out of the industrial sector. Because the IEFN is a directed network, the point intensity is divided into the outgoing intensity $D_{out}(i)$ and the incoming intensity $D_{in}(i)$, which denote the amount of indirect energy flowing from sector $i$ and the amount of indirect energy flowing into sector $i$, respectively, as shown in Equation (5).

$$D(i) = D_{out}(i) + D_{in}(i) \tag{5}$$

where $D_{out}(i) = \sum_{j=1(j\neq i)}^{n} e_{ij}$, $D_{in}(i) = \sum_{j=1(j\neq i)}^{n} e_{ji}$, $i$ and $j$ represent the industry sector, and $e_{ij}$ represents the indirect energy flow from sector $i$ to sector $j$.

(2) Betweenness centrality. The centrality of a point in a network measures the degree of node control over resources, and it can measure to what extent the point controls the connection of other nodes (Strogatz, 2003 #149). It represents the degree to which sector $i$ assumes an intermediary role in the process of energy flow from sector $j$ to sector $k$.

$$B_i = \sum_{j<k} g_{jk}(i)/g_{jk} \tag{6}$$
where \( i, j, k \) represents the industry sector, \( g_{jk} \) represents the number of shortcuts between \( j \) and \( k \), \( g_{jk}(i) \) represents the number of shortest paths between sectors, and \( B_i \) represents the betweenness centrality of point \( i \), and the value range is \([0,1]\).  

(3) Average shortest path length. The speed and efficiency of indirect energy flow between any two sectors can be measured by the average shortest path length \( L \) of the complex network, that is, the number of edges over which indirect energy flows from sector \( i \) to sector \( j \).

\[
L = \frac{\sum_{i<j} d_{ij}}{N(N-1)}
\]  

where \( N \) represents the number of nodes in the network, that is, the number of sectors, and \( d_{ij} \) represents the number of edges on the shortest path between sector \( i \) and sector \( j \), that is, the distance between the two sectors.

(4) Average clustering coefficient. The average clustering coefficient of the network is the average of the clustering coefficients of all industrial sectors, reflecting the tightness of the network. The clustering coefficient of a node refers to the possibility that all nodes connected to the node in the network are also connected. The calculation formula for the clustering coefficient of node \( i \) is shown in Equation (8).

\[
C = \frac{1}{n} \sum_i C_i
\]  

where \( C \) is the average clustering coefficient of the IEFN and \( C_i = \frac{M_i}{k_i(k_i-1)} \), which is the average clustering coefficient of sector \( i \). In a directed network, when node \( i \) has \( k_i \) nodes directly connected to it, \( k_i(k_i-1) \) represents the maximum number of edges that may exist between these \( k_i \) nodes and \( M_i \) represents the number of edges that actually exist.
Modularity. Community detection can make the nodes in the network form clusters in a specific way and divide them into different communities. The industry sectors within the community are closely connected, and the connections between communities are relatively loose. We use the modularity maximization method proposed by Blondel et al. for community detection[21], and the modularity calculation is shown in Equation (9).

$$Q = \frac{1}{2m} \sum_{ij} [A_{ij} - \frac{k_i - k_j}{2m}] \tag{9}$$

where $Q$ represents modularity, $m$ is the weight of the edge in the network, $A_{ij}$ is the weight of the edge between node $i$ and node $j$, $k_i$ and $k_j$ are the sum of the weights of all edges connected by two nodes, and $\frac{k_i - k_j}{2m}$ is the expected value of $A_{ij}$ under random conditions.

Measurement of dependency

To study the degree of interdependence of indirect energy flows between various industrial sectors, we need to build a network model of 30 industrial sectors with the help of the "ecological network" concept. Taking the indirect energy ecological network model of the three industrial sectors shown in Figure 1 as an example[14]: $f_{ij}$ represents the indirect energy flow from industry sector $j$ to industry sector $i$ ($10^4$ tce) and $z_i$ and $y_i$ represent the input and output generated between sector $i$ and the external environment, respectively.

The total input or total output of inflow and outflow sector $i$ are shown in Equations (5) and (6), respectively.
\[ T_{i}^{\text{in}} = \sum_{j=1}^{n} f_{ij} + z_{i} \quad (5) \]
\[ T_{i}^{\text{out}} = \sum_{j=1}^{n} f_{ji} + y_{i} \quad (6) \]

When the system is in a stable state, the total amount of indirect energy flowing into industrial sector \(i\) is equal to the outflow, namely:

\[ T_{i}^{\text{in}} = T_{i}^{\text{out}} = T_{i} \quad (7) \]

![Diagram of indirect energy ecological network model of the three industrial sectors.](image)

The control analysis based on the concept of an "ecological network" originated from Patten and was further developed by researchers such as Schramski[22]. Control analysis can identify the control effect of the indirect energy flow of a certain sector on other sectors. In other words, it can identify the degree of dependence of one sector on another sector. We introduce the dependency matrix \(CN = (c_{nj})\) among sectors to express the degree of dependence and the degree of control between the industrial sectors.

\[ G = (g_{ij}) = \frac{f_{ij}}{T_{ij}}, \quad G' = (g'_{ij}) = \frac{f'_{ij}}{T'_{ij}} \quad (8) \]

\[ N = (n_{ij}) = \sum_{n=1}^{\infty} G^{n} = (I - G)^{-1}, \quad N' = (n'_{ij}) = \sum_{n=1}^{\infty} G'^{n} = (I - G')^{-1} \quad (9) \]

\[ CX = (c_{x_{ij}}) = \frac{n_{ij}}{n'_{ji}} \quad (10) \]
\[ CN = (cn_{ij}) = \begin{cases} 
  cx_{ij} < 1, & cn_{ij} = 1 - cx_{ij} \\
  cx_{ij} > 1, & cn_{ij} = 0 
\end{cases} \]  

where \( g_{ij} \) and \( g'_{ij} \) represent the interdepartmental flow of total output and total input, respectively; \( N \) and \( N' \) represent the dimensionless cumulative output and input flow matrices, respectively; and \( cn_{ij} \) indicates that sector i controls sector j. Thus, the dependence of sector j on sector i is.

**QAP related analysis**

The quadratic assignment procedure (QAP) is a correlation analysis that obtains matrix correlation coefficients by comparing random replacement matrices and performs nonparametric correlation tests, which can be used to study whether two "relationship" matrices are related. The specific calculation steps are as follows: First, all the values of each matrix are regarded as a long vector, and the correlation coefficient \( R \) between the two vectors can be calculated, as shown in Equation (12):

\[ R = \frac{\text{cov}(A,B)}{\sqrt{D(A)D(B)}} \]  

where the \( R \) value is the observed correlation coefficient. Second, we perform random replacement of one matrix datum, calculate the correlation coefficient between the replaced matrix and the other matrix, and repeat the calculation to obtain a correlation coefficient distribution. Finally, the observed correlation coefficient was compared with the distribution of the correlation coefficient calculated according to the rearrangement to determine its significance level[23]. Because the amount of energy flow between industrial sectors, that is, the degree of dependence, is "relational data", the QAP is used for the correlation analysis.
Results and discussion

Small world features

A small-world network refers to a network in which most nodes are not adjacent but can reach each other through a small number of nodes. This type of network can be measured by two indicators, the average clustering coefficient and the average shortest path length. As shown in Table 2, we find that IEFN-1 has a large clustering coefficient of 0.651, indicating that the network has a high effective correlation degree, and most industrial sectors have a high degree of clustering. IEFN-1 has a shorter average shortest path length of 1.113, and energy flows faster. Combining the values of these two indicators, it can be seen that IEFN-1 is a small-world network. According to the data in Table 2, these four indirect energy flow networks all have small-world characteristics, which means that the indirect energy flow relationship between various industrial sectors in the network is relatively close and the impact on one sector may quickly spread to other sectors in the network, thus leading to changes in the entire industrial system.

| Network | Average clustering coefficient | Average shortest path length |
|---------|-------------------------------|-----------------------------|
| IEFN-1  | 0.651                         | 1.113                       |
| IEFN-2  | 0.644                         | 1.297                       |
| IEFN-3  | 0.656                         | 1.287                       |
| IEFN-4  | 0.645                         | 1.296                       |
Identification of key industry sectors

Key industrial sectors can be identified based on two aspects: point intensity and the "media" role. Point intensity is used to measure the influence intensity of the industrial sector. The greater the point intensity, the more important the industrial sector. Intermediary centrality is used to measure the "media" role of the industrial sector. The greater the intermediary centrality, the more important the industrial sector. In IEFN, sectors with greater strength or intermediary centrality are key industrial sectors.

The influence intensity of the industry sector

Figure 2 shows that in IEFN-1, IEFN-2, IEFN-3 and IEFN-4, 20% of the sectors indirectly provide more than 80% of indirect energy, indicating that each network has a scale-free network characteristic. The pattern of these four periods has not changed significantly.

Fig. 2 The cumulative distribution of weighted out-degrees.
In the evolution of indirect energy flows, the indirect energy flows in each year were 228666.8, 671080.8, 858544.8, and 817688.9. The total flow in 2002 was the lowest, and the flow in 2012 was the highest. Further analysis of the few important industrial sector nodes in the network and the weighted in-degree and weighted out-degree distributions of the top 10 industrial sectors are shown in Figure 3 and Figure 4, respectively. In terms of income intensity, the top 10 industrial sectors have not changed much, and the indirect energy consumption of the top seven industrial sectors has little difference. The top ten industrial sectors received 113,362.39, 335,680.24, 438,446.83 and 4,080,541,959 tons of indirect energy in each year, accounting for approximately 50% of the total indirect energy flow. The MPI and the EMEM have consistently ranked among the top 3 and thus represent the main indirect energy consumers.

In terms of output intensity, the top 5 industrial sectors are key sectors of energy output, and they indirectly provide 81.97%, 86.58%, 84.15% and 84.53% of energy to other sectors. The CMI and the MSRP are important indirect energy providers, indicating that they are upstream in the industrial chain. They are the suppliers of energy in the production process, and the energy the product carries is indirectly consumed in the production process of the middle and downstream links. In comparison, the proportion of indirect energy supply in the OSI in 2017 increased compared with that in other years, indicating that the service industry involves all aspects of social production and life and has become increasingly closely connected with corresponding industrial sectors. A comparison of the indirect energy supply and consumption in various years shows that the indirect energy supply among industrial sectors is more...
concentrated than the energy consumption, which provides an important entry point for supply-side structural reform.

Fig. 3 The top ten industry sectors in the weighted in-degree of each network. Note: (a) IEFN-1, (b) IEFN-2, (c) IEFN-3, (d) IEFN-4.
The media role of the industry sector

In the IEFN, certain industrial sectors are relatively low strength but become important because they are connected to many key sectors, that is, these industrial sectors have a high degree of intermediary centrality and can control the indirect energy flow between sectors. Identifying the industrial sectors that have a key intermediary...
role can more objectively maintain the sustainable development of various industrial sectors, accelerate the flow of indirect energy, and generate more effective energy consumption. Table 3 shows the top ten sectors of the intermediary centrality of each network. Six industrial sectors are always in the top ten sectors, which have not changed much; however, the intermediary strength of each sector changes dynamically. Relatively speaking, the PPC and the MSRP are sectors with important intermediary roles.

Table 3 Betweeness centrality (Top10)

|  | IEFN-1 |  | IEFN-2 |  | IEFN-3 |  | IEFN-4 |  |
|---|---|---|---|---|---|---|---|---|
| sector | betweeness centrality | sector | betweeness centrality | sector | betweeness centrality | sector | betweeness centrality |
| 29 | 0.0168 | 14 | 0.0433 | 24 | 0.0409 | 14 | 0.0347 |
| 1 | 0.0139 | 16 | 0.0412 | 11 | 0.0362 | 11 | 0.0346 |
| 11 | 0.0038 | 24 | 0.0310 | 28 | 0.0269 | 13 | 0.0340 |
| 12 | 0.0038 | 30 | 0.0241 | 13 | 0.0268 | 24 | 0.0290 |
| 24 | 0.0038 | 12 | 0.0240 | 16 | 0.0239 | 28 | 0.0179 |
| 14 | 0.0038 | 28 | 0.0213 | 30 | 0.0212 | 12 | 0.0149 |
| 28 | 0.0016 | 15 | 0.0056 | 14 | 0.0169 | 20 | 0.0145 |
| 13 | 0.0015 | 6 | 0.0049 | 12 | 0.0102 | 30 | 0.0134 |
| 20 | 0.0013 | 18 | 0.0040 | 2 | 0.0029 | 16 | 0.0072 |
| 30 | 0.0009 | 20 | 0.0036 | 20 | 0.0024 | 15 | 0.0040 |

Community structure of IEFN

Gephi software was used to divide the four groups of IEFN networks and select the result of communization with the largest modularity. The modularity of each network is 0.082, 0.108, 0.113, and 0.105. The composition and indirect energy flow of various social organizations are shown in Table 4, and the indirect energy flow
between various sectors is shown in Figure 5. The IEFN-1, IEFN-2 and IEFN-3 results are relatively similar. They are divided into community I, in which the CMI is the indirect energy supply center, and community II, in which the MSRP as the indirect energy supply center. The number of sectors included in community I is much larger than that in community II. The indirect energy outflow of community II is always greater than the inflow, which has a strong indirect energy spillover effect. A comparison of IEFN-1 and IEFN-2 shows that the PPCESGM, the EMEM, and the GPS have changed from community I to community II. The MPI and the GEM have changed from community II to community I. A comparison of IEFN-2 and IEFN-3 shows that the GPS has transformed from community II to community I and the instrument, meter and cultural office machinery manufacturing industry has transformed from community I to community II.

The organizational structure of IEFN-4 has changed significantly, and some industrial sectors have been divided into communities with the OSI as the core. Compared with IEFN-3, the PPCESGM and the CSI in IEFN-3 community II are divided into the new community III in IEFN-4. The AFAHF, the OGE, the FMTP, the TXI, the NMOMD, the CEOEEM, the WRAC and the OSI in community I are covered and divided into new community III. Community III takes the OSI as the core of the association, including all aspects of social life. This finding shows that the service industry has been involved in all aspects of social life and has become the main source of indirect energy consumption.
| Network | Number of industry sectors | Internal indirect energy flow | Indirect energy inflow | Indirect energy outflow |
|---------|---------------------------|-------------------------------|------------------------|------------------------|
| IEFN-1 | I 13 19 20 21 22 24 25 26 28 29 30 | 124409.91 | 40464.27 | 38635.73 |
| IEFN-2 | I 15 16 20 21 22 23 24 26 28 29 30 | 279424.86 | 188393.61 | 110859.46 |
| IEFN-3 | I 13 15 16 20 22 23 24 25 26 28 29 30 | 382704.83 | 193395.25 | 164506.03 |
| IEFN-4 | I 14 17 18 19 21 | 45846.48 | 143804.97 | 168672.77 |
|        | II 10 14 17 18 19 21 22 23 24 25 26 28 | 117918.70 | 164506.03 | 193395.25 |
|        | II 10 14 17 18 19 21 22 23 24 25 26 28 | 250646.11 | 125906.15 | 306103.71 |
|        | II 13 14 7 10 13 20 27 29 30 | 14569.89 | 236915.25 | 31849.89 |
The weight of the edge in the IEFN refers to the indirect energy flow between two sectors. The greater the weight of the edge, the greater the indirect energy flow. Figure 6 shows the cumulative probability distribution of the edge weights of each network.

**Key indirect energy flow path of IEFN**
Indirect energy flows are increasingly concentrated among a few industrial sectors, with 10.13% of the edges in IEFN-1 carrying 44.13% of the indirect energy, 10.05% of the edges in IEFN-2 carrying 58.89% of the indirect energy, 10.14% of the edges in IEFN-3 carrying 56.10% of the indirect energy, and 10.00% of the edges in IEFN-4 carrying 50.44% of the indirect energy. A small number of edges control a large amount of the indirect energy flow, which has a huge impact on the entire network. If these edges are weakened or removed, the indirect energy consumption of the industrial sectors connected to the edges will be controlled and then spread to the entire industrial system, thereby reducing the overall energy consumption.

The top 1.31%, 1.22%, 1.15%, and 1.16% of the edges in each network carry 9.36%, 15.91%, 14.55% and 11.08% of the indirect energy flow, respectively. We use these edges as the starting edges to identify the path of indirect energy flow. The input sector of the starting edge is the starting node, and the target node in the starting edge is used as the second input sector to continue to capture the industry sector that has the largest edge-weight relationship with the second input sector. This process is repeated until the last sector returns to the penultimate sector to identify the critical path of each year, as shown in Table 5. The changes in the composition and flow of the critical path industry sectors in each year are relatively small. Most of the paths are based on the starting node of the MSRP, and the manufacturing industry is the target node. Among them, the path that has always carried the most indirect energy flow is the MSRP → MPI path. During the study period, the critical path changes were not strong, and the following paths were relatively stable: the MSRP → EMEM → CEOEEM
→ the ICOMM and the MSRP → the MPI → the GEM → the SEM. Although slight changes were observed in different years, the core of the path did not change significantly and included flows based on the upstream and downstream links of the industrial chain.

Fig. 6 Cumulative distribution of edge weights.

Table 5 Critical path

| Network | Critical path |
|---------|---------------|
| IEFN-1  | the MSRP → the MPI |
|         | the MSRP → the SEM |
|         | the MSRP → the TEM |
|         | the MSRP → the GEM → the TEM |
|         | the MSRP → the GEM → the CEOEEM → the ICOMM |
|         | the MSRP → the EMEM → the CEOEEM → the ICOMM |
| IEFN-2  | the MSRP → the GEM → the TEM → the TEM → the EMEM → the CEOEEM → the ICOMM |
|         | the MSRP → the TEM → the TEM → the EMEM → the CEOEEM → the ICOMM |
|         | the MSRP → the SEM |
|         | the MSRP → the GEM → the SEM |
|         | the MSRP → the EMEM → the CEOEEM → the ICOMM |
|         | the MSRP → the GEM → the SEM |
|         | the MSRP → the SEM |
Dependence relations of industrial sectors

Figure 7 shows the dependency ratio between industry sectors (from column to row). The average dependency among network sectors is 0.324, 0.341, 0.326, and 0.386. The closer the value of dependence between sectors is to 1, the stronger the dependence. Overall, the interdepartmental dependency control relationship in IEFN-4 is obvious. The top three obvious dependencies in IEFN-1 are as follows: the EMEM relies on the CEOEEM (0.821), the CEOEEM rely on the EMEM (0.676), and the TXI depends on the CMI (0.675). The top three obvious dependencies in IEFN-2 are as follows: the MPI depends on the mining and dressing industry (0.745), the EMEM depends on the CEOEEM (0.707), and the CEOEEM depend on the OSI (0.704). The top three obvious dependencies in IEFN-3 are as follows: the MPI depends on the MSRP (0.745), the CEOEEM depends on the OSI (0.712), and the EEMEM is dependent on the CEOEEM (0.678). The top three obvious dependencies in IEFN-4 are as follows: the TXI relies on the CMI (0.986), the GEM relies on the MSRP (0.984), and the PPCESGM relies on the CMI (0.984).

Strong dependence is reflected in the upstream and downstream links of the industrial chain, such as the TXI's dependence on the CMI, the MPI's dependence on
the MMD, and the MSRP. A stronger interdepartmental dependence relationship indicates that indirect energy has a flow relationship from the dependent sector to the dependent sector in the combination. A weaker dependence relationship indicates that the indirect energy flow relationship in the combination is affected by other sectors and that the flow direction is not clear.

From row to column, the proportions of control relationships among industrial sectors are shown. The sectors that have obvious control over other industrial sectors in each year are as follows. IEFN-1 is represented by the TEM (control number is 5) and the GEM (5); IEFN-2 is represented by the GEM (10); IEFN-3 is represented by the GEM (10); and IEFN-4 is represented by the FMTP (9) and the CMW (9). The CMW, the FMTP, the GEM and the TEM are the industrial sectors with the greatest degree of control in each network and can be used as key areas for future industrial restructuring.
Correlation occurs between inter-industry dependence and the indirect energy flow. QAP related analysis shows the close relationship between the upstream and downstream industries of the industrial chain. To test whether a correlation occurs between inter-industry dependence and the indirect energy flow between industrial departments, we performed a QAP correlation analysis to test the correlation between the dependence matrix and the indirect energy flow matrix. As shown in Table 6, a negative correlation was observed between inter-sectoral...
dependence and indirect energy flows in 2002, which was significant at the 0.05 level.

In 2007, 2012 and 2017, inter-sectoral dependence and indirect energy flows were positively correlated, and the significance was obvious. In 2012, the correlation coefficient decreased, which may have been caused by significant changes in China's industrial structure in 2012, and the scale of the tertiary industry once again surpassed that of the secondary industry, resulting in corresponding changes in inter-industry dependencies and indirect energy flows. However, the correlation between the two matrices shows an overall increasing trend, and the similarity between the energy flow relationship between industrial sectors and the inter-industry dependence relationship has become stronger, which shows that the adjustment of China's industrial structure has achieved remarkable results and the industrial chain of commodity production and service has been gradually improved. However, the similarity between the two is not high, and the industrial structure still needs to be further optimized. To reduce the total energy consumption, necessary attention should be focused on the indirect energy flow relationship between the upstream and downstream industries of the industrial chain, and the integrity of the domestic industrial chain should be improved.

Table 6 Dependency relationship and indirect energy flow QAP correlation analysis results

| Years | Correlation coefficient | P  |
|-------|-------------------------|----|
| 2002  | -0.098*                 | 0.034 |
| 2007  | 0.266***                | 0.000 |
| 2012  | 0.214***                | 0.000 |
| 2017  | 0.360***                | 0.000 |

Note: (1) *** means significant at the level of 0.001, p<0.001; * means significant at the level of 0.05, p<0.05; (2) The first column is the Pearson correlation coefficient between the two relationship matrices.
Conclusions

Based on the input–output tables for 2002, 2007, 2012 and 2017, we estimated the indirect energy flow between industrial sectors in the four years. An indirect energy flow network was constructed, and the evolution of the overall characteristics and local characteristics of the network was explored with the help of network topology indicators. The dependency matrix was used to explore the interdependence of indirect energy consumption among departments. Finally, a QAP correlation analysis was performed to clarify the relationship between the indirect energy flow relationship and the dependence relationship between industrial sectors. Based on the above research, the following conclusions are drawn:

(1) A comparison of the indirect energy supply and consumption in various years showed that the indirect energy supply between industrial sectors is more concentrated than the consumption. Therefore, we should focus on adjusting the industrial structure from supply-side structural reform. From the perspective of changes in energy supply and the evolution of community division, indirect energy supply is gradually shifting from the chemical industry to the service industry. At the same time, the total indirect energy consumption in 2017 decreased compared with that in 2012. Therefore, efforts should be made to reduce the energy supply in the chemical sector, optimize the quality of the energy supply in the service sector, and reduce energy consumption.

(2) The indirect energy flow network in each year has the characteristics of a small world, indicating that the indirect energy flow relationship between the various...
industrial sectors in the network is relatively close and an impact on one sector may quickly spread to other sectors in the network. The evolution of individual characteristics of the network shows that different industrial sectors play different roles in the process of indirect energy consumption. The CMI and the MSRP are the main indirect energy suppliers; the PPC and the MSRP play an intermediary role; and the MPI and the EMEM are the main indirect energy consumers. Therefore, when formulating related policies to reduce industrial energy, it is necessary to formulate corresponding strategies for industries that assume different roles. For example, in the process of curbing the flow of inefficient indirect energy, the path of consumption can be blocked by controlling industrial sectors that have a mediating role. Moreover, the consumption of ineffective or inefficient indirect energy can be reduced to reduce energy consumption.

(3) In the process of reducing energy consumption, it is necessary not only to pay attention to the key sectors that assume various roles but also the critical path of indirect energy consumption. The critical path identification results show that the flow paths that carry a high and relatively stable flow of indirect energy are all flow paths based on the production situation of the industrial chain. Therefore, it is necessary to reduce energy consumption from the perspective of the industrial chain. For example, for the MSRP → the MPI, which has always carried the most indirect energy flow, it is necessary to focus on the energy consumption of this path. The supply of ineffective energy in the MSRP must be reduced, the energy consumption quality of the MPI must be improved, and a relative balance between energy supply and consumption must be
formed. Energy supply is driven with energy demand, thereby reducing energy consumption.

(4) A dependency correlation analysis results show that the more explicit dependence between industrial sectors is reflected in the upstream and downstream links of the industrial chain. Therefore, reducing energy consumption needs to proceed starting from the overall situation of the industrial sector. Based on the upstream and downstream relationships between industrial departments, cross-departmental coordination policies should be formulated to promote the coordination of industrial departments to reduce energy consumption. The correlation between dependence and indirect energy flow is increasing as a whole, and the similarities between the two are becoming stronger. This finding shows that the adjustment of China's industrial structure has achieved remarkable results, and the industrial chain of commodity production and service has been gradually improved. However, the similarity between the two is not high, which indicates that the industrial structure still needs to be further optimized. Appropriate attention should be focused on the indirect energy flow relationship between the upstream and downstream industries of the industrial chain, and the integrity of the domestic industrial chain can be improved to reduce the total energy consumption.
Supplementary Information

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Author’s contributions

Conceptualization, Methodology, Investigation, Writing—Original Draft Preparation,
Writing—Review and Editing, Y.J.; Visualization, Supervision, Project Administration, Funding Acquisition, Methodology, Software, Z.D. All authors have read and agreed to the published version of the manuscript.

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Availability of data and materials

The data presented in this study are openly available at the "China Input–Output Table" and the "China Energy Statistical Yearbook".

Declarations

Ethics approval and consent to participate

Not applicable.
Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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