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Energy Use Embodied in China's Construction Industry: A Multi-Regional Input–Output Analysis

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Abstract: The rapid urbanization process was bound to produce considerable energy demand in China, which increased the pressure on sustainable development. This study employed a multi-regional input–output model to investigate energy use embodied in the consumption and interregional trade of China's construction industry. Results show that as a typical demand-driven sector, the construction industry consumed 793.74 million tons of coal equivalent in 2007, which is equal to 29.6% of China's total national energy consumption. Regions have been divided according to different driving forces for energy increment. Shanxi, Liaoning, Heilongjiang, Henan, and Sichuan were identified to be driven by their extensive construction activities and inefficient construction process. Interregional imports of the construction industry represented a resource-dependent geographical distribution. Energy flows are from resource-abundant areas in the central part to resource-deficient areas in the eastern coast. By contrast, energy exports represented a regional discrete distribution, which mainly transferred energy in the form of labor mobility and service supply. This study provided insight into the current energy consumption status of provincial construction industry from both regional and sectoral perspectives, which can be a basis for energy policy making and implementation.

Keywords: Embodied energy, Construction industry, Multi-regional, Input–output model

1. Introduction

Energy and its related problems are a worldwide concern. According to the

International Energy Agency (IEA), the total primary energy supply (TPES) reached a historical high of 13,113 million tons of coal equivalent (Mtce) in 2011, releasing 31,342 million tons of energy-related CO_2 emissions, which is regarded as the major human cause of global warming [1]. China, as a major contributor, accounted for approximately one-fifth of the global TPES and one-fourth of CO_2 emissions. The Intergovernmental Panel on Climate Change (IPCC) reported that the building sector was responsible for 40% of global energy consumption and approximately 25% of global CO_2 emissions [2]. Therefore, a holistic investigation of the embodied energy requirement involving the direct energy input from the onsite production process and the indirect energy consumption from the upstream process becomes imperative [3]. More importantly, ignorance of the environmental pollution caused by interregional trade along with the insufficient understanding of current energy consumption status at the regional and sectoral levels could result in unfair or irrational policies for the construction industry. In addition, given the lack of consideration of regional disparity in traditional perspectives, it is also critical to take account of region-specific characteristics. However, single-region input–output (SRIO) analysis fails to capture the hidden linkage and economic network among interregional trade flows [4–7]. In general, the infinite interrelationship in the supply chain mixes production technology from both domestic and foreign sources. Unfortunately, the SRIO model is applied on the assumption that the manufacturing technology in the domestic production process is the same as the technology used in foreign regions. Therefore, this model is unable to describe these differences in production and economic structure.

Recent improvements in environmental impact accounting allow for a more accurate assessment of embodied energy consumption. Multi-regional input–output (MRIO) model, which presents the environmental interactions by taking account of regional characteristics and sectoral differences, has been extensively studied at the international, national, and regional levels. A clear trend in MRIO analysis is to model energy consumption and carbon emissions embodied in international trade [8–14]. Many studies have also focused on quantifying the embodied energy use and air emissions within the target country because of international trade [15–20]. However, these studies only considered the embodied environmental impacts from the national perspective while ignoring regional disparities within the country. This oversight presents the challenge of investigating strategies from a regional and industrial sector perspective. Only a very few studies have been conducted in the context of China's economy. Liang et al. [21] employed an MRIO model and scenario analysis to explore regional energy requirements and CO_2 emissions in China, which indicates that the population growth has a significant positive relationship with energy use and emissions. Meng et al. [22] emphasized that emissions transfer embodied in trade flows distorted the actual regional emissions and intensity, which lead to unfair reduction policies from central government. Guo et al. [23] provided insight into the characteristic of China's provincial CO_2 emissions with the application of an MRIO model and concluded that the trend of emissions transfer is from the eastern areas to the central areas. Liu et al. [24] employed index decomposition analysis based on time-series inventory data to study China's Greenhouse gas (GHG) emissions from the regional and sectoral perspective; their findings emphasized the importance of reducing the disparity of technology on CO_2 emission reduction. Su and Ang [25] developed a hybrid multi-region model to simulate the CO_2 emissions in trade and emphasized that cooperation should be enhanced between developed and developing regions in China to reduce emissions. Zhou et al. [26] and Guo et al. [27] mainly focused on the measurement of GHG emissions by applying input–output analysis at the urban level; the former study was based on statistical data in 2002, whereas the later one used an input–output table from 2007.

In addition, only a few studies have been undertaken at the industrial level, especially in the construction industry. Wang et al. [28–29] conducted a number of studies regarding the sustainability of the construction industry in China, including the comparison of energy conservation regulations and analysis of sustainable design options. By using input–output analysis, Chang et al. [30–33] conducted a series of studies to measure the sustainability performance of construction projects in China. In addition to the quantification of embodied energy consumption, they also considered the environmental and society indicators by using a SRIO model. Chang and his colleagues also simulated the life cycle energy performance of certain types of building by combining process-based LCA method with an input–output model.

With the aid of a multi-regional input–output model that can reflect the economic interactions in interregional trade, this study evaluates the energy use embodied in the construction industry of China by considering regional diversity and technological differences. This study will help decision makers achieve equitable energy reduction policies at the national or regional level.

2. Methodology and data source

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2.1 Method

The MRIO model has been regarded as an efficient tool and technique to measure environmental impacts from the top-down perspective for many years [34–36]. This model integrates the regional and sectoral energy input flows into economic monetary flows by using input–output analysis. The format of the revised MRIO table is shown in Table 1.

Table 1 Revised MRIO table in 2007

<table>
<tr><td colspan="2" rowspan="4">Input</td><td colspan="10">Output</td><td rowspan="4">Total output</td></tr>
<tr><td colspan="7">Intermediate use</td><td colspan="3">Final use</td></tr>
<tr><td colspan="3">R1</td><td>…</td><td colspan="3">Rm</td><td rowspan="2">R1</td><td rowspan="2">…</td><td rowspan="2">Rn</td></tr>
<tr><td>S1</td><td>…</td><td>Sn</td><td>…</td><td>S1</td><td>…</td><td>Sn</td></tr>
<tr><td rowspan="3">R1</td><td>S1</td><td colspan="7" rowspan="8">u_{ij}^{rk}</td><td colspan="3" rowspan="8">v_i^{rk}</td><td rowspan="8">O_i^r</td></tr>
<tr><td>…</td></tr>
<tr><td>Sn</td></tr>
<tr><td>…</td><td>…</td></tr>
<tr><td rowspan="3">Rm</td><td>S1</td></tr>
<tr><td>…</td></tr>
<tr><td>Sn</td></tr>
<tr></tr>
<tr><td colspan="2">Direct energy input</td><td colspan="7"></td></tr>
</table>

According to Table 1, the basic monetary balance in the input–output table can be expressed as

$$O_i^r = \sum_{k=1}^{m}\sum_{j=1}^{n} u_{ij}^{rk} + \sum_{k=1}^{m} v_i^{rk} \tag{1}$$

where O_i^r represents the monetary value of the total output of sector i in region r, and we assumed that there are m regions and each region has n sectors; u_{ij}^{rk} represents the monetary input from sector i in region r as intermediate use to sector j in region k; v_i^{rk} represents the monetary value of the total final use in region k provided by sector i in region r, which normally includes final consumption (e.g. rural and urban household, government consumption, gross fixed capital formation, and stock increase), exports, and other balanced items.

Combined with the energy flows, the energy balance of sector i in region r can be expressed as

$$e_i^r O_i^r = \sum_{k=1}^{m} \sum_{j=1}^{n} e_j^k u_{ji}^{rk} + q_i^r \tag{2}$$

where e_i^r is the embodied energy intensity of products from sector i in region r, e_j^k is the embodied energy intensity of products from sector j in region k. q_i^r is the direct energy consumption of sector i in region r.

Note that $m \times n$ equations are established under the whole economy, vectors and matrixes that can therefore be introduced to simplify the mathematical expression.

Nominate $E^T = \begin{bmatrix} \begin{pmatrix} e_1^1 \\ \dots \\ e_n^1 \end{pmatrix} \\ \dots \\ \begin{pmatrix} e_1^m \\ \dots \\ e_n^m \end{pmatrix} \end{bmatrix}$ $Q^T = \begin{bmatrix} \begin{pmatrix} q_1^1 \\ \dots \\ q_n^1 \end{pmatrix} \\ \dots \\ \begin{pmatrix} q_1^m \\ \dots \\ q_n^m \end{pmatrix} \end{bmatrix}$ $O = \begin{bmatrix} o_1^1 & 0 & \dots & 0 \\ 0 & o_2^1 & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & o_n^m \end{bmatrix}$

$$U = \begin{bmatrix} \begin{pmatrix} u_{11}^{11} & \dots & u_{1n}^{11} \\ \dots & \dots & \dots \\ u_{n1}^{11} & \dots & u_{nn}^{11} \end{pmatrix} & \dots & \begin{pmatrix} u_{11}^{1m} & \dots & u_{1n}^{1m} \\ \dots & \dots & \dots \\ u_{n1}^{1m} & \dots & u_{nn}^{1m} \end{pmatrix} \\ \dots & \dots & \dots \\ \begin{pmatrix} u_{11}^{m1} & \dots & u_{1n}^{m1} \\ \dots & \dots & \dots \\ u_{n1}^{m1} & \dots & u_{nn}^{m1} \end{pmatrix} & \dots & \begin{pmatrix} u_{11}^{mm} & \dots & u_{1n}^{mm} \\ \dots & \dots & \dots \\ u_{n1}^{mm} & \dots & u_{nn}^{mm} \end{pmatrix} \end{bmatrix}$$

where E and Q are the embodied energy intensity vector and direct energy input vector with $m \times n$ dimension, E^T and Q^T are the transpose of E and Q, respectively; O is the diagonal matrix with $m \times n$ entries, and the coefficients in matrix O are equal to the total economic output. U is the intermediate input matrix in the input–output table with $m \times n$ entries. For the whole economic system, the above group of equations can be expressed in the form of a matrix

$$EO = EU + Q \tag{3}$$

which can be further transformed into

$$E = Q(O-U)^{-1} \tag{4}$$

2.2 Indicators

Based on the embodied energy intensity calculated in Equation (4), the energy use embodied in the final demand can be simply deduced for a general situation. However, as only the construction industry is the focus of this study, further clarification is needed to help understand the embodied energy intensity and interregional energy transfer of the provincial construction industry.

(1) *Embodied energy intensity*. Embodied energy intensity measures the direct and indirect energy input within the entire supply chain of the construction industry, which represents the total energy consumption per unit monetary value in the construction sector. The energy intensity vector for the provincial construction industry $E_c = [e_c^1, e_c^2, ..., e_c^m]$ can be extracted from vector E in section 2.1.

(2) *Sectoral embodied energy input*. Investigating sectoral embodied energy input provides insight to understand the environmental connections among different sectors. The embodied energy input from sector i to the construction industry can be given as

$$EES_i = \sum_{r=1}^{m} \sum_{k=1}^{m} e_i^k u_{ic}^{kr} \tag{5}$$

(3) *Energy embodied in interregional imports and exports*. Analyzing energy use embodied in interregional trade facilitates an exploration of the hidden linkages from regions that produce energy to regions that consume energy. The computational process can be given by

$$IM_c^r = \sum_{k \neq r}^{m} \sum_{i=1}^{n} e_i^k u_{ic}^{kr} \tag{5}$$

$$EX_c^r = e_c^r \left(\sum_{k \neq r}^{m} \sum_{j=1}^{n} u_{cj}^{rk} + \sum_{k \neq r}^{m} d_c^{rk} \right) \tag{6}$$

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where IM_c^r represents the energy use embodied in interregional imports to the construction industry in region r, EX_c^r represents total energy use due to exports from the construction industry in region r, d_c^{rk} represents the final use of region k provided by the construction industry in region r.

2.3 Data source and processing

The latest available MRIO table was compiled by the Chinese Academy of Science in 2007, which provided the economic interaction data on China's 30 regions (including 4 municipalities, 4 autonomous regions, and 22 provinces) for 30 sectors. Tibet is excluded in this table because of the unavailability of data. Therefore, considering the aforementioned theory, the value of m and n are both 30 in this study. The MRIO table 2007 is compiled under the noncompetitive import assumption, which can effectively avoid the distortion of energy use embodied in the interregional trade [37, 38]. The imports item from international trade has been removed to concentrate on the interregional trade flow in China.

Sectoral direct energy input data among different regions are obtained and derived from two sources: the provincial statistical yearbooks and the regional energy balance tables in the Chinese energy statistical yearbook. In addition to the total energy use, the other nine major energy sources are also studied, namely, coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, natural gas, and electricity.

Although the MRIO table provides detailed economic and trade data, the availability of direct energy use data that specifically match the sector classification is a constraint. This constraint is exacerbated by the demand of detailed energy types in this study. More importantly, the format of the provincial statistical yearbook is also inconsistent across different regions. Therefore, the data processing method used in the study by Guo et al. [23] has been also adopted in case of lack of statistics on sectoral energy consumption.

3. Embodiment analysis of the regional energy use of China's construction industry

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3.1 Energy use embodied in the construction industry

3.1.1 Spatial analysis

The total energy use embodied in the construction industry of 30 regions in 2007 is shown in Figure 1. Clearly, the construction industry in China is a typical demand-driven industry where gross fixed capital formation represents the highest relative contribution in all final demand categories. The total embodied energy use from the construction industry in China is 793.74 Mtec, which accounts for approximately 29.6% of the total national energy consumption. This result is also consistent with the study by Chang et al. [30]. In addition, the construction industry of Zhejiang (R11) consumed the most embodied energy of 57.91 Mtec, followed by Jiangsu (R10) with 55.13 Mtec, and Henan (R16) with 49.62 Mtec. However, the underlying fundamentals that drive the energy consumption are different. The energy requirement in Zhejiang (R11) and Jiangsu (R10) is driven by the large amount of local construction activities, whereas the effects of energy intensity involved in the construction process within these two places are negligibly small. Instead, the driving factor for Henan (R16) is the high energy intensity. By contrast, despite the lower amount of energy consumption in Ningxia (R29) and Shanxi (R4), these regions still have drawbacks on high energy intensity because of their inefficient manufacturing and production process. In addition, region division in China is normally based on geographic relationship [21, 22]. However, this study categorizes China based on the value of energy intensity, which aims to provide a holistic map to represent their level in production technology of the construction industry.

Table 2 Description of area categories

Area	Province/municipality	Energy intensity (Tonnes per 10^4 RMB)	Geographic location
1	Hainan (R21), Fujian (R13), Guangdong (R19)	=<1.0E–04	Southern Coastal
2	Jiangxi (R14), Shandong (R15), Anhui (R12), Beijing (R1), Jiangsu (R10), Zhejiang (R11), Shanghai (R9)	1.0E–04~1.2E–04	Central–Eastern Coastal
3	Tianjin (R2), Hebei (R3), Guangxi (R20)	1.2E–04~1.4E–04	-
4	Xinjiang (R30), Yunnan (R25), Liaoning (R6), Hubei (R17)	1.4E–04~1.6E–04	-
5	Gansu (R27), Hunan (R18), Qinghai (R28), Shanxi (R26), Inner Mongolia (R5), Sichuan (R23), Chongqing (R22), Guizhou (R24)	1.6E–04~1.8E–04	West
6	Jilin (R7), Heilongjiang (R8)	1.8E–04~2.0E–04	Northeast
7	Henan (R16), Shanxi (R4), Ningxia (R29)	>=2.0E–04	Central

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Table 2 shows that a geographical relationship is still existing although all regions are divided according to the value of energy intensity. The southern coastal area, eastern coastal, and some parts of the central area have shared similar low energy intensity in the construction industry, which is mainly due to their developed economy and advanced production technology. For regions in the northeast, west, and several places in the central area, the construction industries are representing energy intensive because of their underdeveloped economy and inefficient production process.

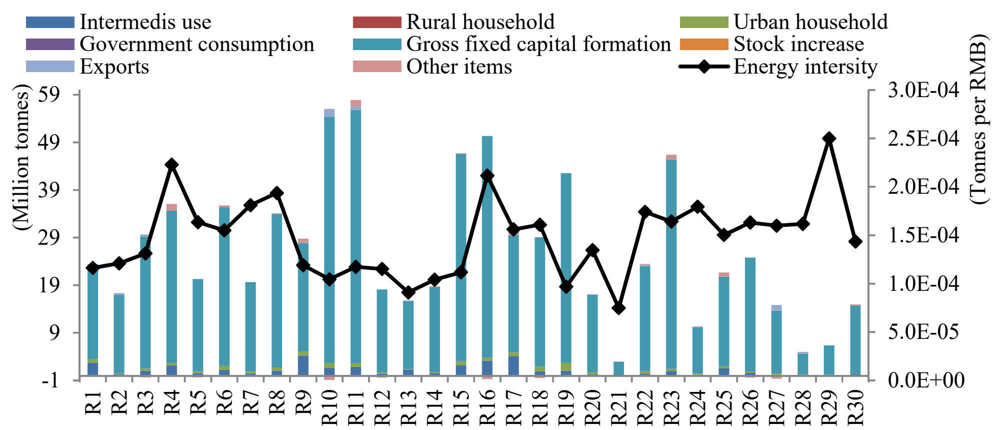

Figure 1. Total energy use embodied in the construction industry by region in terms of demand category

To reflect the current energy consumption status and importance of the construction industry in each region, all 30 regions were further divided into four groups according to their energy intensity and total amount of energy use (see Figure 2). It's worth noting that Shanxi (R4), Liaoning (R6), Heilongjiang (R8), Henan (R16), and Sichuan (R23) in the upper right quadrant not only carried out extensive construction activities but also exhibited higher energy intensity. The energy consumption of the construction industry in Jiangsu (R10), Zhejiang (R11), Shandong (R15), and Guangdong (R19) in the upper left quadrant was mainly driven by their large scale of construction activities. The construction industry in Inner Mongolia (R5), Jilin (R7), Hunan (18), Chongqing (R22), Guizhou (R24), Shaanxi (R26), Gansu (R27), Qinghai (R28), and Ningxia (R29) in the lower right part was driven by high energy intensity.

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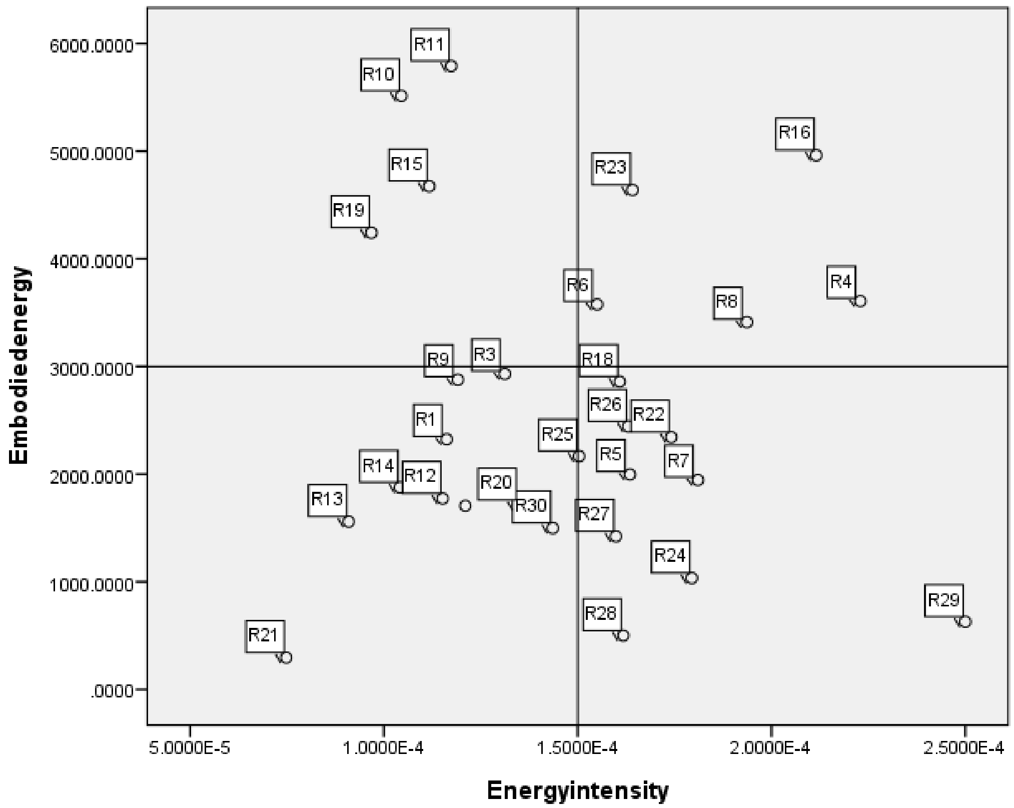

Figure 2. Distribution of thirty regions in categorization coordinates

Ten types of energy have been investigated for the construction industry of each region. However, to avoid double-counting problems that arise from calculating the relative percentage of different energy types, all energy sources have been combined into four types of primary energy, which have been analyzed and presented in Figure 3. With regard to the proportion of primary energy use for each region, coal dominates in all energy types with the percentage ranging from 29.69% in Hainan to 72.03% in Shanxi. This situation could be better understood by especially considering the fact that the consumption of cement and steel in the construction industry was 934.51 and 224.79 Mt in 2007, which accounted for 73.76% and 19.87% of primary material use in China [39]. Coal and crude oil, as the fundamental energy sources for cement and steel production, were consequentially consumed most in the total embodied energy use. In summary, the construction industry in China is typical fossil fuel energy oriented, which leads to a large amount of ecological damage.

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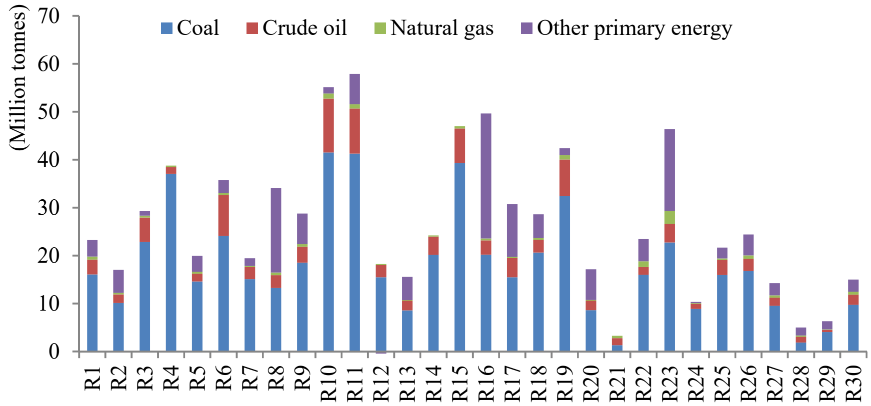

Figure 3. Percentage of different primary energy categories among different regions

3.1.2 Sector analysis

In addition to provide regional environmental connections, MRIO model also explores the hidden linkage among different economic sectors. Table 3 shows the rankings of all energy suppliers for the construction industry across China's entire economy. The following can be identified as the top ten correlated sectors in the construction industry of China: manufacturing of non-metallic mineral products (S13), smelting and pressing of metals (S14), transportation, storage, post, and telecommunications (S25), chemical industry (S12), manufacturing of metal products (S15), manufacturing of electrical machinery and equipment (S18), manufacturing of general and special purpose machinery (S16), processing of petroleum, coking, processing of nuclear fuel (S11), other services (S30), and production and distribution of electric power and heat power (S22). Among them, manufacturing of non-metallic mineral products (S13) and smelting and pressing of metals (S14) represent the highest relative contribution to the embodied energy use from the construction industry in terms of coal, coke, crude oil, fuel oil, natural gas, and electricity. Simultaneously, transportation, storage, post, and telecommunications (S25) is the dominant energy suppliers for gasoline, kerosene, and diesel oil consumption. Besides, the service sector also plays an important role in upstream process of building construction, with energy consumption being mainly a result of labor, financial, and real estate related activities.

Table 3 Rankings of energy suppliers by sector in terms of different energy types

	Total energy	Coal	Coke	Crude oil	Gasoline	Kerosene	Diesel oil	Fuel oil	Natural gas	Electricity

S1	21	22	20	19	19	19	16	21	18	20
S2	16	13	17	23	21	21	18	24	22	19
S3	29	29	29	29	29	29	29	29	29	29
S4	30	30	30	30	30	30	30	30	30	30
S5	4	11	12	11	11	12	9	12	13	10
S6	27	26	28	25	25	27	25	28	26	26
S7	25	25	27	26	28	28	27	26	25	25
S8	23	24	25	22	22	23	22	19	24	23
S9	12	12	11	12	12	11	12	11	12	11
S10	19	20	19	24	24	22	24	20	23	21
S11	11	7	14	3	13	10	13	8	5	12
S12	3	4	6	5	6	8	6	4	3	3
S13	1	1	2	1	2	2	2	1	1	2
S14	2	2	1	2	3	3	3	2	2	1
S15	6	5	3	7	9	9	7	7	9	4
S16	8	8	5	9	8	7	8	9	10	7
S17	18	17	10	16	16	15	17	16	16	16
S18	7	6	4	6	5	5	5	6	8	5
S19	26	27	26	27	27	25	26	25	27	27
S20	28	28	24	28	26	26	28	27	28	28
S21	13	18	15	17	20	18	19	17	21	17
S22	9	3	13	10	15	14	11	5	6	6
S23	20	19	23	18	23	24	23	18	14	18
S24	15	15	9	15	14	16	14	14	19	14
S25	5	9	7	4	1	1	1	3	4	9
S26	14	14	16	13	7	4	10	13	11	13
S27	22	21	22	20	18	17	20	22	17	22
S28	17	16	18	14	10	13	15	15	15	15
S29	24	23	21	21	17	20	21	23	20	24
S30	10	10	8	8	4	6	4	10	7	8

3.2 Energy use embodied in interregional trade

The energy use embodied in interregional imports and exports is shown in Figure 5. Zhejiang (R11) is the leading region with importing embodied energy flow of 24.38 Mtce, followed by Jiangsu (R10, 16.39 Mtce), Beijing (R1, 15.24 Mtce), and Shaanxi (R26, 13.31 Mtce). Shaanxi is also the largest exporter with 9.45 Mtce of embodied energy outflow, followed by Henan (R16, 6.44 Mtce), Hunan (R18, 6.40 Mtce), and Sichuan (R23, 4.90 Mtce). Except for Henan (R16) and Hunan (R18), the remaining 28 regions have positive net embodied energy use, which implies that their construction industry receives energy input from other regions' economy. A close examination of the imports indicates that the energy flow due to interregional trade of construction activities represents a highly region-concentrated distribution. Hebei (R3), Henan (R16), Shaanxi (R26), and Liaoning (R6) have been identified as the major energy suppliers for the construction industry of three economic areas in China. The energy outflow from Henan is dominant in energy imports of Yangtze River Delta area [Shanghai (R9), Jiangsu (R10), and Zhejiang (R11)], accounting for 10.02%, 14.74%, and 16.25% of their total energy imports. Hebei is the primary energy supplier of the Circum–Bohai Sea economic area [Beijing (R1) and Tianjin (R2)], and is responsible for 64.50% and 43.26% of their total imported energy use. Liaoning (R6), Jilin (R7), and Heilongjiang (R8) constitute the northeast area of China where the energy flows represent multi-direction distribution.

Such spatial distribution may have arisen for two reasons. First, developed regions along the eastern coast are highly dependent on the natural and energy resources from central and western parts of China according to their resource limitations. According to the China Statistic Yearbook 2008 [40], as the primary mineral resources for iron, steel, cement, and aluminum production, the ensured reserves of major ferrous metals, major non-ferrous metals, and non-metal minerals of these four regions accounted for 20.92%, 55.39%, and 59.54% of total reserves in China in 2007. This fact made a substantial contribution on energy and resource input in the upstream process of building construction in regions around these resource-abundant areas. Second, a close geographic linkage exists between the energy supply regions and energy required areas because of the convenience of material transportation. Consequently, energy transportation due to interregional imports for the construction industry in China is from the central parts to the eastern coastal areas with a resource-dependent distribution.

Further analysis of energy embodied in exports found that the amount of energy exported from provincial construction industries is scattered among different regions. Such energy outflows are mainly transferred in the form of labor mobility and service supply. More specifically, as the typical labor intensive sector, the construction industry is highly related to the labor input and consulting services provided by professional institutions and enterprises, which is regarded as the major carrier for energy exports from the construction industry. In fact, a further examination of the top four energy exporters shows that Shaanxi (R26), Henan (R16), and Sichuan (R23) are the three largest labor exporters in China. Moreover, the construction industry of Jiangsu (R10) ranked first not only in the number of local construction enterprises but also in the annual revenue in 2007. Such prosperous development of the local construction industry was bound to produce large demand of consulting services.

Hong J.K., *Shen G.Q.P., Guo S., Xue F., Zheng W. (2016). Energy Use Embodied in China's Construction Industry: A Multi-Regional Input-Output Analysis, Renewable & Sustainable Energy Reviews, Vol 53, 1303–1312. DOI: 10.1016/j.rser.2015.09.068, January. (SCI, 5-Year impact factor: 7.445, Ranked 3/29 in Green & Sustainable Science & Technology and 6/88 in Energy & Fuels by JCR in 2015)

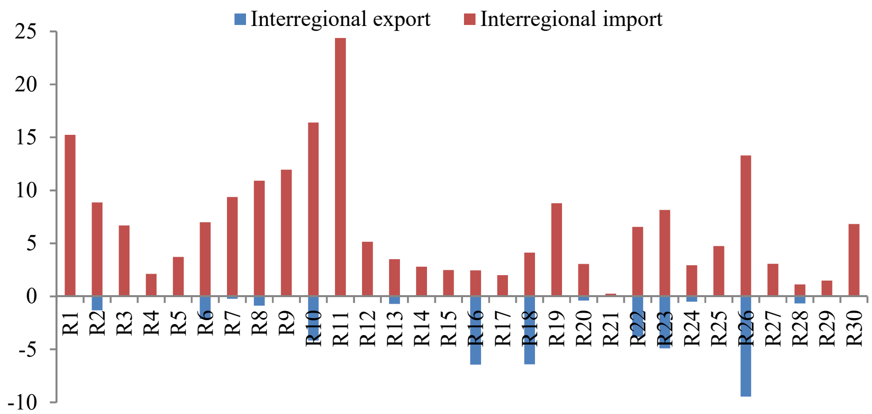

Figure 4. Energy use embodied in interregional imports/exports related to the construction industry

4. Discussions

Since the aim of this study is to analyze the embodied energy use of the construction industry, consideration of the basic features relevant to construction activities is necessary. Therefore, the results obtained in this study have been further validated and compared with previous research. Figure 4 shows the percentage between direct energy input and embodied energy use. The share of direct energy use for the construction industry ranges from 0.7% (Hainan) to 12.02% (Hebei). From the perspective of life cycle analysis, direct energy input for construction projects mainly involves onsite electricity use and fuel consumption by construction equipment and vehicles, whereas the indirect energy use is related to building materials production and transportation in the upstream process. The ratio estimated in this study is in line with previous research where the ratio estimated by the process-based LCA approach ranged from 1.77% to 11.49% [41–44]. This fact further verifies the possible application of the MRIO model for energy assessment in the embodied phase at the industrial or project level.

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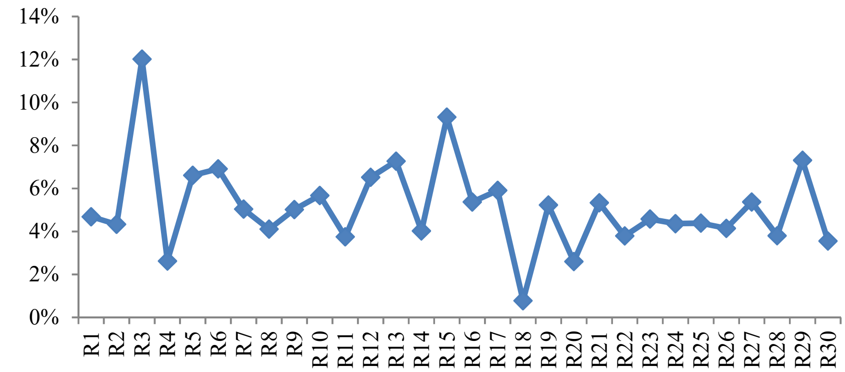

Figure 5. Regional percentage of direct energy input and embodied energy

Recognizing the hidden linkage and energy flow embodied in the interregional trade of the construction industry is of great importance to the holistic understanding of current energy consumption status. According to the aforementioned analysis results, the energy resource flows are from the central part to the eastern coast of China. More specifically, Henan and Hebei province have been identified as the major supplier of the Yangtze River Delta area and the Circum-Bohai Sea economic area. From the traditional production perspective, these energy suppliers need to be restricted by imposing tighter energy policies. However, the exploration of such hidden energy mobility can provide consumption-based insight for policymakers, thereby requiring provinces in developed areas to take more responsibility for reducing the volume of their energy use.

In addition, this study analyzed the embodied energy consumption of the construction industry by taking regional diversity and technology difference into consideration. More specifically, at the regional level, a number of regions [e.g., Ningxia (R29), Shanxi (R4), and Henan (R16)] need to change their production process into intensive mode and improve their manufacturing technology, eliminating conventional low production efficiency and high energy consuming behavior. The other regions [e.g., Jiangsu (R10) and Zhejiang (R11)] face challenges for their highly increased construction volume. Therefore, upgrading energy productivity and optimization of production structure can be regarded as an offset for such driving force. In addition, the current energy consumption model is still fossil fuel oriented, which is the main source of GHG emissions. Therefore, the energy consumption pattern of the construction industry can be adjusted to become more sustainable and clean by enhancing the utilization of renewable power, such as natural gas and electricity.

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At the sectoral level, the top three energy suppliers of the construction industry, namely manufacturing of non-metallic mineral products (S13), smelting and pressing of metals (S14), and transportation, storage, post, and telecommunications (S25), are typical energy-intensive sectors. They are highly related to a number of basic construction activities in the upstream process, including iron and steel production, cement production, and material transportation. Therefore, on the one hand, the increasing use of environmentally friendly materials with low energy intensity is an effective way to reduce energy consumption in construction activities. On the other hand, the inter-industrial economic relationship needs to be further optimized and upgraded within the entire supply chain.

5. Policy implications

China is now in a rapid development period of urbanization. According to the results in this study, gross fixed capital formation is the major contributor to the energy use embodied in the final demand of the construction industry. In fact, the investments in fixed capital formation are closely related to infrastructure construction, retrofit, refurbishment, and real estate development. Such construction activities are the result of rapid urbanization in China, where the urbanization rate will reach a historic high of 51.5% at the end of “The Twelfth Five-Year Plan (2010–2015)” [45]. This inevitable trend is bound to produce large energy demands. Therefore, implementing a fair and equitable energy reduction policy by considering both direct and indirect energy input as well as the interrelationship at the regional and sectoral levels is of crucial importance.

5.1 Regional policy

A combination of various strategies can be established at the sub-region level of China with regard to the construction industry (see Table 4). Based on the aforementioned region classification (Figure 2), the corresponding strategies can be implemented according to their energy consumption status (see Figure 6).

Table 4 Energy saving strategies

	Strategy
Energy intensity	① Adopting advanced production techniques ② Developing less energy-intensive and high value-added products in identified

	primary energy suppliers
	③ Changing the production process from extensive mode to intensive mode
	④ Improving energy productivity
	⑤ Innovative construction techniques (precast construction)
Energy consumption structure	⑥ Improving the share of renewable and clean energy sources
	⑦ Using less energy-intensive fuels
	⑧ Adopting clean-coal technologies
Production structure	⑨ Switching from energy-intensive industry toward energy-efficient lighter industry;
	⑩ Shifting economic growth pattern from resource-intensive oriented to resource efficient

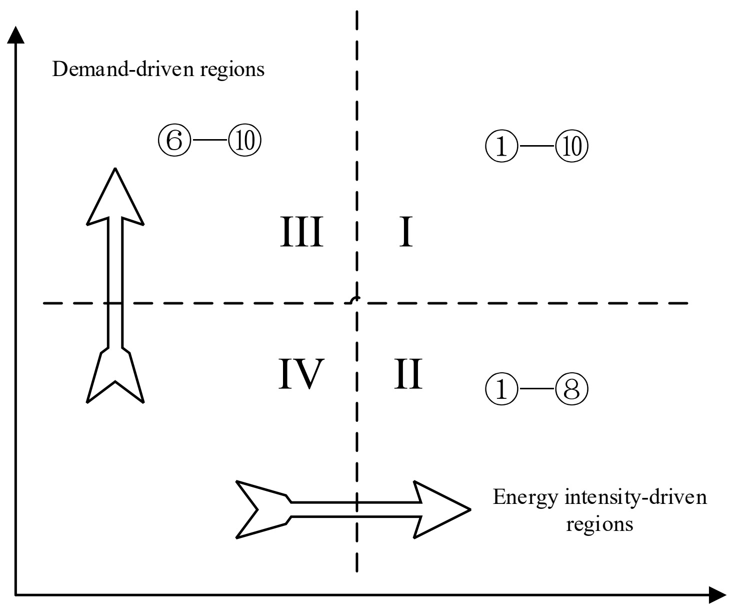

Figure 6 Policy implications for regions with different energy consumption status

The increase of final demand and energy intensity were the major factors that contribute to the growth of embodied energy consumption for the regions in the first quadrant. Therefore, attention should not only be given to improve energy efficiency but also to optimize the energy and production structure, which could offset the energy increment from the rapid growth of final demand. Considering that the application of renewable energy in the building field accounts for only approximately 2% of all energy sources, one effective policy is to optimize the energy consumption structure. It can be achieved by improving the share of renewable and clean energy sources in the construction industry, especially in the regions with abundant renewable energy resources, which can help to compensate for the rapidly increasing energy demands from China’s urbanization. The regions in the second quadrant were driven mostly by the high energy intensity with smaller effects from the increasing volume of final demand. Consequently, authorities should enhance the application of high-efficiency technology and encourage innovative construction techniques. For instance, construction industrialization, which refers to the standard design and production of building materials, units, and components, is an effective method to reduce negative environmental impact due to its high-level quality control. More importantly, housing industrialization is also a critical issue for the development of urbanization in China, which has been emphasized through a series of national guidance and policies, including the Report at the Eighteenth National Congress [46], National Plan on New Urbanization 2014-2020 [47], and Plan on Green Building [48]. The volume of final demand was the primary factor that causes the energy increment for the regions in the third quadrant. Therefore, the policy for the local government should be geared toward optimizing the energy and production structure, which is expected to balance the energy increment from the increase of the final demand.

5.2 Sectoral policy

The results of sectoral analysis revealed the fossil fuel energy-oriented characteristic of the construction industry in China. In fact, the primary building materials (e.g., cement, steel, and aluminum) are highly related to a number of energy-intensive sectors, such as manufacturing of non-metallic mineral products (S13), smelting and pressing of metals (S14). Therefore, from a macroscopic view, central or local government should restructure the economic growth pattern by consistently shifting the production structure from energy-intensive industry towards energy-efficient industry to achieve structural energy savings. From a microscopic view, the selection of building materials plays a major role in energy and emission reduction. Accordingly, encouraging local governments to use low-energy and environmentally friendly materials in the construction industry is critically important, which can guide traditional energy or resource consumption behavior toward a greener and less energy-intensive direction.

5. Conclusions

MRIO analysis has been conducted in this study to explore the direct and indirect energy use due to interregional trade induced by construction activities from a regional and sectoral perspective. The results can be regarded as a solid reference to re-recognize the spatial and sectoral characteristics of embodied energy requirements of the construction industry. The conclusions are as follows:

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(1) The energy use embodied in the entire construction industry is 793.74 Mtec, which is equal to 29.6% of China's total national energy consumption. As a typical demand-driven sector, the gross fixed capital formation represents the highest relative contribution in all final demand categories. In addition, coal and crude oil are extensively consumed during building material production process, implying the fossil fuel oriented characteristic of the construction industry.

(2) Based on the value of construction energy intensity, China (except Tibet) can be divided into seven areas. Regions with high energy intensity are concentrated in the central part, whereas the less energy-intensive regions are located on the southern and eastern coasts. By taking account of different driving forces for energy increment, all regions are further divided into four groups. Such classification enables central or local government to implement specific energy reduction targets.

(3) Five sectors, namely manufacturing of non-metallic mineral products (S13), smelting and pressing of metals (S14), transportation, storage, post, and telecommunications (S25), chemical industry (S12), and mining and processing of non-metal ores (S5), contribute 77.7% of all embodied energy input to the construction industry. Beside, service sector is also highly related to the upstream process of building construction, which consumed energy by providing consulting, financing and real estate services.

(4) Energy imports of the construction industry represent a resource-dependent characteristic with distribution of energy flows from resource-abundant areas in the central part to resource-deficient areas in the eastern coast. By contrast, energy exports are discrete, which mainly transferred energy in the form of labor mobility and service supply.

In summary, policy for the construction industry should focus on encouraging energy efficiency improvements, advanced technology application, and structure optimization in production and energy consumption, rather than on controlling or restricting the volume of consumption demand.

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