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Modeling and implication of coal physical input-output table in China—Based on clean coal concept

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ABSTRACT

In China, coal is not only the main fuel but also the majority substance causing pollution. For the purpose of monitoring and scenario analysis, this paper presents a coal physical input-output table (CPIOT) that shows the complete coal flow in the production system based on clean coal concept. We first depict the material flow of coal in China and construct a theoretical table of CPIOT to describe coal mining, consumption, emission, reuse and recycle, and then, four kinds of coal classification and sixteen sectors are declared for empirical analysis. By data collection, processing and calibration, this paper finally builds a CPIOT in 2012 which can observe the coal industry in detail. Furthermore, we apply it to assess circuits, material recycling and coal reduction effect and find a lot of interesting results, which proves the wide application and huge values of CPIOT in the analysis of China's coal industry.

1. Introduction

As the major energy in China, coal plays a dilemma role between economy development and environment protection (Govindaraju and Tang, 2013). On one hand, since coal is rich but oil and gas are poor, China's fast economic development is heavily dependent on coal. In 2013, the volume of coal consumption was 424.42 million tons which accounted for 67.4% of total energy consumption in China. On the other hand, such massive coal consumption leads to huge carbon emission and other air-pollution issues such as fog and haze (Kalembkiewica and Chmielarz, 2012). Coal is therefore named as "dirty" energy and the government is eager to find a way to decrease coal consumption. For this purpose, China puts forward clean coal concept in Action Plan of Energy Development Strategy (2014–2020) and requires raw coal should be used by a clean and high-efficiency way. Three strategies should be employed in the following years: (1) advanced power generation technologies will be popularized to decrease unit standard coal consumption to 300 g/kwh or lower and make the level of pollution emission close to the one of gas-fired plant; (2) based on coal-washing technology, raw coal will be classified, quality graded and then cascade utilized. That means much more coal will be processed before it is utilized and less SO_2, NO_x and ash will be emitted into the atmosphere; (3) coal gangue or ash will be reused largely to substitute original coal input or put into other industry as raw material, such as for cement production. Compared to other CCTs, these technologies are more mature, economic and easier to diffuse throughout the whole industry.

Since clean coal is the most important "key" to balance economy, energy and environment in China, much academic attention focused on this field (Tang et al., 2015; Chen and Xu, 2010; Horbach et al., 2014; Chen and Rennings, 2014; Li, 2011; Luo and Wang, 2015). But to our knowledge, most of the existing literatures just study raw coal consumption and thereafter carbon emission, and coal usage is taken as a black box which can't give detailed analysis about material flow, coal flux, usage efficiency, reuse and recycle and so on. This is where physical input-output tables (PIOTs) can come into play (Bösch et al., 2015; Bailey et al., 2004; Penela and Villasante, 2008). PIOTs encompass the material flows from nature to the economy, the transformation within the economy and then back to nature. In the past ten years, PIOTs have become an important tool for input-output analysis, particularly in the energy, environmental and economic areas (Weisz and Duchin, 2006; Hoekstra and Jeroen, 2006; Li et al., 2015). For above reasons, the emphasis of this study is on constructing a coal physical input-output table (CPIOT) based on clean coal concept which aims to open this black box in coal usage processing and provide vivid information about coal usage in different sectors, especially for some certain coals, such as briquette coal, coal gangue and fly ash which

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are close-related to circular economy. Thus, CPIOT can be as a useful instrument for further research.

The remainder of the paper is organized as follows: Section 2 describes the development of clean coal in China. In Section 3, we present the methodological framework. Section 4 presents the empirical results, while Section 5 discusses the main findings and perspectives for the future.

2. The development of clean coal in China

2.1. The technologies of clean coal in China

Generally, the concept of clean coal often refers to the clean coal technology (CCT), such as high efficiency combustion and advanced power generation technologies, coal-to-chemicals technologies, IGCC (integrated gasification combined cycle) technologies and CCS (carbon capture and storage) technologies (Na et al., 2015; Chen and Xu, 2010; Long and Henry, 2011). Lu et al. (2008) extended CCTs to the technology of coal processing, comprehensive utilization of coal and emissions reduction treatment. Ministry of Science and Technology (MOST, 2012) also addressed a whole framework ranging from coal processing to post-combustion treatment in China's 12th special clean coal plan (2010–2015) for clean coal technology development (Fig. 1).

But in practice, the development of these technologies in China is not evenly. Ultra Super-critical technology, the representative of advanced power generation technologies is widely used and thus make unit standard coal consumption decreases 2.4% in 2015 comparing to 2012 (National Bureau of Statistics of China, 2016), so it faces a promising development since China is now devoting to upgrade their old inefficient power generating equipment. Though the coal-to-chemicals industry developed a lot in 2011–2015, the step will obviously slowdown in the 13th Five-year Plan when it is facing the problem of lower oil prices, immature technology, high energy consumption, high water consumption and high pollution emission. Compared with them, IGCC and CCS are not even worth mentioned. In 2012, China Huaneng Group applied IGCC technology to generate electricity in Tianjin region, but until now, IGCC still hangs at the stage of demonstration and CCS is just a Shenhua Group's demonstration project located in Inner Mongolia autonomous regions. For their high cost and uncertainty technology, the future of their development is not bright. So, we model our physical coal input-output table based on this concept of clean coal and it will be more applicable for China coal industry nowadays.

2.2. Analysis of material flow of clean coal

Material flow analysis used here has the following advantages: (1) it shows that the amount of coal input into one sector inherently reflects its utilization level of a given technology. The more advanced a technology is, the less coal is used, and vice versa. (2) it can describe clearly how coal is classified, how much of the raw coal is washed, which sector and how much it flows to for each kind of coal, thus being able to figure out the situation of coal's cascade utilization in the industry. (3) it is the best tool to analyze coal circular economy, that is, the waste of coal processing or utilization is reclaimed and reused to reduce original coal consumption.

The lifecycle of coal can be divided into three stages. Firstly, coal, classified as anthracite, bitumite, sub-bitumite and lignite in common, is mined from underground. Since coal is the gift of nature, not the product of human, it should be considered as original material at this stage. Once processed, such as washing process, it begins to be used in different sectors as industrial product. Washed-coal is often regarded as clean coal, while unwashed-coal is known as "dirty coal" and is criticized as being the source of air pollution. After washing process, coal gangue appears and is often considered as solid waste.

Secondly, coal, including washed and unwashed, is then consumed as fuel or raw material in different sectors. As fuel, it burns and gives out heat to satisfy different demand, such as power generation, house heating, and so on. During this process, the different kinds of coal, including raw coal and washed coal, are mixed together to satisfy the special requirement of certain heating equipment, and the remnants are coal ash, waste gas and so on. As raw material in chemical fertilizer industry, washed coal is necessary and becomes the part of final products after processing. During this process, carbon material is internalized in the products and no waste is coming into being. Besides this, some kind of coal is also used in smelting industry as reluctant, and we also regard it as raw material input.

Thirdly, some of the remnant is reclaimed and reused for economic or environmental reasons. For example, coal gangue can be used in gangue power plant. A gangue power plant with $2 \times 50{,}000$ kwh installed capacity can deal with 0.05 million tons coal gangue which is the solid remnants of one mine with 3 million tons production capacity. Coal gangue and coal ash can also be input into cement industry as raw material or agriculture sector as soil amendment. For their wide usage, the government set the proportion of reused ratio as 70%, and this is the important part of China's clean coal strategy.

3. Methodical foundations

3.1. The basic physical input-output table

Based on Fig. 2, a general coal physical input-output table can be constructed as Table 1, including three quadrants, that is intermediate use, final outputs and original inputs. The $z_{ij}(\mathrm{n} \times \mathrm{n})$ matrix represents the quantity consumed by j^{th} sector which is produced by i^{th} sector. The final outputs is divided into useful products and waste products. The useful products are used for domestic consumption $\boldsymbol{d}(n \times 1)$, export $\boldsymbol{e}(n \times 1)$ and inventory $\boldsymbol{w}(n \times 1)$, and the waste products $\boldsymbol{w}(n \times m)$ refers to m kinds of residual which comes from coal consumption and cannot be reused again. The original input is divided into natural objects and recycled objects. The former $\boldsymbol{r}(k \times n)$ refers to k kinds of domestic extraction and imports, and the latter $\boldsymbol{c}(m \times n)$ refers to m kinds of reusable residuals which are generated in coal processing. Output matrix $\boldsymbol{x}(\mathrm{n} \times 1)$ represents the total output of each sector.

$$e_{ij} = \frac{d_{ij}}{d_{jj}} \times x_j, (\mathrm{i, j} = 1, 2, \ldots,) \qquad (1)$$

Where d_{ij} is the Leontief inverse and d_{jj} is diagonal element, e_{ij} stands for that if the sector j is taken away from CPIOT, how much production the sector i will reduce. Furthermore, in order to investigate the substitution effect between coal and other energy sources, this paper proposes potential substitution coefficient p_{ij} based on extraction effect coefficient, that is:

$$p_{ij} = \frac{e_{ij}}{e_{jj}} \times 100 \qquad (2)$$

Where p_{ij} stands for that if sector j stops to use coal (just like this sector is extracted from CPIOT), then how much percentage of gross production will reduce for each of the row sectors.

3.2. Data sources

In this article, considering the huge differences among coal usage, processing and waste disposal, coal is divided into anthracite, bituminous, sub-bituminous and lignite and its residues includes gangue and fly-ash. The advantage of this classification