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The Development and Improvement of the Coal Chemical Circular Economy System in China: a Case Study

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Abstract. Circular economy plays an essential and useful role in China in considering economic and ecological sustainability. Individual firms, as the primary implements of a circular economy, are facing many obstacles particularly regarding the resource efficiency. The study presents an analytical method to help decision makers better solve these problems and to guide resource-based chemical industries in sustainable development. First, this study describes the SFA of a selected coal chemistry firm and identifies the roles and correlations among relevant modules. Furthermore, by applying economic benefit assessment, key potential opportunities for improvement were identified. The results demonstrate that the economic benefit of coal chemical products presents a cascade as methanol > wash oil and asphalt blending component > crude benzene > thermal power product > coke. For the goal of improving resource efficiency of the whole system, materials shall flow to the product categories with high resource benefits. Thus, expanding the production capacity of methanol to make full use of the coke oven gas and establishing a utilization module of coal ash in consistence with the market needs can lead to a more sustainable system for the target company. The method proposed in this paper can be applied, duplicated, and spread not only within the coal chemical industry but also in other resource-based chemical industries.

1. Introduction

China's extraction of resources is increasing dramatically. In response to resource constraints, population pressure and widespread environmental damage from the current development pattern, China implemented the strictest environment and resource strategies, which pose great pressure upon traditional industrial sectors. The coal chemical industry has been regarded as one of the biggest energy and resource consumer, as well as major pollution emitter. Hence, it is more important than ever for relevant firms and companies to seek a more sustainable development path.

BTL Company is a large-scale coal chemical enterprise including coal mining, raw coal washing and dressing, coking, coke-oven gas-to-methanol, coal tar hydrogenation (trial production stage), coke dry quenching, and heating. Since its establishment in 2003, BTL has endeavored to implement circular economy. The raw coal mined can be used to produce metallurgical coke, coal chemical products and building materials after deep processing and can also be used to generate power and heat; and an industrial chain of coal - coke - chemical - power - heat - building materials, etc. has been established, which is presented by Figure 1

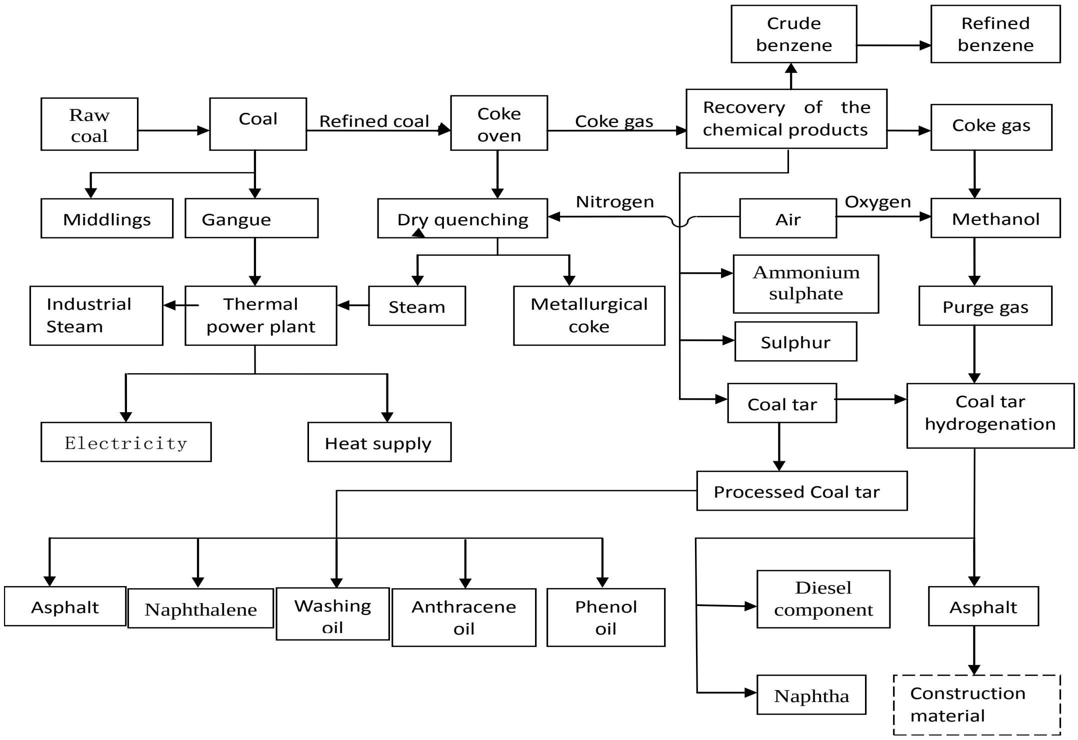

Figure 1. The coal chemical circular economy system illustration

In order to extend the coal-chemical industrial chain to pursue the highest profit, BTL not only increases the added values of the products but also tries to realize the efficient utilization of resources and energy as well as the reduction of emission [1]. In BTL, the raw coal produced from the mine is transported to the plant. Refined coal separated by 4 mt/a dressing plant is fed in 1.58 mt/a coke oven to produce high-quality metallurgical coke which would be supplied to Fushun Steel Company and other plants. By-products of coking including crude benzene, ammonium sulphate, coal tar, coke oven gas are either used onsite or sold to other users. The nitrogen, a by-product produced by air separation of methanol-oxygen, is recovered and used as the nitrogen source for coke dry quenching (CDQ). The waste heat of CDQ and by-products of coal dressing, namely the coal gangues, are used for power generation (CHP). Part of the power generated was self-used, while the rest was connected to the grid. The industrial steam produced by thermal power plant is used for production of the plant and the waste heat is provided for the nearby residence. Through the coal tar hydrogenation process, gasoline, diesel components and asphalt are produced. As for the 300,000 t/a coal tar deep processing project, main products include phenol oil, industrial naphthalene, wash oil, anthracene oil with the by-product of asphalt which is further used as the raw material for the production of needle coke. The wastewater, flue gas and solid wastes generated from the above-mentioned processes are collected together. The wastewater is treated in a comprehensive wastewater treatment system with a processing capacity of 100m^3/h and reused as the supplemental water for quenching and washing processes, so as to achieve the “zero emission" state.

In 2012 and 2013, BTL realized the energy conservation of 10,532 tce and 11,923 tce, respectively. In comparison with other coal chemical plants both domestic and international in terms of energy and resource efficiency, the comprehensive energy consumption and the fresh water usage for per unit product, the utilization rate of coke oven gas, and the water recycling rate in BTL all have reached state-of-the-art level.

In such a complex system as coal chemistry, the material flow, energy flow, and value flow are deeply correlated and mutual relied. The system can only operate smoothly and efficiently when a well-functioned symbiotic relationship is formed. The present research studied the circular economy system of BTL by adopting the industrial metabolism methodology. The coal flow throughout the

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system was analyzed with the association of the economic profits. Some advices were given on basis of the study to improve the current system. The authors believe both the analytical methodology and the conclusion can provide some insights for the establishment and optimization of similar circular economy systems.

2. Research Method

The traditional ecology is the science that studies the relationship between biology and environment. With more and more frequent industrial activities of human beings (mainly the industry) and the ever-increasing impacts on natural systems, the original thought of industrial ecology was formed at the end of 80s. The biological metabolism processes as well as the structure and function units in ecosystem were started to compare and use as analogies to industrial activities. The concept of "industrial metabolism" was first proposed by Robert A Frosch to refer to the use of metabolic process of organisms to simulate the modern industrial production which converts raw materials, energy and labor into products and wastes. N.E.Gallopoulos, et al. then put forward the concepts of "Industrial Ecosystem" and "Industrial Ecology" from the point of view of ecosystem. In 1991, the National Academy of Sciences of the USA and the Bell Labs jointly organized the world's first "Industrial Ecology" forum, which comprehensively and systematically summarized the concept, content, method and application prospects of industrial ecology. The conceptual framework of industrial ecology was basically formed. According to the research carried out by Bell Labs, the industrial ecology is "an interdisciplinary study that identified the relationships among various industrial activities and products with the circumstantial environments" [9].

Industrial metabolism focuses on the simulation and analysis of the material flow and energy flow in the industrial system. Analogic to the natural ecosystem, the industrial ecosystem shall also contain 3 basic components, namely producer, consumer, and decomposer (as shown in Table 1). The metabolic mechanism and cybernetics of industrial ecosystem are studied by analyzing the changes of system structure, functional simulation and analysis of substance flow. The commonly used methods are "supply chain" network analysis (similar to the "food chain network") and material balance accounting [10].

Table 1. Comparison of Components of Industrial and Natural Ecosystems

Component	Natural Ecosystem	Industrial Ecosystem
Producer	Utilizing solar energy or chemical energy to turn inorganic matters into organic matters or converting solar energy into chemical energy to meet their own growth and development needs and provide food and energy for other species (including human beings) at the same time, such as green plants, algae, and chemoautotrophs.	Primary: utilizing basic environment factors (air, water, soil, rocks, minerals and other natural resources) to produce primary products, such as mining plants, and smelters. Senior: deep processing of primary products and production of senior products, such as chemical, fertilizer manufacturing, clothing, food processing, machinery and electronics industries.

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Table 2. Comparison of Components of Industrial and Natural Ecosystems (Cont.)

Consumer	Utilizing organic matters and energy supplied by the producers for growth and development as well as secondary production of organic matters and production of metabolites for the use of decomposers, such as animals (herbivorous animals, carnivorous animals, etc.) and human beings.	Utilizing raw materials provided by producers for their own operation and development, while producing productivity, products and services and other functions, such as administration, commerce, finance, entertainment and service industries.
Decomposer	Decomposing excrement and residual bodies of animals and plants into simple compounds for the use of producers, such as decomposer microorganisms, bacteria, fungi and micro animals.	Disposal, conversion, reuse and so on of by-products and “wastes” produced by industrial enterprises, such as waste recycling companies and renewable resources companies.

3. Substance Flow Analysis

The original business of BTL was coke production. However, with the continuous decline of the coke prices in recent years, the industrial chain kept extending and more products were thus included. At present, besides coke, other coal chemical products such as crude benzene, methanol, wash oil and asphalt blending components, and electricity and heat were also produced. Table 2 present the major inputs and outputs of BTL in the last five years (2011-2015) [2,3,4,5,6].

Table 3. Inputs and outputs of BTL from 2011 to 2015

Raw Material (t)	2011		2012		2013		2014		2015	
Raw coal	2.93E+06		2.16E+06		1.92E+06		2.41E+06		2.73E+06	
Refined coal	1.34E+06		1.01E+06		9.03E+05		1.31E+06		1.37E+06	
Product (t)	Production	Sales	Production	Sales	Production	Sales	Production	Sales	Production	Sales
Coke	1.22E+06	1.23E+06	1.14E+06	1.10E+06	1.09E+06	1.05E+06	1.13E+06	1.11E+06	1.07E+06	1.09E+06
Crude benzene	1.71E+04	1.71E+04	1.64E+04	1.64E+04	1.61E+04	1.65E+04	1.63E+04	1.48E+04	1.49E+04	1.63E+04
Methanol	9.83E+04	9.89E+04	8.57E+04	8.73E+04	6.74E+04	6.95E+04	9.36E+04	9.11E+04	8.65E+04	8.59E+04
Wash oil and asphalt blending component	5.95E+04	5.81E+04	6.56E+04	6.76E+04	6.83E+04	6.48E+04	8.86E+04	8.54E+04	7.25E+04	7.69E+04
Power (kWh)	3.57E+08	1.57E+08	3.46E+08	1.55E+08	3.22E+08	1.45E+08	3.45E+08	1.39E+08	3.61E+08	1.58E+08
Heating (GJ)	4.92E+05	4.92E+05	9.74E+05	9.74E+05	1.60E+06	1.60E+06	2.13E+06	2.13E+06	2.13E+06	2.13E+06

Based on the investigation on technical process of BTL, substance flow analysis was carried out with the focus placed on coal. The layout of the coal flow throughout the BTL circular system is shown in Figure 2 [7].

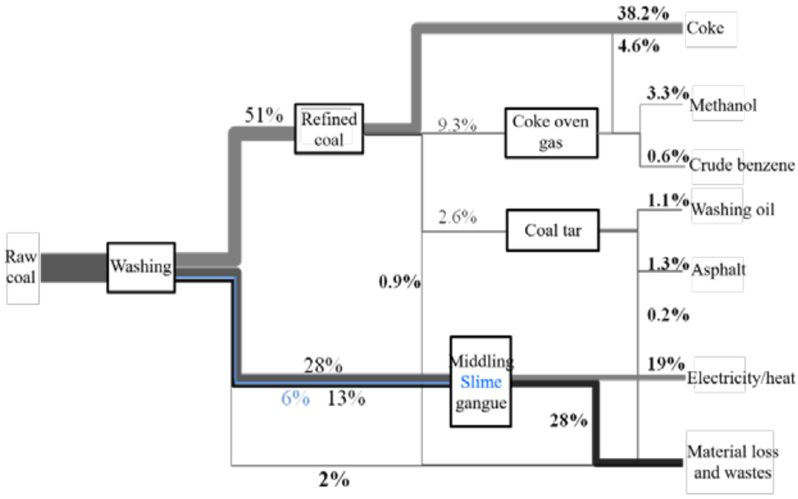

Figure 2. Substance flow analysis of BTL's coal chemical process

From the viewpoint of material flow, "raw coal → refined coal → coke" is the main process of the coal chemical production system of BTL which accounts for 42.8wt% of the coal input. The second major flow of raw coal is the material loss and waste including the emission of gaseous matters (CO_2) as well as fly ash, dust and so on. After coal washing, middlings (28wt%), coal slime (6wt%) and gangue (13wt%) enter the thermal power plant. If the ash contents of the three substance are excluded (20wt% for middlings, 50wt% for slime, and 80wt% for gangue), the part that really contribute to power and heat generation accounts for 19wt% of raw coal mass. Methanol, crude benzene, wash oil and asphalt are produced by using the by-products of coke oven gas (9.3wt%) and coal tar (2.6wt%) during the coking as the raw materials. After exported, half of the coke oven gas returned to the coke oven as fuel and the other half is used for the production of methanol (3.3wt%) and crude benzene (0.6wt%). Coal tar is mainly used to produce wash oil (1.1wt%) and asphalt (1.3wt%).

4 Assessment of Coal Chemical Circle Economy System

4.1. Layout and Roles

On the basis of substance flow analysis, the key links in the existing system can be identified by applying relevant theories of industrial ecology and ecological design tools. The links which are not strongly related with the main material flow are ignored, whereas the ones of greater correlation are merged as illustrated by Figure 3. Furthermore, all modules are classified as producer, consumer, and decomposer according to their roles in the industrial ecosystem. By extending the industrial chain, upgrading the key processes or reusing/recycling the wastes, the overall efficiency of the resources and ecological benefits of the entire system can be improved [8].

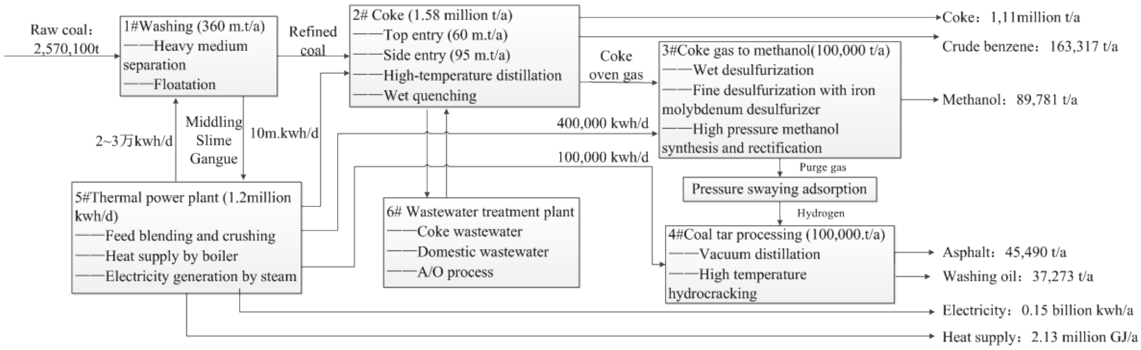

Figure 3. The coal chemical economy system

1# coal washing module (producer): BTL currently has two coal washing plants, namely Plant 1 and Plant 2 with capacities of 1.2 mt/a and 2.4 mt/a respectively. The core technology of coal washing process of BTL is heavy medium separation and flotation. When the raw coal enters the coal washing session, iron, large gangues and woods is manually removed firstly and then the coal is crushed and separated (particle size of less than 50mm). the broken product enters the heavy medium cyclone to separate the raw material into refined coal (51wt%), middlings (28wt%), gangue (13wt%), and coal slime (6wt%). The refined coal enters the coking module, while the middlings, coal slime and gangue enter 5# thermal power plant module.

2# coking module (consumer / producer): Two coke ovens are currently operated in BTL. Oven 1 has a capacity of 600,000 t/a with the entry from top. Oven 2 has a scale of 980,000 t/a with a tamping side entry. The refined coal firstly enters the coaling tower and then is pushed into the coke oven by a coal cart. The refined coal turned into coke in the carbonization chamber for 30h of anaerobic decomposition under 1,280~1,320°C with the by-products of coke oven gas and coal tar. Among them, the conversion rate of refined coal to coke is approximately 75%. The generation of coke oven gas is 400~430m^3/(t· refined coal). The coke is quenched by the reclaimed water from the sewage treatment plant is used for quenching. Beside water quenching, BTL also set up a CDQ system which is not running for now due to the relatively high cost.

3# methanol synthesis module (consumer): the production of coke oven gas to methanol of BTL is 100,000 t/a. The conversion rate is approximate 2,000m^3 coke oven gas for 1t methanol. The purge gas from the methanol synthesis process is of high content of hydrogen (70~80%). After separation and purification, the hydrogen content can raise up to 99.99%, which was transported to 4# coal tar deep-processing module for the hydrogenation of coal tar.

4# coal tar deep-processing module (consumer): the production scale of BTL's deep processing of coal tar is 100,000 t/a. After the vacuum distillation, the coal tar is separated as refined oil (43%) and heavy oil (i.e. asphalt, 55%). After the refined oil is obtained, hydrogenation (purge gas from the methanol plant) is performed and atmospheric pressure separation is used to obtain oil absorbing products (70%); unconverted oil (30%) is used as a starting material for the cracking reactor for circulating use. Asphalt can be used as the raw material for needle coke production in the plant.

5# thermal power plant module (decomposer): the coal slime, middlings and gangue from the coal washing module are supplied to the thermal power plant module. The feed is firstly blended to make its calorific value higher than 2,900kal and then enters the drying shed. After crushing, the product will be delivered to the coal bunker, and finally to the boiler for combustion. The boiler water is provided by the water plant. The superheated steam produced by the boiler is mostly used to propel the turbine to generate power. The generation efficiency of steam turbine is 372kwh/ standard coal (converted to heat value) and the daily power generation is 1.2 million kWh/d totally.

6# Sewage treatment module (decomposer): the coking wastewater and some domestic wastewater are treated in this module. The different influent water was firstly mixed to adjust the COD to less than 6,000mg/L, NH_3 less than 350mg/L, and sulfur content less than 20mg/L. The core process of the sewage treatment module is A/O process. After treatment, the effluent water meets national level II discharge standard and is used for coke quenching.

4.2. Assessment on the System

The present system in BTL is assessed according to the national standard *Specification for Performance Evaluation of Circular Economy of Industrial Parks,* which mainly measures two aspects, namely, resource output rate and resource recycling rate. The resource output rate includes 3 specific indexes as energy output rate, land output rate and water resource output rate. The resource recycling rate includes 2 required indexes, i.e. comprehensive utilization rate of industrial solid waste and reuse rate of industrial water, and 3 optional indexes, i.e. reuse rate of reclaimed water, recycling rate of waste heat resources and recycling rate of waste gas resources.

Compared with industrial parks which normally involve various processes and inputs, the circular economy system in BTL is based on the coal chemistry with coal as the major raw material. Secondly, the circular economy industrial chain of BTL is the extension of original coking. Therefore, all modules are closely correlated. Thirdly, coal is not only the raw material but also the energy source for the system. In order to assess the system more accurately so as to direct the optimization, the economic benefit according to the material distribution are calculated.

1) Evaluation of economic benefit

In this study, the economic benefit is calculated as presented below:

$$EB = \sum_{i=1}^{N}\sum_{j=1}^{N_i}(S_{ij}M_{ij} - P_{ij}C_{ij}) \tag{1}$$

Where, EB (economic benefit) represents the economic benefit of the entire system; i refers the number of module; j represents the product category; N is the number of module; N_i means the number of product categories in module i; S_{ij} and M_{ij} represent the sales and product price of product j in module i respectively; P_{ij} and C_{ij} represent the production and production costs of product j in module i respectively. The relevant data are collected and compiled in Table 3.

Table 4. The average production and sales of the main products

Product *i*	Annual Production *P* (t)	Annual Sales *S* (t)	Production Costs *C* (RMB/unit product)	Product Price *M* (RMB/unit product)
Coke	1,110,041.935	1,101,744.92	764.3023253	750.420365
Crude benzene	15,639.08	15,535.65	420.6551576	3,056.524802
Methanol	90,062.13	88,487.54	563.2234056	1,687.982058
Wash oil and asphalt blending component	80,558.665	81,146.24	1,159.445015	2,039.272673
Power (kWh)	353,043,459.5	148,755,309.5	0.091204743	0.321269827
Heating (GJ)	2,129,747	2,129,747	33.23740214	37.76828272

The economic profits of each products are shown in Figure 4.

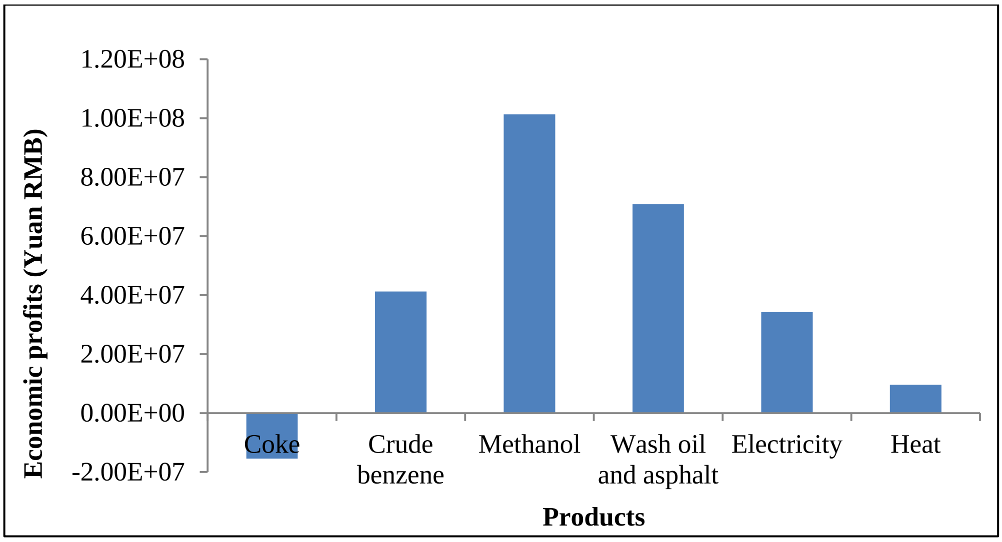

Figure 4. Economic Benefits of Main Products of BTL

As the price of coke has dropped continuously in recent years, production cost per unit coke is higher than the sale price. While the other coal chemical products, as well as power and heating, present better economic benefits, and among which methanol is the most profitable product.

2) Calculation of material distribution

The distribution of raw coal in different materials (including waste and loss) is calculated as below:

$$M_0 = \sum_i \sum_{j=1}^{N_{ip}} {M'_{ij}}_{ij} \delta_{ij} \qquad (2)$$

Where M_0 is the amount of raw coal entering the target system; M'_{ij} is the amount of raw coal required for product j of module i; δ_{ij} is the conversion coefficient between product j of module i and raw coal.

According to the material flow analysis results, the material distribution of the raw coal entering the coal chemical system of BTL in different products is shown in Table 4. Among them, material loss and waste, coke and heat / power are the top consumers in terms of the raw coal.

Table 5. Material distribution of raw coal in different products

Raw coal (t)	Module i	Product j	Conversion Coefficient $1/\delta_{ij}$	Consumption of Raw Coal by Product M'_{ij} (t· raw coal)
2,570,100	Coking module	Coke	0.428	1,100,002.8
	Methanol synthesis module	Methanol	0.033	84,813.3
		Crude benzene	0.006	15,420.6
	Coal tar deep -processing module	Wash oil and asphalt blending product	0.024	61,682.4
	Thermal power plant module	Heat/power	0.19	488,319
	Others	Material loss and waste	0.319	819,861.9
			1	2,570,100

3) Evaluation of resource benefit

The evaluation result of resource benefit is calculated by applying the formula as below:

$$R_{ij} = \frac{EB_{ij}}{M'_{ij}} \tag{3}$$

Where, R_i is the resource benefit of product j of module i and EB_{ij} is the economic benefit of product j in module i.

The resource benefits of the products of the coal chemistry circular economy system in BTL can be seen in Table 5.

Table 6. The resource benefits of the different products

	Economic Benefit (RMB)	Consumption of Raw Coal by Product $M'_{i\ j}$ (t· raw coal)	Product Resource Benefit R_i (RMB/ t· raw coal)
Coke	-15,409,558.16	1,100,002.8	-14.00865358
Crude benzene	4,122,2563.06	84,813.3	486.0389002
Methanol	101,298,160	15,420.6	6,569.015472
Wash oil and asphalt blending component	70,877,741.57	61,682.4	1,149.075613
Thermal power product	43,873,032.22	488,319	89.84502389
Total	241,861,938.7	2,570,100	94.10604205

5. Conclusion

From the point of view of resource benefits, a cascade among the different products exist as methanol > wash oil and asphalt blending component > crude benzene > thermal power product > coke. For the goal of improving the resource output efficiency of the whole system, materials shall flow to the product categories with high resource benefits as far as possible when designing and optimizing the industrial chain of circular economy. For example, in the current industrial chain system of BTL, only half of the coke oven gas produced by the coking module enters the methanol synthesis module and the rest coke oven gas is used as fuel, resulting in a decrease of the overall the resource benefit. Therefore, expanding the production capacity of methanol to make full use of all the coke oven gas can be profitable. With the expansion of methanol production scale, the amount of by-product purge gas will also increase. The extra hydrogen can also be used to produce more wash oil, so the resource benefit of the whole system can be further enhanced.

Although the resource benefits of coke and thermal power product are relatively low, the coking module and the thermal power plant module are special in the circular economy system since they play the roles of producer and decomposer respectively. Among them, the production scale of coke is directly related to the production of coke oven gas and coal tar. Therefore, this part constrains the scales of methanol synthesis and coal tar deep-processing amount. The inputs of thermal power product are middlings, coal slimes and other impurities, whereas the power and steam generated by the thermal power plant module contribute to other modules. Therefore, its actual resource benefit is far higher than the evaluation results may indicate.

In addition, the proportion of material loss and waste to the total input of coal is more than 30% and most of them are in the form of fly ash (28%). Although BTL has established a comprehensive utilization facility of fly ash, the product is not as expected due to depressing market of construction material. Hence, a pressing task at this stage is to add a utilization module of coal ash which is in consistence with the market needs.

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7. Reference

[1] Su, B., Heshmati, A., Geng, Y., Yu, X., 2012. A review of the circular economy in China: moving from rhetoric to implementation. J. Clean. Prod. 42, 215-227.
[2] BTL Annual Report 2011, http://app.finance.ifeng.com/data/stock/ggzw/601011/14009751
[3] BTL Annual Report 2012, http://guba.eastmoney.com/news,601011,74525835.html
[4] BTL Annual Report 2013, http://stock.stockstar.com/notice/JC2014032400004194.shtml
[5] BTL Annual Report 2014, http://app.finance.ifeng.com/data/stock/ggzw.php?id=14948425&symbol=601011
[6] BTL Annual Report 2015, http://app.finance.ifeng.com/data/stock/ggzw.php?id=15591507&symbol=601011
[7] Brunner, P.H., Rechberger, H., 2004. Practical handbook of material flow analysis. Int. J. Life Cycle Assess. 9 (5), 337-338.
[8] Rob_ert, K.H., Schmidt-Bleek, B., Aloisi de Larderel, J., et al., 2002. Strategic sustainable development selection, design and synergies of applied tools. J. Clean. Prod. 10 (3), 197-214.
[9] Yuan Zenghua, Bi Jun, et al., Industrial Ecology. Science Press. 1990.
[10] Singh, R.K., Murty, H.R., Gupta, S.K., Dikshit, A.K., 2009. An overview of sustainability assessment methodologies. Ecol. Indic. 9 (2), 189-212.
[11] Binder, C.R., Graedel, T.E., Reck, B., 2006. Explanatory variables for per capita stocks and flows of copper and zinc. J. Industrial Ecol. 10 (1e2), 111-132.