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

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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. 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

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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.

Keywords: Embodied energy; Input-output analysis; Structural path analysis; Domestic supply chain; Chinese economy

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 tonnes 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 accompanied 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, by considering the inter-industry linkages between energy producers and energy users [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,

$$X = AX + Y - X^{m} \quad (1)$$

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],

$$L^d = (I - A^d)^{-1} = I + A^d + (A^d)^2 + (A^d)^3 + \cdots + (A^d)^t \tag{8}$$

On the right-hand side of Eq. (8), each element in the expansion denotes a different production layer (*PL*) or tier. We define a production layer (*PL*) as each term in the power series expansion, $PL^t=(A^d)^t$. Each additional layer, $PL^{t+1}=PL^tA^d$, represents the production of intermediate products in $(t+1)$th production tier used as inputs into the tth production tier. Thereafter, embodied energy uses in final demands (y^d) can be calculated as,

$$\varepsilon^d (I - A^d)^{-1} y^d = \varepsilon^d I y^d + \varepsilon^d A^d y^d + \varepsilon^d (A^d)^2 y^d + \varepsilon^d (A^d)^3 y^d + \cdots + \varepsilon^d (A^d)^t y^d \tag{9}$$

where $\varepsilon^d (A^d)^t y^d$ represents the contribution of energy uses from the tth production tier. For example, assuming the case where y^d is a demand for a phone: $\varepsilon I y^d$ is the energy use induced in the production of the phone by the phone company. To produce the phone, the phone company needs to buy inputs from other industries ($A^d y^d$), and these industries consume $\varepsilon^d A^d y^d$ of energy use. In turn, these industries also need inputs (i.e., $A^d (A^d y^d)$) and meanwhile $\varepsilon^d (A^d)^2 y^d$ of primary energy are used. And so on and so forth, the infinite expansion of power series continues. Thus, primary energy use in the zeroth tier is the energy use during the assembly phase of the phone. Embodied energy use in the first tier is the energy use associated with producing the parts needed by the phone company. Embodied energy use in the second or higher tier is the energy use to produce the inputs for the components in the supply chain. The quantity of nodes in the production network increases exponentially with each tier. There are n^{t+1} nodes in tier t and n is the number of industrial sectors in the economy. For example, the n^3 second-tier nodes are evaluated as $\varepsilon_k^d A_{kj}^d A_{ji}^d y_i^d$ and denote the path from $i \rightarrow j \rightarrow k$. The same pattern continues for all tiers.

In practice, it is time consuming and impossible to evaluate the infinite number of nodes in the tree. The value of input nodes decreases with path length; the tree is generally 'pruned' when the contribution from the sub-tree below the node is below a specified threshold. Using this tree-pruning concept a dynamic tree data structure is constructed and only the relevant production paths are included. It has proved that this technique provides a more precise representation of the main drivers of primary energy requirements by decomposing the total energy uses of an economy into its subsequent infinite paths within the production system [44,46,50]. Detailed procedures to illustrate the process of SPA can be referred to Skelton et al. [48] and Meng et al. [54].

2.3. Data sources and preparation

In this study, the 2012 economic input–output table of China covering 139 industrial sectors is adopted directly, which is the latest national input–output table compiled by the National Bureau of Statistics of China [62]. For detailed sectoral information, please refer to Table S1 in Supplementary materials.

The primary energy consumption of the Chinese economy draws from six primary sources, i.e., raw coal, crude oil, natural gas, hydro power, nuclear power and other non-hydro renewable energy. The data of primary energy input into Chinese economy are available from China Energy Statistical Yearbook 2014 [63] and China Statistical Yearbook 2015 [5]. The hydropower, nuclear power and other renewable energy inputs are estimated according to electricity generation data and corresponding electricity generation efficiencies. To keep data consistency, the electricity generation efficiencies of nuclear power, hydropower and other renewable energy are all directly obtained from previous studies [15,18-20]. As to the embodiment analysis, raw coal input is directly related with the *Mining and Washing of Coal* sector; both crude oil and natural gas inputs can be attributed to the sector of *Extraction of Crude Petroleum and Natural Gas*; and the last three primary energy categories all belong to the *Production and Supply of Electricity and Steam* sector according to the data availability. Totally, the domestic primary energy inputs into Chinese economic system were 3318.7 Mtce in 2012, of which raw coal accounted for 80.6% of the total, followed by crude oil & natural gas for 13.3% and other means of primary energy for 6.1%.

3. Results

3.1. Embodied energy use intensities

Figure 1 presents the EEU intensity by sector in 2012 through a histogram. Evidently, Sector 6 (*Mining and Washing of Coal*) held the largest EEU intensity of 1426.3 gce/CNY, far more than those of other sectors. Sectors 40 (*Manufacture of Coke Products*), 96 (*Production and Supply of Electricity and Steam*) and 7 (*Extraction of Crude Petroleum and Natural Gas*) also had high EEU intensities, with the value of 592.1 gce/CNY, 437.5 gce/CNY and 411.5 gce/CNY, respectively. In particular, direct energy use intensity took a large proportion of embodied emission intensity for Sectors 6 and 7 (larger than 80%). In the other 137 industrial sectors, their EEU intensities were all dominated by the indirect energy use intensity. Therefore, the estimation of primary energy uses in China's manufacturing, construction, utility and service sectors should take indirect energy uses into account.

[Place Figure 1 here]

Figure 2 shows the composition of sectoral EEU intensity by energy type. Embodied raw coal intensities made up a large proportion of total EEU intensities in most sectors, accounting for 70-90% in most manufacturing and service sectors. Moreover, the proportions of embodied coal use intensities were larger than 90% of the embodied energy use intensities in Sectors 6, 40, 59 (*Manufacture and Casting of Basic Iron and Steel*), 60 (*Processing of Steel Rolling Processing*) and 52 (*Manufacture of Cement,* *Lime and Plaster*). Embodied oil & natural gas use intensities had the significant contributions to the EEU intensities of Sectors 7 (89.1% of the total) and 39 (*Manufacture of Refined Petroleum Products, Processing of Nuclear Fuel*, 78.4%), which were closely related to the conversion and utilization of oil or natural gas. Other main consumers of petroleum products and natural gas such as transportation also had prominent embodied oil & natural gas use intensities, accounting for about 40%-60% of their sectoral EEU intensities. For the embodied intensity of other primary energy resources, the proportion was always less than 10% in the sectoral EEU intensity. Thereafter, fossil fuels were found to be the main contributor to the composition of sectoral EEU intensities.

[Place Figure 2 here]

3.2. Embodied energy uses in final demand

Figure 3 presents the EEUs in final demand in terms of rural consumption, urban consumption, government consumption, capital formation, stock increase and exports. There were remarkable disparities on the sectoral EEUs. Sector 99 (*Construction of Buildings*) held the top EEU in final demand, amounting to 735.0 Mtce and accounting for 22.1% of the national total. Sector 100 (*Civil Engineering*) was the second largest sector with an EEU value of 267.7 Mtce (8.1% of the total). Sectors 96 (*Production and Supply of Electricity and Steam*), 75 (*Manufacture of Motor Vehicles, Except Parts and Accessories for Motor Vehicles*) and 101 (*Construction Installation Activities*) also had significant sectoral EEUs, contributing to 3.9%, 3.6% and 2.5% of the national total, respectively. The 5 sectors mentioned above, out of all 139 sectors, contributed to 40.2% of the national total EEU.

Unsurprisingly, the composition of sectoral EEUs in final demand demonstrated striking disparities. Capital formation was the leading final demand category in 18 sectors such as Sectors 75 (*Manufacture of Motor Vehicles, Except Parts and Accessories for Motor Vehicles*), 99 (*Construction of Buildings*), 100 (*Civil Engineering*) and 101 (*Construction Installation Activities*). Sector 6 had a large amount of EEU in stock increase. As the leading final demand category in 54 sectors, the shares of consumption-driven EEUs in most service sectors were more than 90%. Urban consumption contributed the dominated share in 41 sectors' EEUs such as Sectors 96 (*Production and Supply of Electricity and Steam*). In particular, government consumption was the dominant final demand category in 13 service sectors such as Sectors 139 (*Public Management and Social Organization*) and 127 (*Management of Public Facilities*). Meanwhile, the shares of energy uses embodied in exports were especially high in 62 industrial sectors such as Sectors 41 (*Manufacture of Basic Chemical*), 60 (*Processing of Steel Rolling Processing*) and 31 (*Manufacture of Textile Wearing Apparel*). In some manufacturing sectors, about 80%-90% of their sectoral EEUs can be attributed to this category.

[Place Figure 3 here]

Figure 4 further presents the distribution of EEUs in final demand in terms of energy type, i.e., raw coal, crude oil & natural gas, and other primary energy. Embodied raw coal use was the leading type in 131 sectors, and generally contributed about 70%-90% of the sectoral EEUs. Meanwhile, the shares of embodied crude oil & natural gas uses were especially high in 6 industrial sectors. For instance, crude oil & natural gas accounted for 89.1% and 78.4% of the sectoral EEU in *Extraction of Crude Petroleum and Natural Gas* and *Manufacture of Refined Petroleum Products, Processing of Nuclear Fuel*, respectively. In addition, the average fraction of other primary energy in sectoral EEUs was less than 7%.

[Place Figure 4 here]

The EEU structure of final demand by Chinese economy is further summarized in Fig. 5. In the composition of EEU inventories by final demand category (see the inner circle), investment contributed the largest fraction of 49.5% to the total EEU (i.e., 1641.9 Mtce), followed by consumption 26.9% and exports 23.6%. To reduce the complexity of the economic system, the original 139 sectors have been merged into eight broad categories: *Agriculture*, *Coal*, *Petroleum & Gas*, *Manufacturing*, *Power & Heat*, *Construction*, *Transportation* and *Service*. As to the composition of EEU in final demand in terms of all the eight broad categories (see the outer circle), *Manufacturing* accounted for 44.3% of the total EEUs in final demand, followed by *Construction* for 33.3% and *Service* for 11.6%. The remaining four categories were responsible for only

10.8% of the total.

[Place Figure 5 here]

As the dominant final demand category, 95.0% of the investment-driven EEUs can be attributed to capital formation, and 5.0% can be attributed to stock increase. Investment-driven construction activities such as the buildings construction and civil engineering require a great deal of direct and indirect inputs of electricity and building materials (e.g., cement, metal and nonferrous metal products), which always result in increasing energy-intensive production and huge embodied energy requirements [20]. About one third (33.2%) of the national total EEUs were associated with all the construction sectors. The top two contributors of investment-driven EEUs were Sectors 99 (44.4%) and 100 (16.3%). Some manufacturing sectors such as Sector 75 also had high investment-driven EEUs.

Consumption induced a total EEU of 893.8 Mtce, of which 62.5% were due to urban household consumption, 18.4% rural household consumption and 19.1% government consumption. The EEUs of urban household consumption were 3.4-fold of those of rural household consumption. Obviously, per capita EEUs between urban and rural household consumption presented a wide gap, when considering that the urbanization rate was 52.6% in this year [5]. At the sectoral level, household consumption, especially urban household consumption, was the major driving force of EEUs in the sectors which are closely linked with people’s life such as food, electricity, heat and other services. The largest three sectors of 96, 139 and 131 contributed to 14.0%, 7.5% and 6.0% of the total consumption-driven EEUs, respectively.

The EEUs induced by exports summed up to 783.0 Mtce, accounting for about one fourth of the national total EEU in final demand. For some manufacturing sectors which provided China's major export products, the exports-driven EEUs were relatively higher than those of other industrial sectors. This can be explained by the fact that the structures of China's exports were dominated by textile products, chemical products, primary industrial products, electronic equipment, etc. [41, 37].

3.3. Structural path analysis for embodied energy flows

Embodied energy flows throughout the entire supply chains in the Sankey diagram [64-67] can intuitively present where the primary energy inputs from extraction sectors have gone (production attribution), and where the energy uses embodied in final products have come from (consumption attribution). Figure 6 illustrates the EEUs driven by the final demand at Tier 0, Tier 1 and higher Tiers (Tier 2, 3, 4 and 5→∞). Table 1 further presents the distribution of demand-driven primary energy requirements in each production tier along the supply chains.

[Place Figure 6 here]

[Place Table 1 here]

From consumption-oriented perspective, the embodied energy fluxes from PL^t can be traced to the three aggregated sectors, i.e., *Coal*, *Petroleum & Gas* and *Power & Heat* which all relate to direct primary energy extraction, as shown in Fig. 6 from right to left. These sectors at Tier 0 provided the primary energy to meet final demand directly, contributing to 82.7%, 87.2% and 9.5% of their respective total inputs (see Table 1), respectively. The EEU of *Manufacturing* appeared to be evenly distributed across the production tiers, mainly due to its complex economic relationships among various industrial sectors. In the *Service* sector, most of the EEUs occurred at the third and higher tiers, while the EEUs of *Transportation* and *Agriculture* concentrated on Tier 2 and other higher tiers with a similar structure in sectoral contribution. In contrast, the *Power & Heat* sector drove primary energy usage mainly in Tier 1 (48.8% to its total EEUs), and Tier 2 and all the other tiers contributed the remained half. Meanwhile, final consumption in the eight aggregated sectors had different patterns in inducing EEUs in different tiers. All *Manufacturing* sectors drove about 44.3% of China's total EEUs, the inputs purchased from PL^1 had very high EEUs, mainly in *Manufacture* products (1006.2 Mtce, 68.5%), *Power & Heat* products (159.3 Mtce, 10.8%) and *Coal* products (117.6 Mtce, 8.0%). The *Construction* sector drove about 33.3% of the national total EEUs, and the inputs from PL^1 highly concentrated in the products of *Manufacturing*, accounting for 86.0% (948.9 Mtce) of the total. *Service* drove about 11.6% of the total EEUs, and the inputs purchased from PL^1 also had very high EEUs in the *Manufacturing* products with the proportion of 47.3% (182.6 Mtce), *Service* products of 20.6% (79.6 Mtce), and *Power & Heat* products of 17.9% (69.1 Mtce), respectively. The EEUs in *Transportation* and *Agriculture* had similar pattern with those in *Service* in PL[1].

From production-oriented perspective, the percentage components of direct energy usage in production Tier 0, Tier 1, Tier 2 and higher Tiers (Tier 3→∞) in the supply chain are displayed in Fig. 7. Embodied coal use dominated in most of sectors except for *Petroleum & Gas*. The contribution of oil & gas products was significant in the transport and service sectors. *Manufacturing* used most of embodied coal with an amount of 862.3 Mtce (32.2%) at Tier 3 and higher tiers, followed by *Construction* with an amount of 666.4 Mtce (24.9%) at Tier 3 and higher tiers. In total, embodied coal uses contributed to 86.0% of the total EEUs of *Construction* in its whole production tiers, followed by 82.9% in *Power & Heat* and 79.7% in *Manufacturing*, respectively. It is worthy of noting that consumption of *Manufacturing* and *Service* products drove 56% of China's total primary energy usage, but nearly 90% of which occurred at the second and higher tiers (see Table 1) with an almost identical structure in primary energy contribution (see Fig. 7).

[Place Figure 7 here]

To identify how the final consumption drives energy uses in each tier, we extract and rank individual critical supply chain, which started from the very beginning of the production to intermediate consumption, and eventually to final demand. Table 2 lists the 20 top-ranking paths through which the final demands drove the production processes, representing 48.4% of the national total EEUs in final demand. The path of

"Capital formation→ *Construction of Buildings*→ *Production and Supply of Electricity and Steam*→ *Production and Supply of Electricity and Steam*→ *Mining and Washing of Coal*" contributed the largest share of 6.2%, followed by "Capital formation→ *Construction of Buildings*→ *Production and Supply of Electricity and Steam*→ *Production and Supply of Electricity and Steam*→ *Production and Supply of Electricity and Steam*→ *Mining and Washing of Coal*" of 5.5%, "Urban consumption→ *Production and Supply of Electricity and Steam*→ *Production and Supply of Electricity and Steam*→ *Mining and Washing of Coal*" of 5.0%, and "Capital formation→ *Construction of Buildings*→ *Processing of Steel Rolling Processing*→ *Mining and Washing of Coal*" of 3.5%. The top 10 ranking paths were responsible for 34.7% of the total EEUs. Nine ranking paths were driven by capital formation and nine other paths by urban consumption. Ten of the top 20 ranking paths were associated with *Construction of Buildings*, showing that this sector was the most important transmission channel for embodied energy. The sector of *Production and Supply of Electricity and Steam*, which consumed raw coal and provided electricity to other economic sectors or households, was linked with seven of the high-ranking paths. Other critical transmission sectors included *Construction Installation Activities*, *Transport Via Road*, *Processing of Steel Rolling Processing* and *Manufacture of Refined Petroleum Products, Processing of Nuclear Fuel*. Prominently, 16 paths among all the 20 ranking paths were traced back to the sector of *Mining and Washing of Coal*, which can be identified as the important causes of China's raw coal requirements.

[Place Table 2 here]

4. Discussions

4.1. The role of final demand on primary energy requirements

China consumed about 22% of global primary energy resources [68], imposing huge pressure on the natural ecosystems. Since the energy requirements are not limited to production activities, final consumption demands should be taken into account. From final demand perspective, investment contributed the largest fraction of 49.5% to the national total EEU. In many developing countries, investments in infrastructure are the important driver for maintaining economic growth, and the EEUs in final demand are dominated by investment-driven construction and energy-intensive industrial activities [36,52]. For instance, the length of highways in China had more than doubled from 176.5 million kilometers in 2002 to 423.5 million kilometers in 2012 [5]. Previous studies also demonstrated that investment was responsible for about 40% of the embodied greenhouse gas emissions in China [69,70], and the sectors regarding construction and manufacture of industrial products dominated the embodied emissions induced by gross capital formation. It is important to investigate all the possible energy-saving potentials and pathways in construction activities and suppress unnecessary investment demands [41,69].

Consumption induced a total EEU of 893.8 Mtce (26.9% of the national total), of which 62.5% were due to urban household consumption, 18.4% rural household consumption and 19.1% government consumption. By contrast, larger portions of primary energy requirements in developed countries are used for household consumption [65]. Urban residents always enjoy more luxury lifestyles than rural residents [71], resulting in the big gap in per capita EEU between rural and urban residents. In fact, the average per capita consumption expenditure of urban households in 2012 were 3.1 times larger than that that of rural households [72]. By 2020, more than 100 million people will move to China's cities by a large-scale migration from rural to urban area, thus triggering a large amount of embodied energy uses in household consumption to meet the needs of rural residents changing to urban lifestyle and consumption patterns. Feng and Hubacek [71] reported that an urban resident has the carbon footprint three times the size of a rural resident in China, and moving more than 100 million rural residents to cities by 2020 means more than 1 gigaton additional CO_2 emissions. Wiedenhofer et al.[73] also showed the unequally carbon footprints among the rich and poor due to differences in the scale and patterns of consumption. In view of a huge gap in per capita energy and carbon footprints between rural and urban residents, a big challenge may be imposed to future energy and related environmental policies.

In addition, although China is one of the largest energy importers in the world, the EEUs in exports were equivalent to about one fourth of the total domestic primary energy inputs, owing to the manufacture of industrial products induced by exports. It has been widely discussed that exports generally contributed to about 1/5-1/4 of China's total embodied CO_2 emissions and the emission intensities of exports were always much higher than those of imports [56,70]. Thereafter, trade policy adjustments should consider both the direct energy imports and embodied energy exports.

4.2. Tracing primary energy uses via domestic supply chains

Construction and *Service* sectors had very high EEUs in the *Manufacturing* products. Consumption of manufacturing and service products drove 56% of China's total primary energy usage, but nearly 90% of which occurred at the second and higher tiers with an almost identical structure in primary energy contribution, as illustrated by structural path analysis. These features indicate that restructuring Chinese economy from manufacturing industries to construction and services with huge economic costs cannot fundamentally lead to energy conversation and emission reduction to a certain extent. In the long run, increasing consumption demand for service products in the public and private sectors can also induce substantial embodied energy uses. Since manufacturing industry is the core competence of Chinese economy, technology efficiency gains and energy structure optimization in the industry sector will be more significant to some extent.

China alone consumes about half of global coal, and coal dominates its primary energy mix and electricity generation. Given the importance of coal in energy structure, EEUs in final demand were also sensitive to raw coal input because of the dominated contribution of embodied coal uses in domestic supply chains. In detail, embodied raw coal intensities made up a large proportion of the sectoral EEU intensities. Embodied raw coal use was the leading type in the EEUs of 131 sectors, accounting for about 70%-90% of the EEUs in most manufacturing and service sectors. Coal-related products contributed 86.0% to the total EEU of *Construction* in its whole production tiers, followed by 82.9% of *Power & Heat* and 79.7% of *Manufacturing*, respectively. By tracing the embodied coal flows in supply chains, 16 paths among all the 20 ranking paths were traced back to the sector of *Mining and Washing of Coal*. The major paths associated with direct coal use or coal-dominated electricity consumption can be identified as the important causes of China's raw coal requirements. To optimize the embodied coal use paths induced by final consumption, several paths associated with steel, cement, and non-ferrous metal production related activities should be given special attention.

China's energy policies for achieving the sustainability of energy resource uses may contribute to global energy saving and emission mitigation. Achieving the high-efficiency and clean utilization of traditional fossil fuels, especially developing and deploying clean coal technologies, promoting technology efficiency in production processes, and developing circular economy [74-76], may actually be the important ways to effectively mitigate greenhouse gas emissions from energy activities and lower air pollution and other environmental impacts. Energy-related policy mechanisms to improve coal-dominated energy structure and substitute for fossil fuels include but are not limited to environmental standards, fuel and emissions taxes and emissions permit-trading systems. In the meantime, it is necessary to allocate upstream and downstream responsibilities based on embodied energy and emission inventories. The information of primary energy requirements in structural path analysis is of extreme importance when energy and environmental policies are to be individually applied to different industrial sectors and other economic agents. Effective consumption-side measures at the regional, national and even global supply chains [15,54] will offer a wide range of long-term global environmental and climate co-benefits in the future.

4.3. The impact of energy data, sector resolution and methods

Reliable energy inventories are of fundamental importance for assisting policy-makers in designing energy and environmental policies. The reliabilities of China's energy statistics have been frequently questioned in previous studies, and the significant discrepancies in coal data have been regarded as one of the largest sources of uncertainty in China's emission estimates [77]. In this study, the updated coal data for the year of 2012 were obtained from the latest statistical yearbook. In fact, the data inconsistencies of National Coal Balance Sheet 2012 in different statistical yearbooks can be found, as listed in Table S2. In China Statistical Yearbook 2014 [78], the total raw coal output for the year of 2012 was only 3.645 billion tons, but this value increased to 3.945 billion tons in China Statistical Yearbook 2015 [4], which can be mainly attributed to a significant increase of end-use coal consumption in the industry. In particular, the large statistical gap of total coal output, 300.1 million tons, can rank No. 7 in global coal production and No. 3 in global coal consumption for the year of 2012 [68]. Since coal dominates the apparent uncertainties in China's total energy consumption among different types of energy [77], taking long-term efforts to obtain reliable data in energy statistics are crucially important for verifying the quality of coal data.

Previously, most of input-output analyses for China's resource uses and environmental emissions were limited to no more than 42 sectors. The National Bureau of Statistics of China also provided the 2012 input–output table containing 42 economic sectors. Overall, the differences between 139-sector resolution and 42-sector resolution in allocated EEUs by domestic final consumption, gross capital formation and exports were estimated at 12.0% (+107.7 Mtce), -7.1% (-116.1 Mtce) and 1.1% (+8.5 Mtce), respectively. Moreover, the disparities in sectoral EEU intensities and the EEU in the corresponding sectors could be considerable (See Fig. 8). For instance, there is only one sector in 42-sector input-output table relating to chemical production, i.e., Sector 12 (*Chemical Products Related Industry*), which has an average EEU intensity of 108.3 gce/CNY; however, there were ten sectors (Sectors 41-51) in the 139-sector input-output table relating to such production, and the EEU intensities of these sectors ranged from 44.4 gce/CNY to 202.9 gce/CNY. The evaluation of EEUs in Sector 28 (*Construction*) in the 42-sector resolution were estimated at 976.7 Mtce, but the summation of EEUs from its subsectors (Sectors 99-102) in the 139-sector resolution was determined to be 1103.4 Mtce for all the construction activities. The low sector resolution has introduced apparent inaccuracy into the embodiment analysis [79,80] and distorted the allocation of the EEUs in industrial sectors with large uncertainties. Therefore, caution should be exercised in directly using EEU intensities derived with low sector resolution to link with other process-based data or to input into a hybrid-LCA model. This study chooses the current highest sector resolutions without sectoral aggregation to link the primary energy inputs to the 139-sector IO table for China to reduce inaccuracy, which makes it possible to illustrate the actual EEUs by sector. For detail information of sectoral EEU intensities with the 139-sector and 42-sector classification, please refer to Table S3.

[Place Fig. 8 here]

A major limitation of the input-output modeling process is that the treatment of imports in compiling an imports-adjusted national input-output table. The assumption of the same proportions for the imports input into each economic sector and domestic demand category has resulted in uncertainties, though it's hard to quantify [56-60]. A more accurate evaluation of domestic economic input-output matrix with detailed trade information will fix these uncertainties. In addition, the selection of average electricity generation efficiencies for hydropower, nuclear power and other renewable power may result in some uncertainties for embodied energy estimation [81], though all such inputs accounted for only 6.1% of the national total. Therefore, even considering such uncertainties in both methods and data, the scale of embodied energy uses in domestic supply chains are unlikely to be affected significantly, and the results of the present study may offer fundamental information to the knowledge and understanding of China's current energy production and consumption. Also improving national energy statistics and economic input-output table will be essential to provide a more high-quality embodied energy use inventories, and then reduce uncertainties in dealing with the energy and environmental issues.

5. Concluding remarks

Primary energy requirements have close interaction with resource, technology, environment, infrastructure, as well as the socio-economic development. This study has systematically revealed demand-driven primary energy requirements of the Chinese economy and traced the country's energy uses in extraction, intermediate production and final uses throughout domestic supply chains. The total embodied energy uses in final demand amounted to 3318.7 Mtce in 2012, of which investment contributed 49.5% to the national total, followed by consumption 26.9% and exports 23.6%. The estimation of energy consumption in China's manufacturing, construction, utility and service sectors should take indirect energy uses into account. Raw coal was found to be the dominating energy type and generally contributed about 70%-90% of the sectoral EEUs. After examining the embodied energy fluxes in structural path analysis, some critical economic sectors such as *Construction of Buildings*, *Construction Installation Activities*, *Transport Via Road*, *Production and Supply of Electricity and Steam*, *Manufacture of Refined Petroleum Products*, *Processing of Nuclear Fuel* and *Processing of Steel Rolling Processing*, and crucial routes 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. It is important to investigate all the possible energy-saving potentials and pathways in production and consumption activities, and suppress unnecessary final demands.

No primary energy sources, renewable or nonrenewable, can be free of economic or environmental limitations [1]. Given increasing demands for primary energy resources, global energy development must go through a route characterized by the high-efficiency, clean and low-carbon energy transition. To response to energy challenges faced, energy choices made by the developing countries and developed countries have ramifications for economy, environment and society. This study indicated that primary energy requirements of a national economy can be identified in structural path analysis in terms of extraction, intermediate production and final uses throughout the entire supply chains. More appropriate policy designs for energy saving and emission reduction can then be achieved by considering both effective production-side and consumption-side measures. A well-functioning socio-economic system will enable the regional, national and even global supply chains to extract and use primary energy resources for their full benefits, and ensure access to modern and sustainable energy services for all.

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Supplementary materials

Supplementary materials associated with this article can be found in the online version.

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