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Identifying primary energy requirements in structural path analysis: A case study of China 2012

Bo Zhang [a,b], Xue Qu [a], Jing Meng [c,*], Xudong Sun [a,b]

[a] School of Management, China University of Mining & Technology (Beijing), Beijing 100083, PR China
[b] Research Center for Energy Strategy, State Key Laboratory of Coal Resources and Safe Mining, China University of Mining & Technology (Beijing), Beijing 100083, PR China
[c] School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK

HIGHLIGHTS

- Demand-driven primary energy requirements by Chinese economy 2012 are revealed.
- China's embodied energy exports were equal to 1/4 of its domestic energy supply.
- We trace energy use paths along the supply chains from extraction to final uses.
- Critical economic sectors and routes in driving primary energy uses are identified.
- Restructuring China's economic structures cannot fundamentally conserve energy.

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ABSTRACT

Primary energy requirements have close interaction with resource, technology, environment, infrastructure, as well as the socio-economic development. This study links the entire supply chain of the Chinese economy from energy extraction to final consumption by using input-output analysis and structural path analysis. The results show that the domestic primary energy input amounted to 3318.7 Mtce in 2012, of which 49.5% was induced by investment demands. Despite being one of the world's largest energy importers, embodied energy uses (EEUs) in China's exports were equivalent to about one fourth of its total domestic supply. All *Manufacturing* sectors accounted for 44.3% of the total EEUs, followed by *Construction* for 33.3%, *Services* for 11.6% and *Power & Heat* for 3.9%. After examining the embodied energy paths, critical economic sectors such as *Construction of Buildings*, *Construction Installation Activities*, *Transport Via Road*, *Production and Supply of Electricity and Steam* and *Processing of Steel Rolling Processing*, and supply chain routes starting from final uses to resource extraction such as "Capital formation → *Construction of Buildings* → *Production and Supply of Electricity and Steam* → *Production and Supply of Electricity and Steam* → *Mining and Washing of Coal*", were identified as the main contributors to China's raw coal and other primary energy requirements. Restructuring Chinese economy from manufacturing industries to construction and services with huge economic costs cannot fundamentally conserve energy, owing to their almost identical structures in higher production tiers; more appropriate policies on technology efficiency gains, energy mix improvement, economic structure adjustment and green consumption deserve to be considered in the light of upstream and downstream responsibilities from a systematic viewpoint.

1. Introduction

Energy is one of the most crucial natural resources to sustain socio-economic development [1]. As the world's largest primary energy user, China's unprecedented expansion of energy demand has become a pronounced global concern [2–4]. In 2014, its total primary energy production amounted to 3600 million tons of standard coal equivalent (Mtce), more than twice that ten years ago, of which the output of raw coal reached 3.87 billion tons, crude oil 0.21 billion tons and natural gas 130.2 billion m^3 [5]. Nuclear energy and renewable energy also have increased rapidly in recent two decades, and the total installed generating capacities of hydropower and wind power all rank first in the world [6]. Meanwhile, large-scale energy exploitation and utilization are often accompa-

* Corresponding author.
E-mail addresses: zhangbo@cumtb.edu.cn (B. Zhang), j.meng@uea.ac.uk (J. Meng).

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nied by air pollution, water crisis, ecological damage and greenhouse gas emissions [7,8]. Chinese governments have a great pressure to address prominent energy problems and decrease their adverse environmental impacts [9–11]. In the *Energy Development Strategy Action Plan of China* (2014–2020), the country aims to cap primary energy consumption at 4800 Mtce in 2020 [12]. Also, the share of non-fossil energy in its total primary energy consumption aims to increase to 15% by 2020 and 20% by 2030, and its carbon emissions will peak around 2030 [13]. To achieve these targets, a holistic investigation on how primary energy resources are used along the supply chain, from energy extraction to the final use of associated products [14,15], is imperative to the policy makers.

Demand-driven energy requirements or embodied energy uses, originating from the theory of systems ecology [16], is defined as the direct plus indirect energy resources input through the production processes to produce goods or services used for final demand [17–20]. Since input-output models considering both intermediate and final use can capture the economic relationships among industrial sectors [21], a series of studies have carried out input–output analyses for energy, water and emission embodiments in the economic activities at different scales [22–32]. Particularly, an increasing amount of literature has focused on China's embodied energy uses in final demand and trade from various aspects [33–40]. By using an energy input-output model to connect natural ecosystem with socio-economic system, it is possible to identify how much primary energy resource supply for production can be attributed to a specific final demand throughout the whole supply chain [15,20,41]. Although previous studies have linked the energy consumption in production sector to final users, there is still a lag in relation to knowledge concerning China's primary energy uses starting from original primary energy extraction to embodied energy uses in the socio-economic system.

To reflect the link between primary energy extraction and final user and identify the specific paths that need improvement, structural path analysis (SPA) can be used to excavate intricate sectoral inter-relationships along the supply chain [42–45]. SPA technology provides a powerful tool to examine how final demand purchase initiates production processes, to follow the production network from final demand through the domestic production processes and finally to extract the critical paths that drive dominant resource uses and environmental emissions [46–48]. In the past decade, in view of the importance and merit of SPA, increasing studies have used this method to analyze flows of energy, carbon, water and other physical quantities through industrial networks, and then identify important paths along the domestic supply chain or global supply chain [48–55]. Nevertheless, few have focused on energy interactions between different industrial sectors along the production chains to explore the embodied energy use paths from resource extraction to final use along with vibrant economic activities in China.

The aim of this paper is to illustrate demand-driven primary energy requirements by Chinese economy 2012 based on the latest statistical data and national input-output table, and to set up the first quantitative study for tracing primary energy uses via domestic supply chains by using the SPA method. By extracting important embodied energy use paths starting from consumers to producers, the economic and energy interdependencies among the different industrial sectors and, in addition, among sectors and final consumption will be identified. We not only rank the most important final demand categories, but also find the key economic sectors and embodied energy use paths in Chinese economic systems. More importantly, revealing production-side and consumption-side primary energy uses along the supply chains will be useful to facilitate understanding the upstream and downstream responsibilities of different economic agents on China's energy and related environmental issues.

2. Method and data sources

2.1. Input-output embodiment analysis

The basic row balance for China's economic input-output table can be expressed as,

$$X = AX + Y - X^m \tag{1}$$

where X is the total output; A is the technology coefficients matrix to describe the relationship between all sectors of the economy, of which the element is $a_{ij} = Z_{ij}/X_j$, with Z_{ij} and X_j standing for the input from Sector i to Sector j and the total output of Sector j, respectively; Y is the final demand vector including rural and urban households consumption, government consumption, gross capital formation, exports and others; and X^m is the imports.

Since we focus on sectoral allocation of energy inputs in domestic production, the import items are removed to isolate the domestic supply chain in China. Following previous studies [56–60], we assume that each economic sector and domestic demand category utilize sectoral imports in the same proportions. Thus, new requirements coefficient matrices in which only domestic goods are included can be derived as,

$$A^d = (I - M)A \tag{2}$$

$$m_{ii} = \frac{X_i^m}{X_i + X_i^m - f_i^e} \tag{3}$$

where $M = diag(m_{ii})$, m_{ii} is the share of imports in the supply of products and services to each sector.

The new balance equations are shown as [60]

$$X = Z^d + y^d = Z^d + f^d + f^e = A^d X + f^d + f^e \tag{4}$$

where Z^d is the matrix of domestic intermediate demands; y^d is the vector of final demand excluding imports for final consumption; f^d is the vector of domestic final consumption; and f^e is the vector of domestic exports.

Rearranging Eq. (4) leads to following basic equations,

$$X = (I - A^d)^{-1}(f^d + f^e) = L^d(f^d + f^e) \tag{5}$$

where I is the identity matrix; and $L^d = (I - A^d)^{-1}$ is the domestic Leontief inverse matrix, whose element l_{ij} tracks the overall direct and indirect input along the domestic supply chain from Sector i while generating unit output in Sector j.

According to Eq. (5), it is easy to formulate the total embodied energy uses (EEUs) as

$$EEU = \varepsilon^d L^d (f^d + f^e) = \varepsilon(f^d + f^e) \tag{6}$$

where ε^d represents the direct energy intensity (i.e., the direct primary energy input per unit of value of industrial output); ε is the domestic EEU (direct plus indirect) intensity; εf^d is the domestic energy uses embodied in domestic final consumption; and εf^e is the domestic energy uses embodied in exports. The relationship between the embodied energy use intensity and direct primary energy input intensity can be further indicated as,

$$\varepsilon_j = \varepsilon_1^d l_{1j}^d + \varepsilon_2^d l_{2j}^d + \cdots + \varepsilon_n^d l_{nj}^d \tag{7}$$

2.2. Structural path analysis

To perform SPA for the embodied energy use paths, the revised Leontief inverse in Eq. (5) is expanded using Taylor series approximation as [54,61],