

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

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8

9 **Abstract**

10 Primary energy requirements have close interaction with resource, technology,  
11 environment, infrastructure, as well as the socio-economic development. This study  
12 links the entire supply chain of the Chinese economy from energy extraction to final  
13 consumption by using input-output analysis and structural path analysis. Results show  
14 that the domestic primary energy input amounted to 3318.7 Mtce in 2012, of which  
15 49.5% was induced by investment demands. Despite being one of the world's largest  
16 energy importers, embodied energy uses (EEUs) in China's exports were equivalent to  
17 about one fourth of its total domestic supply. All *Manufacturing* sectors accounted for  
18 44.3% of the total EEUs, followed by *Construction* for 33.3%, *Services* for 11.6% and  
19 *Power & Heat* for 3.9%. After examining the embodied energy paths, critical economic

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1 sectors such as *Construction of Buildings, Construction Installation Activities,*  
2 *Transport Via Road, Production and Supply of Electricity and Steam* and *Processing of*  
3 *Steel Rolling Processing*, and supply chain routes starting from final uses to resource  
4 extraction such as “Capital formation→ *Construction of Buildings*→ *Production and*  
5 *Supply of Electricity and Steam*→ *Production and Supply of Electricity and Steam*→  
6 *Mining and Washing of Coal*”, were identified as the main contributors to China’s raw  
7 coal and other primary energy requirements. Restructuring Chinese economy from  
8 manufacturing industries to construction and services with huge economic costs cannot  
9 fundamentally conserve energy, owing to their almost identical structures in higher  
10 production tiers; more appropriate policies on technology efficiency gains, energy mix  
11 improvement, economic structure adjustment and green consumption deserve to be  
12 considered in the light of upstream and downstream responsibilities from a systematic  
13 viewpoint.

14

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

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## 18 **1. Introduction**

19 Energy is one of the most crucial natural resources to sustain socio-economic  
20 development [1]. As the world’s largest primary energy user, China’s unprecedented  
21 expansion of energy demand has become a pronounced global concern [2-4]. In 2014,  
22 its total primary energy production amounted to 3600 million tonnes of standard coal

1 equivalent (Mtce), more than twice that ten years ago, of which the output of raw coal  
2 reached 3.87 billion tons, crude oil 0.21 billion tons and natural gas 130.2 billion m<sup>3</sup>  
3 [5]. Nuclear energy and renewable energy also have increased rapidly in recent two  
4 decades, and the total installed generating capacities of hydropower and wind power all  
5 rank first in the world [6]. Meanwhile, large-scale energy exploitation and utilization  
6 are often accompanied by air pollution, water crisis, ecological damage and greenhouse  
7 gas emissions [7,8]. Chinese governments have a great pressure to address prominent  
8 energy problems and decrease their adverse environmental impacts [9-11]. In the  
9 *Energy Development Strategy Action Plan of China (2014-2020)*, the country aims to  
10 cap primary energy consumption at 4800 Mtce in 2020 [12]. Also, the share of non-  
11 fossil energy in its total primary energy consumption aims to increase to 15% by 2020  
12 and 20% by 2030, and its carbon emissions will peak around 2030 [13]. To achieve  
13 these targets, a holistic investigation on how primary energy resources are used along  
14 the supply chain, from energy extraction to the final use of associated products [14,15],  
15 is imperative to the policy makers.

16 Demand-driven energy requirements or embodied energy uses, originating from the  
17 theory of systems ecology [16], is defined as the direct plus indirect energy resources  
18 input through the production processes to produce goods or services used for final  
19 demand [17-20]. Since input-output models considering both intermediate and final use  
20 can capture the economic relationships among industrial sectors [21], a series of studies  
21 have carried out input–output analyses for energy, water and emission embodiments in  
22 the economic activities at different scales [22-32]. Particularly, an increasing amount of

1 literature has focused on China's embodied energy uses in final demand and trade from  
2 various aspects [33-40]. By using an energy input-output model to connect natural  
3 ecosystem with socio-economic system, it is possible to identify how much primary  
4 energy resource supply for production can be attributed to a specific final demand  
5 throughout the whole supply chain, by considering the inter-industry linkages between  
6 energy producers and energy users [15,20,41]. Although previous studies have linked  
7 the energy consumption in production sector to final users, there is still a lag in relation  
8 to knowledge concerning China's primary energy uses starting from original primary  
9 energy extraction to embodied energy uses in the socio-economic system.

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

1 in China.

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

14

## 15 **2. Method and data sources**

### 16 *2.1. Input-output embodiment analysis*

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

$$18 \quad X = AX + Y - X^m \quad (1)$$

19 where  $X$  is the total output;  $A$  is the technology coefficients matrix to describe the  
20 relationship between all sectors of the economy, of which the element is  $a_{ij}=Z_{ij}/X_j$ , with  
21  $Z_{ij}$  and  $X_j$  standing for the input from Sector  $i$  to Sector  $j$  and the total output of Sector  $j$ ,  
22 respectively;  $Y$  is the final demand vector including rural and urban households

1 consumption, government consumption, gross capital formation, exports and others;  
 2 and  $X^m$  is the imports.

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

$$8 \quad A^d = (I - M)A \quad (2)$$

$$9 \quad m_{ii} = \frac{X_i^m}{X_i + X_i^m - f_i^e} \quad (3)$$

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

12 The new balance equations are shown as [60]

$$13 \quad X = Z^d + y^d = Z^d + f^d + f^e = A^d X + f^d + f^e \quad (4)$$

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

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

$$18 \quad X = (I - A^d)^{-1}(f^d + f^e) = L^d(f^d + f^e) \quad (5)$$

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

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

1 as

$$2 \quad EEU = \varepsilon^d L^d (f^d + f^e) = \varepsilon (f^d + f^e) \quad (6)$$

3 where  $\varepsilon^d$  represents the direct energy intensity (i.e., the direct primary energy input  
4 per unit of value of industrial output);  $\varepsilon$  is the domestic EEU (direct plus indirect)  
5 intensity;  $\varepsilon f^d$  is the domestic energy uses embodied in domestic final consumption;  
6 and  $\varepsilon f^e$  is the domestic energy uses embodied in exports. The relationship between  
7 the embodied energy use intensity and direct primary energy input intensity can be  
8 further indicated as,

$$9 \quad \varepsilon_j = \varepsilon_1^d l_{1j}^d + \varepsilon_2^d l_{2j}^d + \dots + \varepsilon_n^d l_{nj}^d \quad (7)$$

## 10 2.2. Structural path analysis

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

$$13 \quad L^d = (I - A^d)^{-1} = I + A^d + (A^d)^2 + (A^d)^3 + \dots + (A^d)^t \quad (8)$$

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

$$20 \quad \varepsilon^d (I - A^d)^{-1} y^d = \varepsilon^d I y^d + \varepsilon^d A^d y^d + \varepsilon^d (A^d)^2 y^d + \varepsilon^d (A^d)^3 y^d + \dots + \varepsilon^d (A^d)^t y^d \quad (9)$$

21 where  $\varepsilon^d (A^d)^t y^d$  represents the contribution of energy uses from the  $t$ th production tier.

22 For example, assuming the case where  $y^d$  is a demand for a phone:  $\varepsilon I y^d$  is the energy

1 use induced in the production of the phone by the phone company. To produce the phone,  
 2 the phone company needs to buy inputs from other industries ( $A^d y^d$ ), and these  
 3 industries consume  $\varepsilon^d A^d y^d$  of energy use. In turn, these industries also need inputs (i.e.,  
 4  $A^d (A^d y^d)$ ) and meanwhile  $\varepsilon^d (A^d)^2 y^d$  of primary energy are used. And so on and so forth,  
 5 the infinite expansion of power series continues. Thus, primary energy use in the zeroth  
 6 tier is the energy use during the assembly phase of the phone. Embodied energy use in  
 7 the first tier is the energy use associated with producing the parts needed by the phone  
 8 company. Embodied energy use in the second or higher tier is the energy use to produce  
 9 the inputs for the components in the supply chain. The quantity of nodes in the  
 10 production network increases exponentially with each tier. There are  $n^{t+1}$  nodes in tier  
 11  $t$  and  $n$  is the number of industrial sectors in the economy. For example, the  $n^3$  second-  
 12 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  
 13 pattern continues for all tiers.

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



1 2.3. *Data sources and preparation*

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

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

22

1 **3. Results**

2 *3.1. Embodied energy use intensities*

3 Figure 1 presents the EEU intensity by sector in 2012 through a histogram. Evidently,  
4 Sector 6 (*Mining and Washing of Coal*) held the largest EEU intensity of 1426.3  
5 gce/CNY, far more than those of other sectors. Sectors 40 (*Manufacture of Coke*  
6 *Products*), 96 (*Production and Supply of Electricity and Steam*) and 7 (*Extraction of*  
7 *Crude Petroleum and Natural Gas*) also had high EEU intensities, with the value of  
8 592.1 gce/CNY, 437.5 gce/CNY and 411.5 gce/CNY, respectively. In particular, direct  
9 energy use intensity took a large proportion of embodied emission intensity for Sectors  
10 6 and 7 (larger than 80%). In the other 137 industrial sectors, their EEU intensities were  
11 all dominated by the indirect energy use intensity. Therefore, the estimation of primary  
12 energy uses in China's manufacturing, construction, utility and service sectors should  
13 take indirect energy uses into account.

14

15 [Place Figure 1 here]

16

17 Figure 2 shows the composition of sectoral EEU intensity by energy type. Embodied  
18 raw coal intensities made up a large proportion of total EEU intensities in most sectors,  
19 accounting for 70-90% in most manufacturing and service sectors. Moreover, the  
20 proportions of embodied coal use intensities were larger than 90% of the embodied  
21 energy use intensities in Sectors 6, 40, 59 (*Manufacture and Casting of Basic Iron and*  
22 *Steel*), 60 (*Processing of Steel Rolling Processing*) and 52 (*Manufacture of Cement,*

1 *Lime and Plaster*). Embodied oil & natural gas use intensities had the significant  
2 contributions to the EEU intensities of Sectors 7 (89.1% of the total) and 39  
3 (*Manufacture of Refined Petroleum Products, Processing of Nuclear Fuel*, 78.4%),  
4 which were closely related to the conversion and utilization of oil or natural gas. Other  
5 main consumers of petroleum products and natural gas such as transportation also had  
6 prominent embodied oil & natural gas use intensities, accounting for about 40%-60%  
7 of their sectoral EEU intensities. For the embodied intensity of other primary energy  
8 resources, the proportion was always less than 10% in the sectoral EEU intensity.  
9 Thereafter, fossil fuels were found to be the main contributor to the composition of  
10 sectoral EEU intensities.

11  
12 [Place Figure 2 here]

13  
14 *3.2. Embodied energy uses in final demand*

15 Figure 3 presents the EEUs in final demand in terms of rural consumption, urban  
16 consumption, government consumption, capital formation, stock increase and exports.  
17 There were remarkable disparities on the sectoral EEUs. Sector 99 (*Construction of*  
18 *Buildings*) held the top EEU in final demand, amounting to 735.0 Mtce and accounting  
19 for 22.1% of the national total. Sector 100 (*Civil Engineering*) was the second largest  
20 sector with an EEU value of 267.7 Mtce (8.1% of the total). Sectors 96 (*Production and*  
21 *Supply of Electricity and Steam*), 75 (*Manufacture of Motor Vehicles, Except Parts and*  
22 *Accessories for Motor Vehicles*) and 101 (*Construction Installation Activities*) also had

1 significant sectoral EEUs, contributing to 3.9%, 3.6% and 2.5% of the national total,  
2 respectively. The 5 sectors mentioned above, out of all 139 sectors, contributed to 40.2%  
3 of the national total EEU.

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

20

21

[Place Figure 3 here]

22

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

10

11

[Place Figure 4 here]

12

13 The EEU structure of final demand by Chinese economy is further summarized in  
14 Fig. 5. In the composition of EEU inventories by final demand category (see the inner  
15 circle), investment contributed the largest fraction of 49.5% to the total EEU (i.e.,  
16 1641.9 Mtce), followed by consumption 26.9% and exports 23.6%. To reduce the  
17 complexity of the economic system, the original 139 sectors have been merged into  
18 eight broad categories: *Agriculture, Coal, Petroleum & Gas, Manufacturing, Power &*  
19 *Heat, Construction, Transportation* and *Service*. As to the composition of EEU in final  
20 demand in terms of all the eight broad categories (see the outer circle), *Manufacturing*  
21 accounted for 44.3% of the total EEUs in final demand, followed by *Construction* for  
22 33.3% and *Service* for 11.6%. The remaining four categories were responsible for only

1 10.8% of the total.

2

3

[Place Figure 5 here]

4

5 As the dominant final demand category, 95.0% of the investment-driven EEUs can

6 be attributed to capital formation, and 5.0% can be attributed to stock increase.

7 Investment-driven construction activities such as the buildings construction and civil

8 engineering require a great deal of direct and indirect inputs of electricity and building

9 materials (e.g., cement, metal and nonferrous metal products), which always result in

10 increasing energy-intensive production and huge embodied energy requirements [20].

11 About one third (33.2%) of the national total EEUs were associated with all the

12 construction sectors. The top two contributors of investment-driven EEUs were Sectors

13 99 (44.4%) and 100 (16.3%). Some manufacturing sectors such as Sector 75 also had

14 high investment-driven EEUs.

15 Consumption induced a total EEU of 893.8 Mtce, of which 62.5% were due to urban

16 household consumption, 18.4% rural household consumption and 19.1% government

17 consumption. The EEUs of urban household consumption were 3.4-fold of those of

18 rural household consumption. Obviously, per capita EEUs between urban and rural

19 household consumption presented a wide gap, when considering that the urbanization

20 rate was 52.6% in this year [5]. At the sectoral level, household consumption, especially

21 urban household consumption, was the major driving force of EEUs in the sectors

22 which are closely linked with people's life such as food, electricity, heat and other

1 services. The largest three sectors of 96, 139 and 131 contributed to 14.0%, 7.5% and  
2 6.0% of the total consumption-driven EEUs, respectively.

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

### 9 *3.3. Structural path analysis for embodied energy flows*

10 Embodied energy flows throughout the entire supply chains in the Sankey diagram  
11 [64-67] can intuitively present where the primary energy inputs from extraction sectors  
12 have gone (production attribution), and where the energy uses embodied in final  
13 products have come from (consumption attribution). Figure 6 illustrates the EEUs  
14 driven by the final demand at Tier 0, Tier 1 and higher Tiers (Tier 2, 3, 4 and  $5 \rightarrow \infty$ ).  
15 Table 1 further presents the distribution of demand-driven primary energy requirements  
16 in each production tier along the supply chains.

17

18 [Place Figure 6 here]

19

20 [Place Table 1 here]

21

22 From consumption-oriented perspective, the embodied energy fluxes from PL<sup>1</sup> can

1 be traced to the three aggregated sectors, i.e., *Coal, Petroleum & Gas* and *Power &*  
2 *Heat* which all relate to direct primary energy extraction, as shown in Fig. 6 from right  
3 to left. These sectors at Tier 0 provided the primary energy to meet final demand directly,  
4 contributing to 82.7%, 87.2% and 9.5% of their respective total inputs (see Table 1),  
5 respectively. The EEU of *Manufacturing* appeared to be evenly distributed across the  
6 production tiers, mainly due to its complex economic relationships among various  
7 industrial sectors. In the *Service* sector, most of the EEUs occurred at the third and  
8 higher tiers, while the EEUs of *Transportation* and *Agriculture* concentrated on Tier 2  
9 and other higher tiers with a similar structure in sectoral contribution. In contrast, the  
10 *Power & Heat* sector drove primary energy usage mainly in Tier 1 (48.8% to its total  
11 EEUs), and Tier 2 and all the other tiers contributed the remained half. Meanwhile, final  
12 consumption in the eight aggregated sectors had different patterns in inducing EEUs in  
13 different tiers. All *Manufacturing* sectors drove about 44.3% of China's total EEUs, the  
14 inputs purchased from PL<sup>1</sup> had very high EEUs, mainly in *Manufacture* products  
15 (1006.2 Mtce, 68.5%), *Power & Heat* products (159.3 Mtce, 10.8%) and *Coal* products  
16 (117.6 Mtce, 8.0%). The *Construction* sector drove about 33.3% of the national total  
17 EEUs, and the inputs from PL<sup>1</sup> highly concentrated in the products of *Manufacturing*,  
18 accounting for 86.0% (948.9 Mtce) of the total. *Service* drove about 11.6% of the total  
19 EEUs, and the inputs purchased from PL<sup>1</sup> also had very high EEUs in the  
20 *Manufacturing* products with the proportion of 47.3% (182.6 Mtce), *Service* products  
21 of 20.6% (79.6 Mtce), and *Power & Heat* products of 17.9% (69.1 Mtce), respectively.  
22 The EEUs in *Transportation* and *Agriculture* had similar pattern with those in *Service*



1 in PL<sup>1</sup>.

2 From production-oriented perspective, the percentage components of direct energy  
3 usage in production Tier 0, Tier 1, Tier 2 and higher Tiers (Tier 3→∞) in the supply  
4 chain are displayed in Fig. 7. Embodied coal use dominated in most of sectors except  
5 for *Petroleum & Gas*. The contribution of oil & gas products was significant in the  
6 transport and service sectors. *Manufacturing* used most of embodied coal with an  
7 amount of 862.3 Mtce (32.2%) at Tier 3 and higher tiers, followed by *Construction* with  
8 an amount of 666.4 Mtce (24.9%) at Tier 3 and higher tiers. In total, embodied coal  
9 uses contributed to 86.0% of the total EEUs of *Construction* in its whole production  
10 tiers, followed by 82.9% in *Power & Heat* and 79.7% in *Manufacturing*, respectively.  
11 It is worthy of noting that consumption of *Manufacturing* and *Service* products drove  
12 56% of China's total primary energy usage, but nearly 90% of which occurred at the  
13 second and higher tiers (see Table 1) with an almost identical structure in primary  
14 energy contribution (see Fig. 7).

15

16 [Place Figure 7 here]

17

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

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

22

1 [Place Table 2 here]

2

### 3 **4. Discussions**

#### 4 *4.1. The role of final demand on primary energy requirements*

5 China consumed about 22% of global primary energy resources [68], imposing huge  
6 pressure on the natural ecosystems. Since the energy requirements are not limited to  
7 production activities, final consumption demands should be taken into account. From  
8 final demand perspective, investment contributed the largest fraction of 49.5% to the  
9 national total EEU. In many developing countries, investments in infrastructure are the  
10 important driver for maintaining economic growth, and the EEUs in final demand are  
11 dominated by investment-driven construction and energy-intensive industrial activities  
12 [36,52]. For instance, the length of highways in China had more than doubled from  
13 176.5 million kilometers in 2002 to 423.5 million kilometers in 2012 [5]. Previous  
14 studies also demonstrated that investment was responsible for about 40% of the  
15 embodied greenhouse gas emissions in China [69,70], and the sectors regarding  
16 construction and manufacture of industrial products dominated the embodied emissions  
17 induced by gross capital formation. It is important to investigate all the possible energy-  
18 saving potentials and pathways in construction activities and suppress unnecessary  
19 investment demands [41,69].

20 Consumption induced a total EEU of 893.8 Mtce (26.9% of the national total), of  
21 which 62.5% were due to urban household consumption, 18.4% rural household  
22 consumption and 19.1% government consumption. By contrast, larger portions of

1 primary energy requirements in developed countries are used for household  
2 consumption [65]. Urban residents always enjoy more luxury lifestyles than rural  
3 residents [71], resulting in the big gap in per capita EEU between rural and urban  
4 residents. In fact, the average per capita consumption expenditure of urban households  
5 in 2012 were 3.1 times larger than that that of rural households [72]. By 2020, more  
6 than 100 million people will move to China's cities by a large-scale migration from  
7 rural to urban area, thus triggering a large amount of embodied energy uses in household  
8 consumption to meet the needs of rural residents changing to urban lifestyle and  
9 consumption patterns. Feng and Hubacek [71] reported that an urban resident has the  
10 carbon footprint three times the size of a rural resident in China, and moving more than  
11 100 million rural residents to cities by 2020 means more than 1 gigaton additional CO<sub>2</sub>  
12 emissions. Wiedenhofer et al.[73] also showed the unequally carbon footprints among  
13 the rich and poor due to differences in the scale and patterns of consumption. In view  
14 of a huge gap in per capita energy and carbon footprints between rural and urban  
15 residents, a big challenge may be imposed to future energy and related environmental  
16 policies.

17 In addition, although China is one of the largest energy importers in the world, the  
18 EEUs in exports were equivalent to about one fourth of the total domestic primary  
19 energy inputs, owing to the manufacture of industrial products induced by exports. It  
20 has been widely discussed that exports generally contributed to about 1/5-1/4 of China's  
21 total embodied CO<sub>2</sub> emissions and the emission intensities of exports were always much  
22 higher than those of imports [56,70]. Thereafter, trade policy adjustments should

1 consider both the direct energy imports and embodied energy exports.

#### 2 4.2. Tracing primary energy uses via domestic supply chains

3 *Construction* and *Service* sectors had very high EEUs in the *Manufacturing* products.

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

15 China alone consumes about half of global coal, and coal dominates its primary  
16 energy mix and electricity generation. Given the importance of coal in energy structure,  
17 EEUs in final demand were also sensitive to raw coal input because of the dominated  
18 contribution of embodied coal uses in domestic supply chains. In detail, embodied raw  
19 coal intensities made up a large proportion of the sectoral EEU intensities. Embodied  
20 raw coal use was the leading type in the EEUs of 131 sectors, accounting for about  
21 70%-90% of the EEUs in most manufacturing and service sectors. Coal-related  
22 products contributed 86.0% to the total EEU of *Construction* in its whole production

1 tiers, followed by 82.9% of *Power & Heat* and 79.7% of *Manufacturing*, respectively.  
2 By tracing the embodied coal flows in supply chains, 16 paths among all the 20 ranking  
3 paths were traced back to the sector of *Mining and Washing of Coal*. The major paths  
4 associated with direct coal use or coal-dominated electricity consumption can be  
5 identified as the important causes of China's raw coal requirements. To optimize the  
6 embodied coal use paths induced by final consumption, several paths associated with  
7 steel, cement, and non-ferrous metal production related activities should be given  
8 special attention.

9 China's energy policies for achieving the sustainability of energy resource uses may  
10 contribute to global energy saving and emission mitigation. Achieving the high-  
11 efficiency and clean utilization of traditional fossil fuels, especially developing and  
12 deploying clean coal technologies, promoting technology efficiency in production  
13 processes, and developing circular economy [74-76], may actually be the important  
14 ways to effectively mitigate greenhouse gas emissions from energy activities and lower  
15 air pollution and other environmental impacts. Energy-related policy mechanisms to  
16 improve coal-dominated energy structure and substitute for fossil fuels include but are  
17 not limited to environmental standards, fuel and emissions taxes and emissions permit-  
18 trading systems. In the meantime, it is necessary to allocate upstream and downstream  
19 responsibilities based on embodied energy and emission inventories. The information  
20 of primary energy requirements in structural path analysis is of extreme importance  
21 when energy and environmental policies are to be individually applied to different  
22 industrial sectors and other economic agents. Effective consumption-side measures at

1 the regional, national and even global supply chains [15,54] will offer a wide range of  
2 long-term global environmental and climate co-benefits in the future.

### 3 *4.3. The impact of energy data, sector resolution and methods*

4 Reliable energy inventories are of fundamental importance for assisting policy-  
5 makers in designing energy and environmental policies. The reliabilities of China's  
6 energy statistics have been frequently questioned in previous studies, and the significant  
7 discrepancies in coal data have been regarded as one of the largest sources of  
8 uncertainty in China's emission estimates [77]. In this study, the updated coal data for  
9 the year of 2012 were obtained from the latest statistical yearbook. In fact, the data  
10 inconsistencies of National Coal Balance Sheet 2012 in different statistical yearbooks  
11 can be found, as listed in Table S2. In China Statistical Yearbook 2014 [78], the total  
12 raw coal output for the year of 2012 was only 3.645 billion tons, but this value increased  
13 to 3.945 billion tons in China Statistical Yearbook 2015 [4], which can be mainly  
14 attributed to a significant increase of end-use coal consumption in the industry. In  
15 particular, the large statistical gap of total coal output, 300.1 million tons, can rank No.  
16 7 in global coal production and No. 3 in global coal consumption for the year of 2012  
17 [68]. Since coal dominates the apparent uncertainties in China's total energy  
18 consumption among different types of energy [77], taking long-term efforts to obtain  
19 reliable data in energy statistics are crucially important for verifying the quality of coal  
20 data.

21 Previously, most of input-output analyses for China's resource uses and  
22 environmental emissions were limited to no more than 42 sectors. The National Bureau

1 of Statistics of China also provided the 2012 input–output table containing 42 economic  
2 sectors. Overall, the differences between 139-sector resolution and 42-sector resolution  
3 in allocated EEU by domestic final consumption, gross capital formation and exports  
4 were estimated at 12.0% (+107.7 Mtce), -7.1% (-116.1 Mtce) and 1.1% (+8.5 Mtce),  
5 respectively. Moreover, the disparities in sectoral EEU intensities and the EEU in the  
6 corresponding sectors could be considerable (See Fig. 8). For instance, there is only one  
7 sector in 42-sector input-output table relating to chemical production, i.e., Sector 12  
8 (*Chemical Products Related Industry*), which has an average EEU intensity of 108.3  
9 gce/CNY; however, there were ten sectors (Sectors 41-51) in the 139-sector input-  
10 output table relating to such production, and the EEU intensities of these sectors ranged  
11 from 44.4 gce/CNY to 202.9 gce/CNY. The evaluation of EEU in Sector 28  
12 (*Construction*) in the 42-sector resolution were estimated at 976.7 Mtce, but the  
13 summation of EEU from its subsectors (Sectors 99-102) in the 139-sector resolution  
14 was determined to be 1103.4 Mtce for all the construction activities. The low sector  
15 resolution has introduced apparent inaccuracy into the embodiment analysis [79,80]  
16 and distorted the allocation of the EEU in industrial sectors with large uncertainties.  
17 Therefore, caution should be exercised in directly using EEU intensities derived with  
18 low sector resolution to link with other process-based data or to input into a hybrid-  
19 LCA model. This study chooses the current highest sector resolutions without sectoral  
20 aggregation to link the primary energy inputs to the 139-sector IO table for China to  
21 reduce inaccuracy, which makes it possible to illustrate the actual EEU by sector. For  
22 detail information of sectoral EEU intensities with the 139-sector and 42-sector



1 classification, please refer to Table S3.

2

3

[Place Fig. 8 here]

4

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

21

## 1 **5. Concluding remarks**

2 Primary energy requirements have close interaction with resource, technology,  
3 environment, infrastructure, as well as the socio-economic development. This study has  
4 systematically revealed demand-driven primary energy requirements of the Chinese  
5 economy and traced the country's energy uses in extraction, intermediate production  
6 and final uses throughout domestic supply chains. The total embodied energy uses in  
7 final demand amounted to 3318.7 Mtce in 2012, of which investment contributed 49.5%  
8 to the national total, followed by consumption 26.9% and exports 23.6%. The  
9 estimation of energy consumption in China's manufacturing, construction, utility and  
10 service sectors should take indirect energy uses into account. Raw coal was found to be  
11 the dominating energy type and generally contributed about 70%-90% of the sectoral  
12 EEU's. After examining the embodied energy fluxes in structural path analysis, some  
13 critical economic sectors such as *Construction of Buildings*, *Construction Installation*  
14 *Activities*, *Transport Via Road*, *Production and Supply of Electricity and Steam*,  
15 *Manufacture of Refined Petroleum Products*, *Processing of Nuclear Fuel* and  
16 *Processing of Steel Rolling Processing*, and crucial routes such as "Capital formation  
17 → *Construction of Buildings* → *Production and Supply of Electricity and Steam* →  
18 *Production and Supply of Electricity and Steam* → *Mining and Washing of Coal*", were  
19 identified as the main contributors to China's raw coal and other primary energy  
20 requirements. It is important to investigate all the possible energy-saving potentials and  
21 pathways in production and consumption activities, and suppress unnecessary final  
22 demands.

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

14

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20

## 21 **Supplementary materials**

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

1

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