Evaluation research on the circular economy efficiency of the coal industry based on DEA model

The coal industry plays a very important role in the process of economic development in China. The efficient operation of the coal industry chain is the important foundation for the development of coal circular economy. In this paper, we mainly discuss the three types of coal industry chains, and establish a model to measure the efficiency of the coal industry chain based on the DEA theory. Then by using the coal industry data from 28 provinces and cities nationwide during 2012-2015, we measure the efficiency of the coal industry chain in China. The results show that the efficiency of the national coal industry chain during 2012-2015 was on steady increase, and that the pure technical efficiency is the main factor affecting the efficiency of the coal industry chain in China.

Keywords: *Coal industry, circular economy, DEA model, efficiency evaluation.*

1. Introduction

Coal is the most basic energy, and the coal industry plays a very important role in the economic development process in China. However, in the coal mining process, the large quantity of wastes generated has brought a lot of negative impact on the resources and the environment (Yuan et al., 2010). Circular economy is an environmental-friendly economic development model (Geng et al., 2012) and an important approach to enhance the comprehensive development of industry chains (Li and Ma, 2015). Therefore, many industry chains consider circular economy as the guide (Song, 2008). In the coal industry, developing circular economy and establishing a coal industry chain are of great significance to promoting the rational development and effective utilization of coal resources as well as relieving the tension in energy consumption in China. Therefore, developing circular economy in the coal industry is an important step towards the achievement of a resource-saving society in China.

Mr. Dongfeng Yi, School of Civil & Environment Engineering, University of Science and Technology Beijing, Beijing 100 083 and School of Business Administration, Shandong Institute of Business and Technology, Yantai 264 005, China. E-mail: ydfbkd@163.com

2. Theories and methods of industry chain efficiency measurements

(1) Basic theory of DEA

The basic theory of DEA was established by Charnes and Cooper in the early 1970s. It is a method and tool to study the relative effectiveness between departments of the same type (Hu et al., 2011; Ma et al., 2014). Each department or unit is called a decision making unit (DMU). The efficiency of DMU refers to the output-input ratio. The input and output of DMU can be regarded as the input and output indicators in the DEA model, respectively (Abu-Ghunmi et al., 2016). In this research, the efficiency of the industry chain is the corresponding output-input ratio of DMU.

The earliest model of DEA is the C^2R model (Elia et al., 2016). Suppose there are n DMUs and in each DMU there are m inputs and s outputs. $x_j = (x_{1j}, x_{2j}..., x_{mj})^T$ is the input vector, $y_j = (y_{1j}, y_{2j}..., y_{sj})^T$ is the output vector, and the ratio between output and input is the efficiency. Through the Charnes-Cooper and dual transformations, and by introducing the slack variable s^- and the surplus variable s^+, we establish the following linear programme:

$$min\left[\theta - \varepsilon\left(\hat{e}^T s^- + e^T s^+\right)\right]$$

$$s.t.\begin{cases} \sum_{j=1}^{n} x_j \lambda_j + s^- = \theta x_0, \\ \sum_{j=1}^{n} y_j \lambda_j - s^+ = y_0, \\ \lambda_j \geq 0,\ j = 1,2,...,n, \\ s^- \geq 0, s^+ \geq 0. \end{cases} \quad ... \quad (1)$$

where, $\hat{e}^T = (1,1,...,1) \in E^m$ and $e^T = (1,1,...,1) \in E^s$, ε is the non-archimedean infinitesimal; λ is the coefficient of the linear combination of DMU; and θ is the effective value of the decision making unit.

The prerequisite for the C^2R model is that the returns to scale remain constant, but in the course of business, the returns to scale are constantly changing. Therefore, Cooper et al. proposed an improved model – the BC^2 model (Li et al., 2010; Mathews and Tan, 2011), which adds the condition $\sum_{j=1}^{n} \lambda_j = 1$ on the basis of the C^2R model to make the economies of scale of production change and break the comprehensive efficiency down into pure technical efficiency and scale efficiency. The BC^2 model is as follows:

$$\min\theta$$

$$s.t.\begin{cases}\sum_{j=1}^{n} x_j\lambda_j + s^- = \theta x_0, \\ \sum_{j=1}^{n} y_j\lambda_j - s^+ = y_0, \\ \sum_{j=1}^{n}\lambda_j = 1, \\ s^- \geq 0, s^+ \geq 0, \lambda_j \geq 0,\ j = 1,2,\ldots,n. \end{cases} \quad \ldots \quad (2)$$

In this research, the use process of the DEA theory is shown in Fig.1.

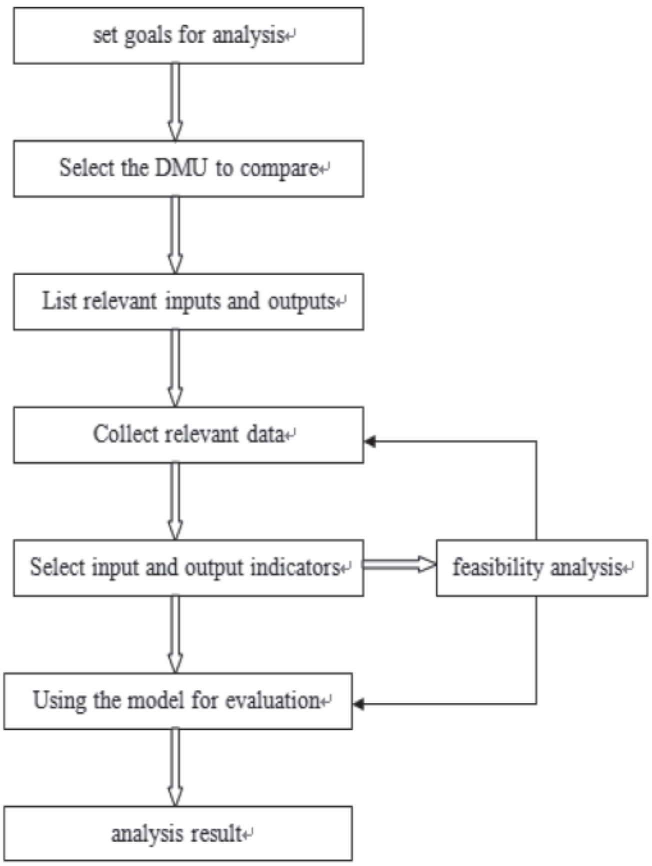

Fig.1 The use process of DEA

(2) Basic framework of the industry chain efficiency evaluation

In order to determine an appropriate DMU, we need to decompose the industry chain. In this paper, we decompose it spatially. We take the industry chain in each area as the decision making unit (DMU) and then virtualize a DMU, whose input-output ratio is the arithmetic mean value of those of DMUs, that is, $\bar{I} = \sum_{j=1}^{n}\frac{I_j}{n}$ and $\bar{U} = \sum_{j=1}^{n}\frac{U_j}{n}$, and then the industry chain efficiency is:

$$PE = \max\{\theta : (\bar{I}, \bar{U}\cdot\theta) \in T\}$$
$$(T \text{ is the production possibility set}) \quad \ldots \quad (3)$$

In this paper, we introduce the shadow price of product (i.e. increment in the relative efficiency of DMU resulting from each additional unit of input and output), which is decomposed according to the principle of the DEA model (Geng and Zhang, 2013).

The first is pure technical efficiency, which is the comparison between the actual output value and the optimal value (or maximum output) of each DMU based on the existing input-output structure when the input remains constant (Li, 2006; Feng and Yan, 2007). The formula is as follows:

$$PTE = \frac{\sum_{j=1}^{n}(\dot{p} - U_j)}{U\cdot p} = \sum_{j=1}^{n}\frac{\dot{p}\cdot PTE_j\cdot U_j}{p\cdot U} =$$
$$\sum_{j=1}^{n}\left(\frac{\dot{p}\cdot U_j}{p\cdot U}\cdot PTE_j\right) \quad \ldots \quad (4)$$

where, $U = \sum_{j=1}^{n} U_j$ is the total output of the industry chain; U_j is the actual output of each DMU. $\dot{p}$ and p are the shadow prices of the actual output of each DMU and the total output of the industry chain.

When only one output indicator is selected:

$$PTE = \sum_{j=1}^{n}\left(\frac{U_j}{U}\cdot PTE_j\right) \quad \ldots \quad (5)$$

The second is the production structure efficiency, which is the ratio between the maximum output of each DMU under the relatively optimal production structure and that under the current production structure, i.e. the comparison between the projection point of the output of each DMU in the CRS model and that in the VRS model (CRS is the production frontier when the returns to scale are constant, i.e. the production frontier at the optimal production scale, and VRS is the frontier of the production when the returns to scale are variable) (Geng et al., 2013). The formula is as follows:

$$PSE = \frac{\sum_{j=1}^{n} PE_j\cdot U_j\cdot\dot{p}}{\sum_{j=1}^{n} p\cdot(PTE_j\cdot U_j)} = \frac{\sum_{j=1}^{n} PSE_j\cdot\dot{U}_j\cdot\dot{p}}{\sum_{j=1}^{n}(p\cdot\dot{U}_j)}$$
$$= \sum_{j=1}^{n}\left(\frac{\dot{p}\cdot\dot{U}_j}{p\cdot\dot{U}}\cdot PSE_j\right) \quad \ldots \quad (6)$$

where, $\dot{U} = \sum_{j=1}^{n}\dot{U}_j$, $\dot{U}_j$ is the target output of each DMU in the variable returns to scale model (VRS model).

When only one output indicator is selected:

$$PSE = \sum_{j=1}^{n}\left(\frac{\dot{U}_j}{\dot{U}}\cdot PSE_j\right) \quad \ldots \quad (7)$$

The third is the scale efficiency, which is the ratio between the output of each DMU at the optimal combination efficiency and the weighted value of the optimal output of individual DMUs. The formula is as follows:

$$PRE = \frac{PE \cdot U \cdot \dot{p}}{\sum_{j=1}^{n} PE_j \cdot U_j \cdot p} = \frac{PE \dfrac{\sum_{j=1}^{n} \dot{p} \cdot PTE_j \cdot U_j}{PTE}}{PSE \cdot \sum_{j=1}^{n} p \cdot \left(PTE_j \cdot U_j\right)} \quad \ldots \quad (8)$$

By substituting the above formulas into the previous one, we obtain:

$$PE = PSE \cdot PRE \cdot PTE \quad \ldots \quad (9)$$

So the industry chain efficiency is the product of pure technical efficiency (PTE), production structure efficiency (PSE) and scale efficiency (PRE).

3. Measurement and analysis of the coal industry chain efficiency in China

(1) Basic types of coal industry chains

The first is the coal-electricity industry chain. This industry chain mainly uses the poor-quality coal to generate electricity, which effectively reduces the emissions of harmful substances. It is an effective way of clean utilization of coal, which improves both coal use efficiency and environmental benefits and can achieve the sustainable development of coal enterprises and power generation enterprises. The specific process chart is shown in Fig.2.

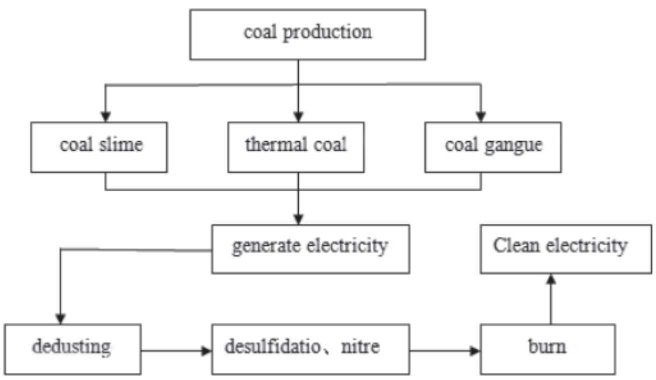

Fig.2 Coal-electricity industry chain

The second is the coal-liquefaction (gasification) industry chain. Coal gasification and liquefaction are advanced clean coal production approaches that can effectively reduce environmental pollution. Coal gasification and liquefaction have great development prospects and are in line with the requirements for development of circular economy in the coal industry, so these are the main development trends of the coal industry in the future. The structure is shown in Fig.3.

The third is the coal-electricity-high energy consumption (high power consumption) industry chain. The coal industry

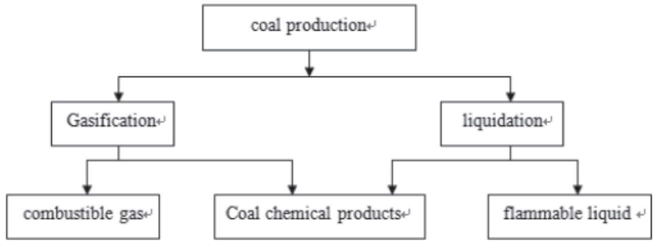

Fig.3 Coal-liquefaction (gasification) industry chain

can effectively coordinate with some other industries with high energy consumption (high power consumption) and form industry chains. For example, it can form a coal - electricity - metallurgy industry chain with the metallurgy industry. Take a company producing electrolytic aluminum for example. The specific industry chain structure is shown in Fig.4, which builds the coal - electricity - aluminum industry chain into representative enterprises in the circular economy industry.

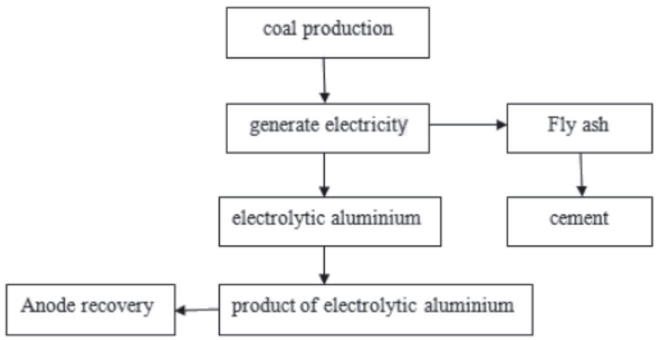

Fig.4 Coal-electricity-aluminum industry chain

(2) Construction of the efficiency evaluation indicator system for the coal industry chain

Under normal circumstances, the inputs of an enterprise in production mainly include human, material and financial resources and the outputs are mainly goods or services. In this research, we select labour and capital as the input indicators. For the labour indicator, we use the number of employees in the industry chain ring in each province, and for the capital indicator, we adopt the total assets and the cost of sales in the industrial chain ring in each province. For the output indicator, we use the sales revenue (Table 1).

(3) Sample selection, measurement and evaluation

In this paper, we group the industrial data of coal enterprises by province or municipality and use them as the research object. We select the data from 28 provinces or municipalities as the samples; in other words, in this paper, we evaluate 28 DMUs, namely DMU_1, DMU_2, ……DMU_{28}, in the evaluation process to represent and reflect the operation status of the coal industry. The data of the indicators are mainly from the development data of relevant industries in the coal industry chains in each province or region during the period of 2012-2015 listed in China Industrial Economic

Table 1: Evaluation on the efficiency of the coal industry chain

	Total assets
Input indicators	Cost of sales
	Number of workers
Output indicators	Sales revenue

Table 2: Efficiency evaluation results of the coal industry chain in 2012

	Region	Comprehensive economic efficiency	Technical efficiency	Scale efficiency
1	Bei Jing	1.000	1.000	1.000
2	Tian Jin	1.000	1.000	1.000
3	He Bei	0.744	0.978	0.782
4	Shan Xi	0.624	0.992	0.675
5	Nei Meng-gu	0.601	0.874	0.703
6	Liao Ning	0.812	0.998	0.802
7	Ji Lin	0.803	0.892	0.935
8	Hei Long-jiang	0.689	0.921	0.803
9	Jiang Su	0.702	0.845	0.853
10	Zhe Jiang	0.851	0.901	0.971
11	An Hui	0.743	0.962	0.783
12	Fu Jian	0.698	0.695	0.986
13	Jiang Xi	0.761	0.841	0.903
14	Shan Dong	0.684	0.992	0.704
15	He Nan	0.719	1.000	0.763
16	Hu Bei	0.719	0.768	0.972
17	Hu Nan	0.824	0.962	0.865
18	Guang Dong	0.302	0.995	0.301
19	Guang Xi	0.801	0.803	0.973
20	Chong Qing	0.783	0.852	0.926
21	Si Chuan	0.783	0.971	0.802
22	Gui Zhou	0.743	0.872	0.874
23	Yun Nan	0.752	0.749	0.998
24	Shan Xi	0.675	0.814	0.792
25	Gan Su	0.596	0.626	0.996
26	Qing Hai	0.702	0.952	0.792
27	Ning Xia	0.759	0.893	0.897
28	Xin Jiang	0.701	0.704	0.975

Comprehensive rating: PE = 0.679; PTE = 0.946; PSE = 0.763; PRE = 0.943

Statistical Yearbook. We use the software DEAP2.1 to measure the efficiency of the coal industry chain and the detailed evaluation results are listed in Tables 2-5.

Based on the calculation results of the coal industry chain efficiency in 28 provinces or municipalities from 2012 to 2015, we obtain the trend chart of various industry chain efficiency indicators, as shown in Fig.5.

By analyzing the efficiency of the coal industry chains in 28 provinces or municipalities in China from 2012 to 2015, we can see that:

Table 3: Efficiency evaluation results of the coal industry chain in 2013

	Region	Comprehensive economic efficiency	Technical efficiency	Scale efficiency
1	Bei Jing	1.000	1.000	1.000
2	Tian Jin	1.000	1.000	1.000
3	He Bei	0.852	0.872	0.982
4	Shan Xi	0.964	0.999	0.941
5	Nei Meng-gu	0.998	0.996	0.998
6	Liao Ning	0.863	0.825	0.997
7	Ji Lin	0.782	0.804	1.000
8	Hei Long-jiang	0.802	0.799	0.993
9	Jiang Su	0.851	0.841	0.982
10	Zhe Jiang	0.835	0.998	0.834
11	An Hui	0.842	0.842	0.982
12	Fu Jian	0.998	1.000	0.996
13	Jiang Xi	0.895	0.893	0.991
14	Shan Dong	0.941	0.999	0.934
15	He Nan	0.923	1.000	0.915
16	Hu Bei	0.894	0.975	0.925
17	Hu Nan	0.988	1.000	0.984
18	Guang Dong	0.998	0.998	1.000
19	Guang Xi	0.841	0.925	0.902
20	Chong Qing	0.902	0.917	0.984
21	Si Chuan	0.903	0.952	0.952
22	Gui Zhou	0.897	0.886	0.962
23	Yun Nan	0.841	0.843	1.000
24	Shan Xi	0.972	0.983	1.000
25	Gan Su	0.904	0.981	0.989
26	Qing Hai	0.907	1.000	0.901
27	Ning Xia	0.843	0.828	0.994
28	Xin Jiang	0.946	0.956	1.000

Comprehensive rating: PE = 0.912; PTE = 0.973; PSE = 0.994; PRE = 0.962

Firstly, from the changes in the efficiency of the industry chain in all these years, the efficiency is on a slow growing trend. In 2012, the efficiency was low – only 67.9%; in 2015, the efficiency rose to 93.4%, because in recent years, China has been promoting the marketization of coal and helped maintain the supply and demand balance in the coal market.

Secondly, the technical efficiency is the main factor affecting the efficiency of the coal industry chain. Take 2015 for example. In this year, the efficiency of the coal industry chain in China was 93.4%, indicating that the output could be increased by 6.6% with the same input. The PTE was 95.6%, the PSE was 99.8% and the PRE was 98.2%, showing that with the input remaining the same, improving the technology level can increase the output by 4.4% and adjusting the structure and the allocation of factors can increase the output by 0.2% and 1.8%, respectively. Therefore, PTE has greater impact on the efficiency of the coal

TABLE 4: EFFICIENCY EVALUATION RESULTS OF THE COAL INDUSTRY CHAIN IN 2014

	Region	Comprehensive economic efficiency	Technical efficiency	Scale efficiency
1	Bei Jing	1.000	1.000	1.000
2	Tian Jin	1.000	1.000	1.000
3	He Bei	0.831	0.901	0.934
4	Shan Xi	0.856	0.998	0.872
5	Nei Meng-gu	0.998	0.999	0.999
6	Liao Ning	0.756	0.768	1.000
7	Ji Lin	0.769	0.723	0.992
8	Hei Long-jiang	0.762	0.765	1.000
9	Jiang Su	0.203	0.205	0.982
10	Zhe Jiang	0.803	1.000	0.802
11	An Hui	0.698	0.769	0.985
12	Fu Jian	0.221	0.235	0.721
13	Jiang Xi	0.901	0.901	0.996
14	Shan Dong	0.927	1.000	0.934
15	He Nan	0.889	1.000	0.903
16	Hu Bei	0.868	0.918	0.928
17	Hu Nan	0.998	0.998	1.000
18	Guang Dong	0.692	1.000	0.698
19	Guang Xi	0.697	0.895	0.841
20	Chong Qing	0.802	0.802	1.000
21	Si Chuan	0.874	0.971	0.942
22	Gui Zhou	0.897	0.866	1.000
23	Yun Nan	0.871	0.847	0.998
24	Shan Xi	0.998	0.998	0.998
25	Gan Su	0.847	0.849	0.989
26	Qing Hai	0.859	1.000	0.895
27	Ning Xia	0.721	0.703	0.982
28	Xin Jiang	0.795	0.785	0.979

Comprehensive rating: PE = 0.923; PTE = 0.969; PSE = 0.982; PRE = 0.969

TABLE 5: EFFICIENCY EVALUATION RESULTS OF THE COAL INDUSTRY CHAIN IN 2015

	Region	Comprehensive economic efficiency	Technical efficiency	Scale efficiency
1	Bei Jing	1.000	1.000	1.000
2	Tian Jin	1.000	1.000	1.000
3	He Bei	0.876	0.952	0.901
4	Shan Xi	0.802	1.000	0.804
5	Nei Meng-gu	0.974	0.998	0.987
6	Liao Ning	0.702	0.702	0.991
7	Ji Lin	0.803	0.791	0.998
8	Hei Long-jiang	0.754	0.762	0.993
9	Jiang Su	0.782	0.798	1.000
10	Zhe Jiang	0.798	1.000	0.783
11	An Hui	0.769	0.784	0.974
12	Fu Jian	1.000	0.999	0.999
13	Jiang Xi	0.901	0.901	0.984
14	Shan Dong	0.998	0.999	0.999
15	He Nan	0.854	1.000	0.846
16	Hu Bei	0.820	0.894	0.975
17	Hu Nan	1.000	0.999	0.999
18	Guang Dong	0.809	1.000	0.804
19	Guang Xi	0.779	0.903	0.795
20	Chong Qing	0.852	0.888	0.989
21	Si Chuan	0.934	1.000	0.926
22	Gui Zhou	0.893	0.869	1.000
23	Yun Nan	0.814	0.827	1.000
24	Shan Xi	0.999	0.998	0.997
25	Gan Su	0.798	0.798	1.000
26	Qing Hai	1.000	1.000	1.000
27	Ning Xia	0.698	0.703	0.979
28	Xin Jiang	0.674	0.704	0.991

Comprehensive rating: PE = 0.934; PTE = 0.956; PSE = 0.998; PRE = 0.982

industry chain. In the coal industry chains in 28 provinces and municipalities, the efficiency the eastern region was the highest, followed by that in the central and western regions. In the western provinces and autonomous regions, Xinjiang with high coal production had the lowest PTE mainly because the coal industry chain there is incomplete and the coal resources are scattered, and the geographic environment is harsh, making it very difficult to develop coal. Shanxi Province had the highest PTE, but the overall efficiency was low, mainly because the PRE was low. Beijing and Shandong had high PTE, mainly because these areas have complete coal industry chain structures and have accumulated advanced technologies. In Zhejiang, the biggest coal consumer in China, PTE was relatively high, mainly because in this region, the technology level is advanced.

Thirdly, in terms of PSE in all these years, PSE in 2012 was the lowest – 76.3%, but from 2013 to 2015, it was at a high level – above 90%. The coal industry in China is now in the rapid development stage. As resources are limited, in order to maintain the stability of the domestic coal market, China has imposed certain control over the output and price of coal to form a rational output structure.

Fourthly, in terms of PRE in all these years, during 2012-2015, the PRE of the industry chain was always at a high level and did not change much. At present, the layout of the coal industry chain in China is rational, which improves the utilization efficiency of coal resources.

4. Conclusions

(1) The coal industry plays a very important role in the economic development process in China. The efficient operation of the coal industry chain is the important foundation for the development of coal circular economy. There are three types of coal industry chains, namely coal-

electricity industry chain, coal-liquefaction (gasification) industry chain and coal-electricity-high energy consumption (high power consumption) industry chain.

(2) In this paper, we establish a model to measure the efficiency of the coal industry chain based on the DEA theory. Then by using the coal industry data from 28 provinces and cities nationwide during 2012-2015, we measure the efficiency of the coal industry chain in China. The results show that the efficiency of the national coal industry chain during 2012 -2015 was on slow and steady increase, and that the pure technical efficiency is the main factor affecting the efficiency of the coal industry chain in China.

References

1. Abu-Ghunmi, D., Abu-Ghunmi, L., Kayal, B. and Bino, A. (2016): "Circular economy and the opportunity cost of not 'closing the loop' of water industry: the case of Jordan." *Journal of Cleaner Production*, Vol. 131, pp. 228-236.
2. Song, F. (2008): "Promotion of circular economic by law to realize sustainable development." *Annals of the New York Academy of Sciences*, Vol. 452, No. 1, pp. 67-78.
3. Yuan, F., Li, Z. and Li, C. (2010): "Analysis of and countermeasures for coal circular economy developing model in china." *Bioresource Technology*, Vol. 101, No. 14, pp. 5633-5637.
4. Li, H. M. (2006): "The development of circular economy in China." *Aquatic Ecosystem Health & Management*, Vol. 9, No. 1, pp. 99-103.
5. Mathews, J. A. and Tan, H. (2011): "Progress toward a circular economy in China." *Journal of Industrial Ecology*, Vol. 15, No. 3, pp. 435-457.
6. Hu, J., Xiao, Z., Zhou, R., Deng, W., Wang, M. and Ma, S. (2011): "Ecological utilization of leather tannery waste with circular economy model." *Journal of Cleaner Production*, Vol. 19, No. 2-3, pp. 221-228.
7. Ma, S. H., Wen, Z. G., Chen, J. N. and Wen, Z. C. (2014): "Mode of circular economy in china's iron and steel industry: a case study in wu'an city." *Journal of Cleaner Production*, Vol. 64, No. 1, pp. 505-512.
8. Elia, V., Gnoni, M. G. and Tornese, F. (2016): "Measuring circular economy strategies through index methods: a critical analysis." *Journal of Cleaner Production*.
9. Li, W., Xie, W. L., Wang, Y. and Sun, D. P. (2010): "Circular economy analysis in planning environmental impact assessment." *Environmental Science & Technology*, Vol. 33, No. 1, pp. 178-182.
10. Geng, Y., Fu, J., Sarkis, J. and Xue, B. (2012): "Towards a national circular economy indicator system in china: an evaluation and critical analysis." *Journal of Cleaner Production*, Vol. 23, No. 1, pp. 216-224.
11. Geng, Y., Sarkis, J., Ulgiati, S. and Zhang, P. (2013): "Environment and development. measuring China's circular economy." *Science*, Vol. 339, No. 6127, pp. 1526-7.
12. Geng, Y. and Zhang, P. (2013): "Measuring china's circular economy." *Science*, Vol. 339, No. 6127, pp. 1526-1527.
13. Li, Y. and Ma, C. (2015): "Circular economy of a papermaking park in china: a case study." *Journal of Cleaner Production*, Vol. 92, pp. 65-74.
14. Feng, Z. and Yan, N. (2007): "Putting a circular economy into practice in China." *Sustainability Science*, Vol. 2, No. 1, pp. 95-101.