A comparison of coal supply-demand in China and in the US based on a network model*

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(Received 24 October 2012; revised manuscript received 19 March 2013)

Through analysis the actual coal supply and demand in the US and China, the properties of the coal supply-demand market in both countries are investigated based on the energy supply-demand network. The validity of our model is verified by comparing numerical results with empirical results. The comparison of empirical results and the comparison of coal network model parameters between in the US and in China reveal the essence of the internal differences and similarities of coal supply and demand in these two countries. The third stage of China's coal network was close to that of the US in 1995, indicating that the evolutional situation of China's coal market begins to transit to an oligopolistic type. Finally, suggestions for China's coal supply-demand strategy are put forward.

Keywords: coal supply-demand network, node weight, edge weight, coal production

PACS: 89.30.ag, 05.65.+b, 89.75.Da **DOI:** 10.1088/1674-1056/22/10/108901

1. Introduction

As is well known, the industrial development of coal is closely related to a country's economy, even the world economy at large. Due to the enormous reserves of coal and its gasification technology maturing with the rapid development of science and technology, research into the development of the coal industry has practical significance for economic development and energy strategic planning.

Study of the development of the coal industry receives much attention. Most previous researches on the coal industry have focused on the relationship between coal consumption and economic growth, the forecast of coal production, etc. The vector autoregressive (VAR) framework and the Panel co-integration and error-correction modeling framework have been applied to the study of the relationship between coal consumption and economic growth.[1–6] Several system dynamics models have been established to study coal pricing, production, the sustainable development of the coal industry, etc.[7–11] Many mathematical analysis methods have been applied to the study of the forecast of coal production, including grey system theory, logistic curve, Gaussian curve, genetic algorithm (GA) and system dynamics (SD), and so on.[12–17] There are also several investigations about coal industry geographic concentration and coal market concentration. Chen and Zhou[18] employed a fixed-effect model with a variable intercept to account for the coal industrial geographic concentration, and found that resource endowments, scale economies, and market demand are positively correlated with geographical concentration. Pan *et al.*[19] analyzed and evaluated the industrial policy orientation and corporate restructuring of China's coal market by comparing Chinese coal market concentration and its influencing factors with that of the US.

The coal market can be regarded as a complex system. It consists of two types of enterprise: enterprise of coal supply and demand. Every enterprise in the coal market has its own business strategy, aiming to improve its competitiveness to obtain more profits. It follows simple market rules and adapts to the environment continuously. The complicated interaction and relations between the two types of enterprises constitute a typically self-organizing and adaptive network system. Therefore, research which only focuses on coal production forecasting or the relationship between coal consumption and economic growth is insufficient. An application of a complex network method to coal market research will reveal mechanisms in the market which may not be found by using other methods. Moreover, such a mechanism has a reference value for operation management and scientific decision. Many real systems can be modeled by complex networks, typical examples include the World Wide Web,[20] power grids,[21] airline networks,[22–24] online social networks,[25] metabolic networks,[26] scientific collaboration networks,[27] producer-consumer networks,[28] epidemic spreading,[29] among many others. By means of some methods such as graph theory and statistical physics, a complex network can be used to capture and describe system evolution mechanisms, evolution laws, and overall behavior. Xu *et al.*[21] presented a dynamical model to reproduce the developing process of the Chinese power grid. In a power grid the nodes are defined as electric power stations or transformer substations and the edges can be defined as high-voltage transmission lines. Wang *et*

*Project supported by the National Natural Science Foundation of China (Grant Nos. 71073071 and 71273119) and the Major Program of Social Science Foundation of Jiangsu Education Office, China (Grant No. 2010-2-10).

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al.[28] constructed a bipartite producer–consumer network to describe the industrial structure. The edge from consumer to producer represents the choice of the consumer for the final products, and the degree of consumer represents its market share. Sun *et al.*[30] established the energy supply-demand network model; the properties of this supply-demand network are investigated by theoretical analysis, numerical simulation, and empirical analysis.

There are many similarities between the US' and China's coal supply-demand. First, the two country's coal products are mainly supplied for their own needs, unlike such countries as Australia which mainly exports coal. Second, coal needs to be transported due to the unbalanced distribution of coal production and consumption. Third, they are subject to the impact of market supply and demand. Market may cause the "bidirectional preference" between coal supply and coal demand enterprises, and thus, the fittest will survive.

In view of these similarities, we use an energy supply-demand network model to describe the properties and the evolution trends of the coal supply-demand in the US and China .[30] We mainly make a comparative analysis of the following three aspects. First, we compare the empirical results of coal production in the US and the business revenue of China's first top 100 coal enterprises with the numerical results obtained using the established model. Second, we make a comparison of the parameters involved in the models of the coal supply and demand between in the US and in China. Third, we compare the empirical results reflected from the coal supply and demand between in the US and in China. All of three comparisons reveal internal differences and similarities of coal supply and demand in the US and China, indicating that the evolutional situation of China's coal network is close to that of the US.

The remainder of this paper is organized as follows. In Section 2, the evolution model of coal supply-demand network is established. In Section 3, the comparison between numerical results of the model and empirical results is presented. In Section 4, a comparison of coal supply-demand network between in the US and in China is performed. Finally, some conclusions and discussion are presented in Section 5.

2. Coal supply-demand network evolving model

The network consists of two kinds of nodes: supply nodes and demand nodes. The node weight of supply node H is defined as S_i that corresponds to the supply capacity of the supply enterprise, which includes production, price, service, and other factors. The greater the production, the lower the price and the better the quality service of the supply enterprise then the greater the node weight of supply nodes is. The node weight of demand node α is defined as γ that corresponds to the purchasing power of the demand enterprises, which includes demand and credit rank. The greater the demand and the higher the credit rank of the demand enterprise then the greater the node weight of demand nodes is. The edge weight between demand node L_{ij} and supply node R is defined as S_i that corresponds to the transaction cost between demand node α and supply node γ, which includes transportation cost, sales cost, and other factors. The smaller the transaction cost then the greater the edge weight is. m represents the ratio of number of demand nodes to that of supply nodes.

The attachment probability between demand node j and supply node i is determined by

$$\Pi^{(1)}_{j\to i} = \frac{pS_i + (1-p)L_{ij}}{\sum_i [pS_i + (1-p)L_{ij}]},$$

where p and $1-p$ are the weights of the node weight S_i and the edge weight L_{ij}.

The attachment probability between supply node i and demand node j is determined by

$$\Pi^{(2)}_{i\to j} = \frac{qf_j + (1-q)L_{ij}}{\sum_j [qf_j + (1-q)L_{ij}]},$$

where q and $1-q$ are the weights of the node weight f_j and the edge weight L_{ij}.

With time evolution, the node weight S_i, f_j, and edge weight L_{ij} are modified according to the following equations:

$$S_i(t) = S_i(t-1) + \sum_{j=mt-m+1}^{mt} \left[f_j(t) \cdot \Pi^{(1)}_{j\to i}(t) \right], \tag{1}$$

$$f_j(t) = f_j(t-1) + S_i(t) \cdot \Pi^{(2)}_{i\to j}(t), \tag{2}$$

$$L_{ij}(t) = L_{ij}(t-1) + S_i(t) - S_i(t-1) + f_j(t) - f_j(t-1). \tag{3}$$

Here, $\Pi^{(1)}_{j\to i}$ and $\Pi^{(2)}_{i\to j}$ represent the bidirectional preference of coal supply enterprise and coal demand enterprises. With time going by, the weight p value may increase gradually. Then the principle a "larger coal mine has a competitive advantage" is more evident in the market selection. At the same time, the weight q value may decrease gradually; the weight $1-q$ value may increase gradually. Then the principle "a closer power plant has a more competitive advantage" is more evident in the market selection. Equation (1) shows that coal demand enterprises will be more likely to transact with coal supply enterprises with large weight, which makes their supply node weight increase much more and supply capacity become stronger. Equation (2) shows that coal supply enterprises will be more likely to transact with coal demand enterprises with large weight, which makes their demand node weight increase much more and purchasing power become stronger. Equation (3) shows that coal supply enterprises with large weight will be more likely to transact with large weight coal demand enterprises, which makes the edge weight between them increase. This model embodies the idea that two types of nodes

gather around the larger weight node. Large weight supply nodes (big coal mines) are not easy to move; therefore only the large weight demand nodes (big power plants) gather around the large weight supply nodes (big coal mines). (For example the establishment of the pithead power plants.)

The model can well reflect the multiple connection mechanism in the actual coal network. Therefore when one of the coal supply enterprises closes down or encounters other unexpected events, such as temporary adjustment of national policy, changing of the international coal environment, and natural disasters, demand enterprises can buy coal from other suppliers to ensure its stability of supply. However, in an actual coal network, the demand enterprises will transact with those large-scale supply enterprises with lower transaction cost. In fact, from the perspective of the long-term average effects of the model evolution, the network model and the actual coal supply and demand network are the same.

3. Comparison between the numerical results of the model and empirical results

The model is in good agreement with real coal networks in the US and China when the parameters take different values. The numerical results obtained from the model and the empirical results from the US and China are compared.

3.1. The US coal supply-demand network

Based on data from EIA,[31] we obtain the cumulative distribution of the coal enterprises' production H in the US from 1991 to 2010. The abscissa and ordinate coordinates are both double-logarithmic coordinates. The abscissa coordinate indicates the sum of production H_c and the "shifting coefficient" α (unit: 10^4 t); the ordinate coordinate indicates the number of coal enterprises whose production is equal to or more than H_c defined as P. The distribution shows SPL function, namely $P(H) = (H+\alpha)^{-\gamma}$. (Power-law distribution exists widely in our daily life and its significant feature is that the higher the grade, the more uneven the power-law distribution is. It contains a few nodes with a very high degree and many nodes with a low degree. Network presents power-law distribution, which indicates that this network has scale-free feature.[32] Scale-free networks are robust against random failures of nodes but fragile to intentional attacks. Scale-free network is in failure and even paralyzed when high degree nodes or the edge connected to these nodes are destroyed.) The US' coal supply-demand network's empirical results of seven years (1992, 1995, 1999, 2004, 2007, 2009, and 2010) and the numerical results of the model are compared (see Table 1).

From Table 1 we can see that the numerical results obtained from the model are in good agreement with the empirical results in these seven years. The same situation happens to other years. The sixth column of Table 1 shows that the weight p of node weight S_i turns larger with the evolution of time, which indicates that coal demand enterprises' dependence on the node weight increases and their dependence on the edge weight gradually decreases. In the actual US coal network, due to the improvement of rail and other modes of transport with the evolution of time, the unit transportation cost of coal reduces. The establishments of pithead power plants lower the factor of distant influence. So demand enterprises take more into consideration supply capacity (node weight) of supply enterprises. The ratio between the values of number m for the two types of nodes also becomes larger, the "shifting coefficient" α turns smaller, which indicates that the scale-free feature of the network is getting better (as indicated in the seventh and third columns in Table 1).

Table 1. A comparison between the coal network in the US and the numerical results.

Year	Real α/(10^4 t)	Model γ	Real α	Model γ	p	m
1992	50	5	1.62249	1.62897	0.35	3
1995	46	4.6	1.43386	1.42996	0.71	3
1999	42	4.2	1.28717	1.29412	0.75	5
2004	41	4.1	1.20342	1.20892	0.85	6
2007	25	2.5	1.09083	1.08071	0.85	9
2009	22	2.2	1.07381	1.06879	0.85	9
2010	19	1.9	0.90198	0.89898	0.87	9

Notes: The first column is the year in the US coal supply-demand network. The second and fourth columns are the value of the "shifting coefficient" α and the scaling exponent γ in the US coal production cumulative distribution. The third and fifth columns are the value of the "shifting coefficient" α and the scaling exponent γ of the SPL distribution of the supply node weight S_i corresponding to the US coal network. The sixth and seventh columns are the model parameters — the weight p of node weight S_i, and the ratio of two types of nodes number m. The shifting coefficient α in the second column is 10 times the value of model α, which is due to the fact that they are in different units.

We put the statistical parameters of cumulative distribution of coal enterprises' production H in the US from 1991 to 2010 and make the comparison in Fig. 1. The "shifting coefficient" α ranges from 22 to 62 and the scaling exponent γ ranges from 1.0 to 1.7. Coal supply-demand network shows scale-free feature. As the network evolves, its "shifting coefficient" α and the scaling exponent γ show the characteristics of increasing or decreasing simultaneously. But the overall trend is reduced which means that power-law feature of the curve becomes better. This indicates that the market domination of major enterprises is stronger. The leading role of these enterprises is totally a result of market competition.

From Fig. 1 we can see that the "shifting coefficient" α and the scaling exponent γ had minimum and maximum values in 1993 and 1996 respectively. The reason for this phenomenon may be reorganization and expansion of coal enterprises. Peabody Energy Co. is the largest private listed coal enterprise in the US and around the world. In 1990, Hanson PLC jointly established by the US and UK enterprises

acquired the Peabody Energy Co. In 1996, Hanson PLC acquired Peabody Energy Co. and one UK power enterprise and established Energy Group Company, bringing its annual sale revenue to US$ 0.6 billion. Kennecott Energy & Coal Co., a foreign-owned enterprise, is the third coal enterprise in the US. The company, established in 1993, started to purchase large amounts of high quality coal, and became the fifth coal enterprise in the US that year. In the same year it purchased Cordero Mine from Sun Company Inc., and purchased Coronado ore from Drummond Company in 1997. The Coronado Joint is the merger of these two mines.

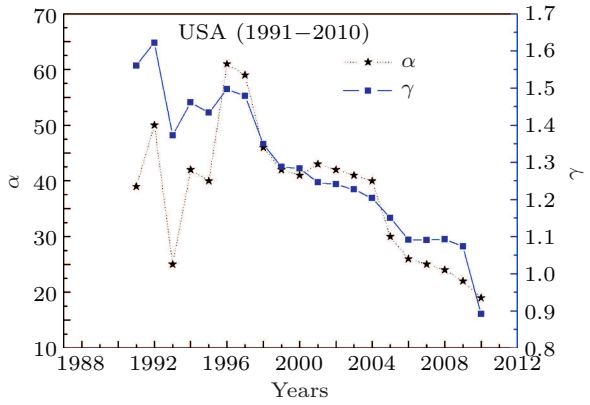


Fig. 1. (color online) "Shifting coefficient" α and scaling exponent γ of the cumulative distribution of the coal production each as a function of the year in the US from 1991 to 2009.

Based on data from EIA, we obtain the frequency distribution of coal transaction volume between US states in 2010. From it, it can be seen that a small trading volume has more frequency (Fig. 2). We also obtain the cumulative distribution of the coal transaction volume between US states in 2010 (see Fig. 3). The abscissa and ordinate are both double-logarithmic coordinates. The abscissa indicates the coal transaction volume L_c (unit: 10^4 t), and the ordinate indicates the number of coal enterprises whose coal transaction volume is equal to or more than L_c defined as P. The smaller the transaction costs between states, the larger the transaction volume is. So the transaction volume here is equivalent to the edge weight in our model. Figure 4 is the numerical results of edge weight L_{ij} corresponding to the US' coal network in 2010. From Figs. 3 and 4 it can be seen that the general directions of the two graphs are the same. To the actual coal supply-demand system, the bidirectional preference for the coal mines (supply nodes) and power plants (demand nodes) will result in two types of nodes gathered around the large weight node. From Figs. 3 and 4, we can see that the anterior half part of the distribution of the edge weight L_{ij} (the edge weight between supply nodes and demand nodes is small) follows a power-law distribution, and the posterior half part (the edge weight between supply nodes and demand nodes is large) is close to the exponential distribution. The reasons are as follows: when the edge weight between coal supply enterprises and coal demand enterprises is small, namely the transaction cost between them is large, it is more preferential to be selected between the two kinds of nodes. When the edge weight between the two kinds of nodes is large, namely the transaction cost between them is small, it is more random to be selected between the two kinds of nodes.

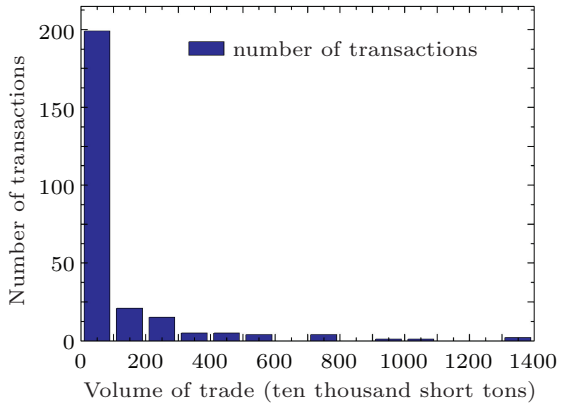


Fig. 2. (color online) Histogram of the transaction volume between states in the US in 2010.

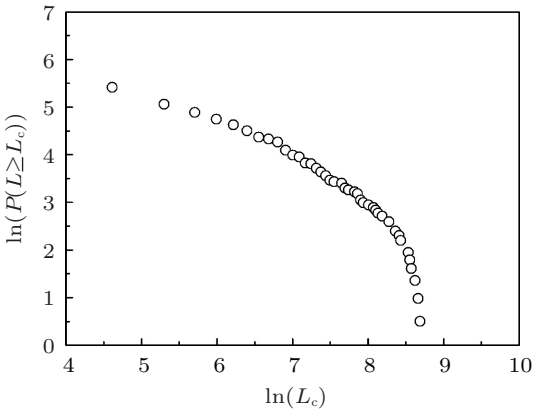


Fig. 3. Cumulative distribution of the transaction volume between states in the US in 2010.

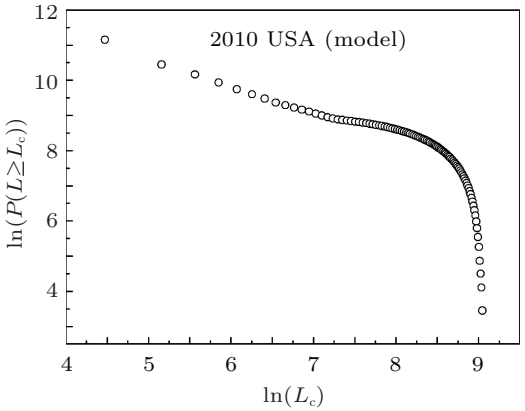


Fig. 4. Numerical results on the distribution of edge weight L_{ij} corresponding to the US' coal network in 2010.

3.2. China's coal supply-demand network

Theoretically, on condition that coal price is stable in the same period of time, coal production and corresponding business revenue should be positively related. Business revenue

has been used for statistical analysis instead of coal production due to failure to collect coal production data in China. Based on data from China State Coal Industry Network,[33] we obtain the cumulative distribution of the first top 100 coal enterprises revenue R of China from 2002 to 2010. To conserve space, we only give the cumulative distribution in 2009 (see Fig. 5). The abscissa and ordinate are both double-logarithmic coordinates. The abscissa indicates the sum of revenue R_c and the "shifting coefficient" α (unit: 10^9 Yuan), and the ordinate indicates the number of coal enterprises whose business revenue is equal to or more than R_c defined as P. Figure 6 shows the numerical results on the SPL distribution of node weight S_i corresponding to China's coal network in 2009. Comparing Fig. 5 with Fig. 6, we can see that the numerical result obtained from the model is in good agreement with the empirical result.

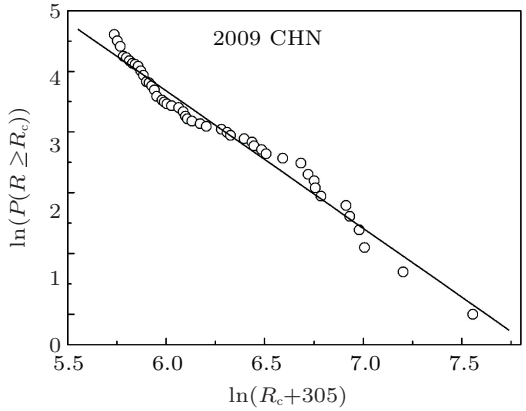


Fig. 5. Empirical results on the cumulative distribution of the coal business revenue R in China in 2009.

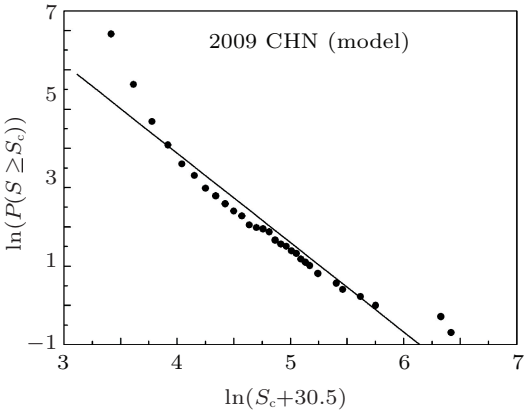


Fig. 6. Numerical results on the SPL distribution of node weight S_i corresponding to China's coal network in 2009.

China's coal supply-demand network's empirical results from 2004 to 2010 and the numerical results of the model are compared (see Table 2).

From Table 2 we can see that the weight p of node weight S_i becomes larger with the evolution of time, which indicates that coal demand enterprises' dependence on the node weight increases and their dependence on the edge weight gradually decreases. The reason is the same as that for the US' actual coal network. The ratio between the values of number m of two types of nodes is a fixed value (as seen in the seventh column in Table 2).

We put together the statistical parameters of cumulative distribution of the first top 100 coal enterprises business revenue R of China from 2002 to 2010 and make the comparison in Fig. 7. China's coal supply-demand network shows considerable randomness. As the network evolves, its "shifting coefficient" α and the scaling exponent γ show the characteristic of increasing or decreasing simultaneously.

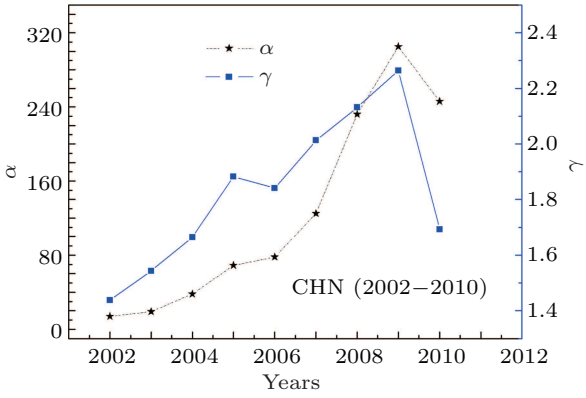


Fig. 7. (color online) "Shifting coefficient" α and scaling exponent γ of cumulative distribution of the coal business revenue each as a function of the year in China from 2002 to 2010.

From Fig. 7 we can put the China's coal network divided into three stages (see Table 3). From Fig. 7 and Table 3 we can see that the "shifting coefficient" α and the scaling exponent γ increased simultaneously before 2009 (the first stage and second stage) and suddenly became smaller in 2010 (the third stage). The reason may be the flooding of small coal mines in China during 2002 to 2009, the order of the coal market is in confusion. At the end of 2009, China made great efforts to

Table 2. A comparison between the data from the coal network in China and the numerical results.

Year	Real α(10^9 Yuan)	Model α	Real γ	Model γ	p	m
2004	35	3.5	1.63193	1.63933	0.2	3
2005	66	6.6	1.85598	1.8652	0.177	3
2006	75	7.5	1.81827	1.81744	0.21	3
2007	127	12.7	2.02453	2.01459	0.2	3
2008	231	23.1	2.1273	2.12925	0.25	3
2009	305	30.5	2.26346	2.27361	0.26	3
2010	246	24.6	1.6934	1.68287	0.67	3

Notes: The meaning of each column is the same as that in Table 1.

Table 3. Three stages of China's coal network.

	Year	Real $\alpha(10^4$ t)	Model α	Model γ	Real γ	p	m
The first stage	2002–2005	34	3.4	1.68951	1.68291	0.4	3
The second stage	2006–2009	198	19.8	2.17631	2.16718	0.5	3
The third stage	2010	246	24.6	1.68287	1.6934	0.67	3

integrate coal resources by closing 1000 small coal mines and reduced the number of mines down to 1.5×10^4. This helped to improve China's coal market concentration, and the scale-free feature of China's coal supply-demand network becomes more prominent, indicating that the network is robust against random failures, so the values of the "shifting coefficient" α and the scaling exponent γ become smaller.

4. Comparison of coal supply-demand network between in the US and in China

The similarity between the US' and China's coal supply-demand network is as follows. From Figs. 1 and 7 we can see that "shifting coefficient" α and scaling exponent γ show the feature of simultaneous increase or decrease as network evolves. From Tables 1 and 2 we can see the weight p of node weight S_i increases as network evolves. These two tables also indicate that the weight p of node weight S_i and the ratio between the values of node number m are important model parameters.

The dissimilarity between the US' and China's coal supply-demand network are as follows. (i) The weight p of node weight S_i in China's coal supply-demand network is smaller than the US' (See Tables 1 and 2), indicating that China's coal demand enterprises depend more on edge weight and less on node weight in the choice of coal supply enterprises than the US'. (ii) The "shifting coefficient" α and the scaling exponent γ in the US' coal supply-demand network are smaller than China's, indicating that the US' coal market is scale-free while China's market shows relative randomness. (iii) The ratio between the values of node number m of two types of nodes in China's coal supply-demand network is smaller than the US', indicating that the number of China's coal supply nodes is big compared with that of its demand nodes, the market concentration of China's coal enterprises is not high. The reasons can be listed as follows. First, coal enterprises in the US have all the ownership of their products, and suffer from less government intervention. China's medium and small coal production enterprises also have non-standard operations and violate the market principles. China's coal market has much government intervention and shows relative randomness. Second, the technical equipment and operation mode of China's coal rail transport are slightly behind the US', therefore China's coal demand enterprises depend more on distance in the choice of coal supply enterprises than the US'. Third, the number of China's pithead power plants is less than that of the US', which also makes distance greatly influence the development of China's coal industry.

From empirical analysis (see Figs. 1 and 7) we can see that the "shifting coefficient" α and the scaling exponent γ increase simultaneously during 1993–1995 in the US and during 2002–2009 in China, while decrease simultaneously after 1995 in the US and after 2010 in China. From 1993 to 1995, the coal market structure in the US is competitive, later shifting from a competitive type to an oligopolistic one. From 2002 to 2009, China coal market shows relative randomness. After 2010, China's coal market gradually transforms to oligopolistic one due to the restructuring of the small coal mines and the establishment of enterprise groups. The scale-free feature of China's coal supply-demand network becomes more prominent, indicating that the network is robust against random failures.

From model analysis (see Tables 1 and 3) we can see that the weight p and m in the model corresponding to China's coal network in 2010 are close to the US' in 1995. The model results are in good agreement with the empirical analysis, indicating that the evolutional situation of the model corresponding to the US after 1995 is the evolution trend of China's coal network after 2010. The US' management of their coal market after 1995 has a guiding significance to China's present and the next stage's policy formulation.

5. Conclusions and suggestions

In this paper, the properties of coal supply-demand market in the US and China are investigated based on energy supply-demand network. Numerical results obtained from the model are in good agreement with empirical results of the US' and China's coal supply-demand network, indicating the validity of our model. The comparison of model parameter of coal network between in the US and in China reveals the essence of internal differences and similarities of coal supply and demand in these two countries. From the comparison of empirical result and the comparison of model parameter of coal network between in the US and in China, we can see that the evolution trend of China's coal network is close to that of the US' coal network. The evolution trend of the model can well predict the future coal supply-demand in China. The coal supply-demand network proposed in this paper has universal application to resource supply-demand network.

Through the comparison of coal supply-demand network between in the US and in China, some suggestions are provided here for China's coal supply-demand.

i) Perfect the competition mechanism of China's coal market, promoting China's coal market to shift from a random type to an oligopolistic one. It is suggested that the Chinese government should withdraw from direct market intervention as possible as it can and reduce its direct interference in the production and operation activities of entities. It should take on the role of market referee, further loosen price controls, perfect the competition mechanism of China's coal market, allow necessary capital concentration in a reasonable way, and speed up the construction of large-scale coal enterprises (or enterprise groups). In doing so, there will appear the coexistence of the market pattern with a relatively small number of large coal enterprises (or enterprise group) as the main body and a large number of small and medium-sized ones.

ii) Enhance the competitiveness of China's coal enterprises. It is suggested that Chinese government formulates relevant policies and incentive measures. Planning and distribution scientifically should be formulated so as to allow China's coal enterprises to utilize scale superiority and quality assets to improve their competitiveness in the domestic and overseas market.

iii) Improve the transport capacity of coal rails. The construction of coal rails needs to be accelerated and transport capacity needs to be improved in the future to ensure the stability of coal supply. The southern coastal provinces with less or no coal reserves are encouraged to import coal and the layout of coal freight terminal ports needs to be rationalized. The storage capacity of coastal ports is expected to be improved to facilitate the coal transport.

iv) Encourage the construction of pithead power plants. The government should encourage coal enterprises and power enterprises to jointly build pithead power plants to shift from coal transportation to power transportation and cut down the cost of coal transportation. Due to geographical differences between coal distribution and power consumption, electricity supply is largely restricted by coal transportation. However, China's railway currently fails to meet the needs of coal transportation. Joint construction of pithead power plants can be more economical. When China establishes the pithead power plants, the environmental factor, the condition of exhausted coal resource, and the influence of diversified coal energy should be taken into consideration, through adopting different running strategies, choosing new power plant site reasonably and installing environmental clean device to ensure the competitiveness of pithead power plants.

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