Renewable and Sustainable Energy Reviews 53 (2016) 1602–1610

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Optimal embodied energy abatement strategy for Beijing economy: Based on a three-scale input-output analysis

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ARTICLE INFO

Article history:
Received 24 June 2014
Received in revised form
15 June 2015
Accepted 18 September 2015
Available online 10 November 2015

Keywords:
Beijing
Three-scale input-output analysis
Abatement strategy
Embodied energy

ABSTRACT

Energy strategies in China's 11th and 12thzfive-year Plan failed to reduce the total energy consumption and misled the implementation of energy saving measures, as they were focused towards the direct energy input as well as formulated based on incomplete energy consumption information. Therefore, an optimal energy abatement strategy built on comprehensive information on overall embodied energy consumption is in urgent need. Adopting the three-scale input-output analysis, this study uses Beijing as a case to depict a specific urban economy's overall energy consumption impacted by local direct energy use, domestic and foreign trade. The results show that energy embodied in domestic trade dominated Beijing's energy consumption, while local direct energy is accounting for less than 1/3 of Beijing's total embodied energy consumption. The quantity of energy embodied in imports far exceeds that embodied in exports, making the city a net embodied energy importer and indicating that policies considering direct energy use only will cause energy leakage problem. These findings suggest that the current measures such as displacing energy-intensive sectors to other regions lead to “local reduction but overall rise”. Moreover, analysis for five abatement scenarios (average, intensity share, absolute share, discriminatory absolute and discriminatory intensity) was carried out to figure out the optimal abatement strategy for Beijing. Due to less loss of potential output, it is found that intensity share scenario is the optimal one among all the scenarios concerned. Analysis in this study suggests that each region should break limits of self-centered perceptions and multi-scale governance for more appropriate responsibility assignment is recommended for overall energy abatement.

Contents

1. Introduction . . . 1603
2. Methodology and data . . . 1604
   2.1. Three-scale input-output model . . . 1604
   2.2. Scenario analysis . . . 1604
   2.3. Data description . . . 1605
3. Results . . . 1605
   3.1. Sectoral embodied energy consumption . . . 1605
   3.2. Energy embodied in trade balance . . . 1606
   3.3. Energy embodied in final consumption . . . 1606
   3.4. Embodied energy consumption of each district . . . 1607
   3.5. Abatement scenarios . . . 1607
4. Discussion . . . 1608

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http://dx.doi.org/10.1016/j.rser.2015.09.090
1364-0321/

5. Conclusions . . . 1609
Acknowledgments . . . 1609
Appendix . . . 1609
Embodied energy intensities . . . 1609
References . . . 1610

1. Introduction

According to IEA, China emitted 8250 Mt CO_2 via fuel combustion in 2012, accounting for over a quarter of world's total emissions [1]. Fuel related CO_2 emissions from China alone exceed the sum of that from USA and European Union 15. As one of the leading consumers of primary energy and emitters of the carbon emissions around the world, China is under multiple pressures for energy related issues. On one hand, China's energy production capacity cannot satisfy its vast energy requirement, which makes it heavily reliant on energy imports and poses potential threatens to the energy security [2]. On the other hand, the environmental problems such as greenhouse gas emissions (GHGs) and pollution accompanied with energy consumption brought about both domestic and international pressures to China [3–5]. To cope with these pressures, China has long been striving for combating the dilemma of economic growth and energy consumption related problems. Consequently, a series of ambitious energy conservation and emissions reduction goals have been set, and, numerous policy instruments have been implemented to guide China's development in a more sustainable way.

In response to the pressure on climate change, Chinese government solemnly pledged to the international society to reduce China's carbon emissions per unit Gross Domestic Product (GDP) by 40–45% in 2020 on the baseline of 2005 level, during UN climate change Summit 2009 in Copenhagen [6]. At the meantime, blueprint has been drawn to confront the people's dissatisfaction with environmental degradation and social problems caused by excessive energy use. The latest two national five-year plans (11th and 12th), which cover all-around social and economic development initiatives and play the leading role of mapping strategies for China during 2006–2015, devote significant attention to energy conservation and greenhouse gas emissions reduction [7,8]. The newly released 12th five-year plan requires that the energy consumption per GDP should be reduced by 16% by 2015, compared to the level of 2010 and the amount of carbon emissions induced by per unit GDP will also be reduced by 17% in the same period [8]. Further, started from the 11th five-year plan, the government mobilized a national campaign aiming at promoting energy efficiency and low carbon development in 10,000 corporations, especially the largest and least efficient energy consuming enterprises [9].

Resulted from the efforts on national energy regulation, energy intensity was reduced by 19.3% from 2006 to 2010 [8]. However, these policies and measures are not that promising as it seems. Behind the success of decreasing energy intensity, serious problems arose and controversial phenomenon appeared. For instance, contrary to the declining trend of energy intensity, the total amount of energy consumed continued to increase [10,11], reflecting that the energy burden on China has kept growing instead of alleviating. Additionally, it was reported that during the period of the 11th five-year plan, most of the regions in China failed to meet the abatement schedule one year before the deadline. Some local governments made arbitrary decisions such as switching off power and limiting electricity supply to ensure the achievement of the binding energy targets. These extreme measures not only brought inconvenience to life of residents but also led to economic loss [12]. Some industrial users had to leave their factories and mines running short of the full capacity due to lack of power.

The problems mentioned above resulted in a deviation of those policies' original purposes, implying that the energy conservation measures guided by the current strategies such as five-year plans suffer some shortcomings. One key shortcoming is that those strategies for energy conservation and energy intensity decrease in China did not fully consider regional and sectoral heterogeneities, the subsequent results of which are highlighting only the direct energy use of end-users and neglecting the effects of trade [13].

Recent works have been carried out to quantify the energy embodied in trade (i.e., direct and indirect energy consumed during the supply chains of traded goods and services) between different regions at different scales [14–17]. Strong evidence shows embodied energy transfer via interregional trade further influences the regional energy indicators such as the real energy consumption, energy use per capita and energy use per unit GDP [18,19]. The picture of real energy consumption in terms of embodied energy consumption is in stark contrast to the nominal energy use in terms of direct energy input. For example, Zhang et al. [20] shows that embodied energy requirements of some eastern provincial regions such as Beijing, Shanghai, Guangdong, Zhejiang, and Jiangsu (energy consumer) are several times of their direct energy inputs. However, the situation for some western provincial regions such as Inner Mongolia, Shanxi, Xinjiang (energy producer) is the exact opposite. The inconformity of achievement performance of the different regions also correlates to the embodied energy flows between the producers and consumers. Most of the eastern regions have favorable conditions to fulfill the energy conservation targets because energy-intensive industries contribute smaller proportion to their economies. Ultimately, the satisfaction of energy requirements of eastern regions displaces the direct energy use related environmental impacts in western regions. That explains why it is easier for the eastern regions to have better performance of completing the mandate objectives than western regions, as the current policies neglect the indirect effects.

Another vital shortcoming of the current energy regulation strategy originates from the energy abatement responsibility assignment mechanism. As reported, central government reallocates the energy reduction tasks to each provincial region by setting up mandate targets through administrative negotiations rather than rational planning based on scientific evaluation [21]. Furthermore, the current energy abatement policies are also confined in the framework of the direct energy accounting. The absurd energy-saving phenomenon as well as the disturbances in the socio-economy has shown that the current policies are not appropriate as they are not built on solid scientific basis. Therefore, systematic assessment should be performed to streamline energy abatement rationally in the context of overall energy abatement [22].

In this article, the case we choose is Beijing, the capital city of China which faces with great challenges, to study its embodied energy consumption by taking the impacts of both domestic and foreign trade into consideration. Beijing is an ideal case to study the embodied energy due to its tertiary industry dominated economic structure and heavy dependence on domestic and international trade. Moreover, Beijing's energy regulation tasks are also allocated to its sub-regions under the municipal government administration. Various regulation scenarios are analyzed to find out a reasonable energy regulation scheme in virtue of the directional distance function based on the embodied energy consumption. Therefore, we can establish a more reasonable energy conservation mechanism through the both the embodied energy and energy regulation scenario analysis.

2. Methodology and data

2.1. Three-scale input-output model

Input–output analysis is a powerful instrument to stimulate embodied energy flows in a specific economic system [15,23,24]. For urban regions, a certain number of studies have accounted the energy and environmental emissions embodied in commodities flowing into and outside the city boundary based on input–output analysis [25–27]. However, these literatures can be regarded as single scale analysis, i.e., they consider the local, domestic and foreign have the same embodied energy or emission intensity. This treatment would lead to significant uncertainties as the industrial structure, the types of resources consumed and technology level in one region are most likely different from those in another region [18,28–33]. Therefore, to reflect the actual energy consumption by an urban economy, it is vital to differentiate the energy embodied in commodities from different scales. A good choice for regional ecological element modeling is to employ the multi-scale approach [34,35]. As the economic input–output table lists the information on input from local, domestic and foreign sources, a three-scale input–output method based on three-scale energy intensity database was adopted. The detailed illustration of the three-scale input–output method is elaborated as follows.

According to Chen et al. [36], the physical balance of energy of Sector i in Beijing based on three-scale input–output model can be described as:

$$C_i+\sum_{j=1}^{n} e_j^L z_{j,i}^L+\sum_{j=1}^{n} e_j^D z_{j,i}^D+\sum_{j=1}^{n} e_j^F z_{j,i}^F=e_i^L x_i \tag{1}$$

where C_i denotes the direct energy input into Sector i, $e_{j,i}^L$, $e_{j,i}^D$ and $e_{j,i}^F$ denotes the corresponding embodied energy intensity of local intermediate input ($e_{j,i}^L$), domestic intermediate input ($e_{j,i}^D$) and foreign intermediate input ($e_{j,i}^F$) assigned from Sector j to Sector i, x_i is the vector of total output of Sector i.

The corresponding equation can be expressed in a compressed matrix form as:

$$C+E^LZ^L+E^DZ^D+E^FZ^F=E^LX \tag{2}$$

where $C=[c_i]_{1\times n}$, $E=[e_i]_{1\times n}$, $Z=[z_{i,j}]_{n\times n}$, and diagonal matrix $X=[x_{i,j}]_{n\times n}$, where $i,j\in(1,2,\ldots,n)$,$x_{i,j}=x_i(i=j)$, and $x_{i,j}=0(i\neq j)$.

Matrix C can be obtained from the vector of direct energy input, combined with properly given intermediate input matrix Z^F,Z^D,Z^L total output matrix X^, and the domestic and foreign embodied mercury intensity matrix E^F,E^D,the three scale embodied energy intensity matrix is E^L obtained as:

$$E^L=(C+E^DZ^D+E^FZ^F)(X-Z^L)^{-1} \tag{3}$$

Thus, the embodied energy consumption ($C_{embodied}$) by Beijing economy can be calculated as follows:

$$C_{embodied}=EB \tag{4}$$

where B is the output of Beijing economy in the commodities set.

For the calculation of energy embodied in trade, the energy embodied in trade balance (EEB) can be formulated as:

$$EEB=EEI-EEE \tag{5}$$

where EEI representing for energy embodied in imports can be derived by multiplying the corresponding embodied energy intensities with the amount of imports from domestic and foreign scales, EEB denoting energy embodied in exports can be obtained in the same way.

2.2. Scenario analysis

The scenario analysis is based on an approach named directional distance function, which has been extensively used in the area of energy and environment modeling, as both the desired and undesired outputs can be revealed by using this approach [37–39]. Investigated in this study are five possible principles to distribute the quantities of abatement responsibilities of energy consumption between the entities:

(1) Average Principle (AP): All the districts are treated equally as each district is requested to reduce the same percentage of energy intensity in the period concerned. And the difference between each district's absolute amounts of energy is not taken into consideration.
(2) Intensity share principle (ISP): The energy abatement task is allocated based on the weight of energy intensity for each district, i.e., the contribution of each district's energy intensity to the Beijing's overall energy intensity. The heavier the weight the district has, the more abatement responsibility it will hold.
(3) Absolute share principle (ASP). The energy abatement target for each district is assigned according to the ratio of the absolute amount of energy consumed by a specific district to Beijing's total energy consumption. The higher the ratio is, the more abatement responsibility the district will take.
(4) Discriminatory intensity principle (DIP). All the districts are divided into various subsets and each district within the same subset take the same responsibility. The energy abatement tasks for subsets are allocated in the same way as for ISP while each subset is discriminated.
(5) Discriminatory absolute principle (DAP). The first step is also to divide all the districts into different subsets like DIP and the districts in the same subset share the same abatement responsibility. Each subset is discriminated and the abatement responsibility for each subset is assigned based on ASP.

Energy consumption is considered as undesirable outputs under regulation in the production process. Therefore, the nominal output can be estimated in a joint production framework that includes desirable and undesirable outputs. Originated from [40], directional distance function has been widely used in research fields such as environmental efficiency [41] and energy performance [42]. We employed the directional distance function to evaluate the output cost variance in various abatement scenarios. During the production process, the entities use x ($x\in R_+^N$) as the inputs to generate a series of desirable output y ($y\in R_+^M$) such as industrial added value along with some undesirable output b ($b\in R_+^H$) like energy consumption.

Conceptually, the direction distance function can be described as:

$$\mathrm{S}=\{(x,\ y,b)x \text{ can produce } y \text{ and } b\} \tag{6}$$

Following our previous research [22], the present study assumes that capital and labor are the major inputs while GDP and energy consumption is desirable and undesirable output, respectively. Moreover, according to Färe et al. [43], the output set S is often assumed to be a closed set.

As the strong disposability is considered as irrational, the weak disposability assumption should be imposed on S for a reasonable model of joint-production [44,45]. The weak-disposability assumption implies that undesirable output such as energy consumption abatement in this study comes at a cost of reductions in GDP. Following these previous studies, the directional distance functions of different abatement allocations can be expressed as follows:

$$\begin{aligned}
&\beta_w^* = \max \beta_w \\
&s.t. \sum_{k=1}^{K} z_k x_n^k \le x_n^{k'}, n = 1, 2, ..., N \\
&\sum_{k=1}^{K} z_k y_m^k \ge (1+\beta_w) y_m^{k'}, m = 1, 2, ..., M \\
&\sum_{k=1}^{K} z_k b_h^k \ge b_h^{k'}, h = 1, 2, ..., H \\
&z_k \ge 0, k = 1, 2, ..., K
\end{aligned} \tag{7}$$

where Z is a vector of embodied energy intensity variables and β denotes the scaling factors.

Accordingly, the regulated vision of the directional distance function for districts can be described as:

$$\begin{aligned}
&\beta_s^* = \max \beta_s \\
&s.t. \sum_{k=1}^{K} z_k x_n^k \le x_n^{k'}, n = 1, 2, ..., N \\
&\sum_{k=1}^{K} z_k y_m^k \ge (1+\beta_s) y_m^{k'}, m = 1, 2, ..., M \\
&\sum_{k=1}^{K} z_k b_h^k = b_h^{k'}, h = 1, 2, ..., H \\
&z_k \ge 0, k = 1, 2, ..., K
\end{aligned} \tag{8}$$

Hence, in the case of all the undesirable outputs are regulated, scaling factor of District k can be obtained as:

$$\rho_k = \beta_w^* - \beta_s^*, k = 1, 2, ..., K \tag{9}$$

And the corresponding cost of nominal output can be defined as $\rho_k Y$.

2.3. Data description

The data on Beijing comes from Beijing Statistical Yearbook [46]. Beijing, the capital city of China, covers an area of 16,410.54 Km^2. After China implemented its reform and opening policies, the extraordinary economic achievement has been seen in Beijing. The local GDP of Beijing reached 1411.4 billion Yuan, compared to 10.9 billion Yuan in 1978. Per capita of Beijing amounted to 75,943 Yuan in 2010, equivalent to 11,218 US dollars. Tertiary industry dominates the economy, contributing over three quarters of the total, followed by secondary industry’s 24% and primary industry’s 1%. Along with the economic growth and rural-to-urban migration, the population also witnessed annual growth and its permanent resident has increased from 8.72 million in 1978 to 19.62 million in 2010.

Up to 2010, the municipal city has been divided into 14 districts and 2 counties (here district and county are at the same administrative level and we use district to stand for county thereafter), namely, Dongcheng (DC), Xicheng (XC) (Chongwen and Xuanwu have been merged with Dongcheng and Xicheng since 2010), Chaoyang (CY), Fengtai (FT), Shijingshan (SJS), Haidian (HD), Mentougou (MTG), Fangshan (FS), Tongzhou (TZ), Shunyi (SY), Changping (CP), Daxing (DX), Huairou (HR), Pinggu (PG), Miyun (MY) and Yanqing (YQ). Out of the 16 county regions, Dongcheng, Xicheng, Chongwen, Xuanwu, Chaoyang, Fengtai, Shijingshan, Haidian are called the 8 urban districts, as they together form Beijing’s urban areas.

Table 1
Basic information of each district in Beijing.

District	Land	Population	GDP (Billion RMB)			
	Km^2	10^4 person	Primary industry	Secondary industry	Tertiary industry	Total
DC	41.86	91.90		5.58	116.78	122.36
XC	50.53	124.30		22.19	183.58	205.77
CY	455.08	354.50	0.14	32.08	248.20	280.42
FT	305.80	211.20	0.10	17.81	55.57	73.48
SJS	84.32	61.60	0.00	12.71	16.84	29.55
HD	430.73	328.10	0.14	39.90	237.12	277.16
FS	1989.54	94.50	1.45	23.77	11.93	37.15
TZ	906.28	118.40	1.48	16.76	16.25	34.48
SY	1019.89	87.70	2.22	37.35	47.22	86.79
CP	1343.54	166.10	0.56	19.63	19.80	39.99
DX	1036.32	136.50	1.76	11.72	17.71	31.19
MTG	1450.70	29.00	0.14	4.45	4.06	8.64
HR	2122.62	37.30	0.68	8.96	5.16	14.80
PG	950.13	41.60	1.27	5.49	5.05	11.79
MY	2229.45	46.80	1.64	6.39	6.11	14.15
YQ	1993.75	31.70	0.86	1.90	4.01	6.77

Table 1 summarizes some basic information of the 16 county regions in Beijing [47]. As shown in Table 1, owing to the location advantage and development of tertiary industry, the 8 urban districts concentrate a large share of Beijing's wealth, especially Haidian, Chaoyang, Xicheng and Dongcheng, together with a percentage 62.77% of the total GDP. On the contrary, the suburban county regions have comparative lower GDP due to the comparatively backward industrial structure and regional disadvantage. Yanqing and Mentougou have the lowest GDP with the value of 6.77 billion RMB and 8.64 RMB.

Contrary to GDP, the suburban county regions, most of which are larger than 1000 Km^2, cover the majority part of Beijing. Miyun has the largest land area up to 2229 Km^2, while the smallest Dongcheng has an area of less than 50 Km^2. Benefiting from the large land area, the government now promotes agriculture and industry development in these suburban areas. Haidian has the largest population, with a number of over 2 million people, followed is Chaoyang with a number of 1.78 million. Huairou has the smallest population, only 0.26 million people inhabit in this county.

The embodied energy intensities at domestic and global scale are demonstrated in Appendix Table A1 and Table A2. According to the 12th five-year plan, Beijing's per unit GDP energy intensity should decrease by 17% in 2015 compared to that in 2010. Hence, the annual decrease rate is 3.4% in the same period.

3. Results

3.1. Sectoral embodied energy consumption

Fig. 1 shows the three-scale sectoral embodied energy intensities of Beijing economy 2010. The average embodied energy intensity of all the 42 sectors is 30.71 GJ/10^4 RMB, slightly lower than that in 2007 (31.13 GJ/10^4 RMB) estimated by Guo [48]. Among all the three scales, energy embodied in domestic trade is responsible for the majority of sectoral embodied energy intensity, with a proportion of about 60%. Followed is local direct energy use, contributing about a quarter to the average sectoral embodied energy intensity. Energy embodied in foreign trade which plays a less important role was responsible for less than 15% of the three-scale embodied energy intensity.

Presented in Fig. 2 is the structure of embodied energy intensity contributed by each scale. It is obvious that the top 3 energy-

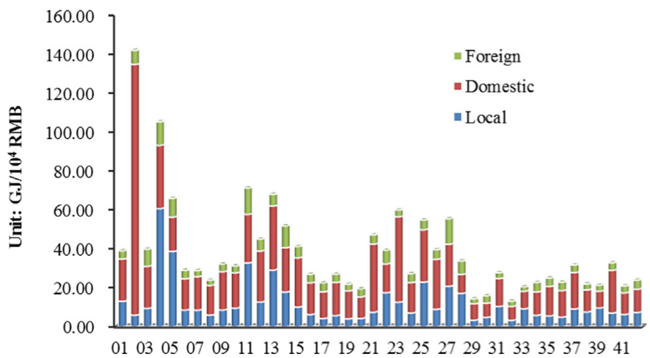

Fig. 1. Three-scale sectoral embodied energy intensities.

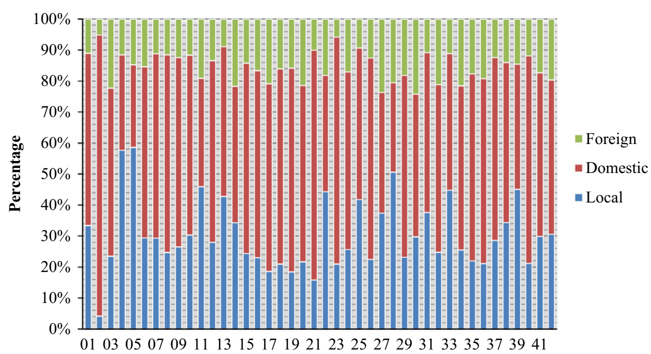

Fig. 2. The structure of the three-scale embodied energy intensity.

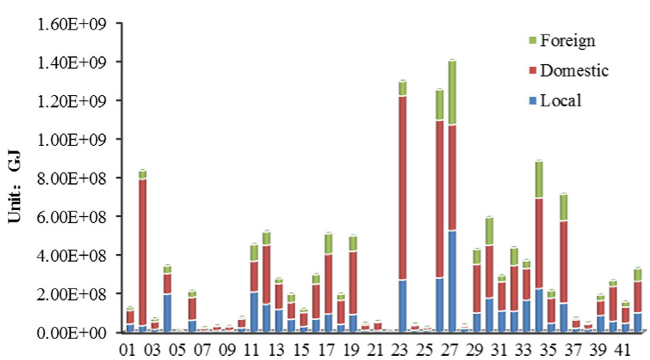

Fig. 3. The sectoral embodied energy consumption.

intensive sectors all belong to secondary industry (Sector 2–26). For each 10,000 RMB of output, Sector 2 (*Coal Mining and Dressing*) requires 141.99 GJ embodied energy, followed by Sector 4 (*Ferrous and Nonferrous Metals Mining and Dressing*)'s 105.24 GJ and Sector 11 (*Petroleum Processing and Coking, Gas Production and Supply*)'s 71.30 GJ. It also should be noted that direct energy use plays more important role in secondary industry than in primary industry and tertiary industry.

Embodied energy of each sector is also calculated based on their corresponding embodied energy intensities (Fig. 3). The overall picture of sectoral embodied energy consumption varies from that of sectoral intensities. Sector 27 (*Transportation*) has the largest individual embodied energy consumption, with an amount of 1.41E+09 GJ. Sector 23 (*Electric Power/Steam and Hot Water Production and Supply*) is the second largest embodied energy consumer, due to its role of secondary energy producer. Driven by the ongoing large-scale infrastructure construction, Sector 26 (*Construction*) ranks the third among all the sectoral embodied energy consumers. Notably, although the average embodied energy intensity of tertiary industry is much smaller than that of

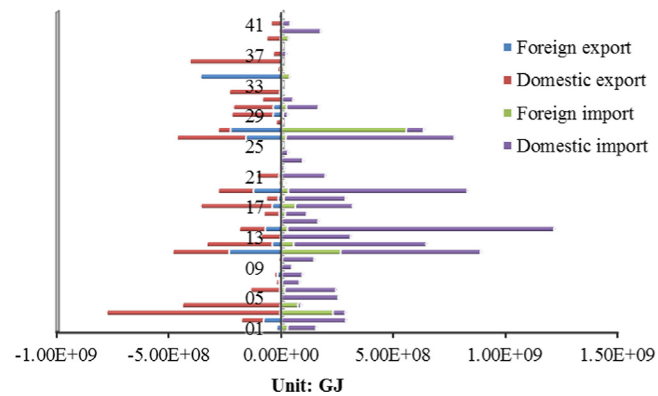

Fig. 4. Energy embodied in trade.

secondary industry; the total amount of embodied energy input to tertiary industry is comparable to that of secondary industry. The reason can be explained by the large output of tertiary industry in Beijing economy. In 2010, the monetary value of tertiary industry of tertiary industry is 2773.4 billion RMB, which was 1.5 times that of secondary industry [46]. Besides, the embodied GHG emission intensity of second industry is much higher than that of tertiary industry. Even though with a lower economic output, the embodied energy input to secondary industry is comparative to that of tertiary industry after multiplying the corresponding intensity.

3.2. Energy embodied in trade balance

The estimated imported and exported embodied energy of each sector is presented in Fig. 4. In general, energy embodied in domestic trade (both imports and exports) is greater than that embodied in foreign trade, except for a few sectors such as Sector 3 (*Petroleum and Natural Gas Extraction*), 26 (*Construction*) and 34 (*Leasing and Commercial Services*). Another interesting fact is that for secondary industry, Beijing has a larger amount of imported embodied energy than exported embodied energy. However, for tertiary industry, the exported embodied energy is much more than imported embodied energy. The difference reflects the features of Beijing's economy, which is tertiary industry dominated economy with heavy dependence on goods imported from other regions. Based on the sectoral trade, it is obtained that the total amount of energy embodied in imports and exports amounted to 8.71E+09 GJ and 6.16E+09 GJ. Thus, a positive embodied energy balance appeared in Beijing, making the region a net importer of embodied energy.

3.3. Energy embodied in final consumption

Fig. 5 shows the energy embodied in final consumption. It is calculated that Beijing's final embodied energy consumption amounted to 4.62E+09 GJ in 2010. The direct energy consumption calculated by the Statistic Yearbook is 2.04E+09 GJ, which is less than half of the total embodied energy consumption by Beijing. The huge difference implies that strong energy leakage will be caused if only the direct energy input is taken into account. Domestic scale still contributes the largest share to the energy embodied in final consumption, with a proportion of 57.95%. Local scale with a proportion of 27.61% is the second biggest contributor. The rest of energy embodied in final consumption came from other countries, with the smallest share of 14.44%.

Energy embodied in four categories of final demands, namely, household consumption including both rural and urban household consumption, government consumption, capital formation and inventory increasing, is compared in Fig. 5. Capital formation is the

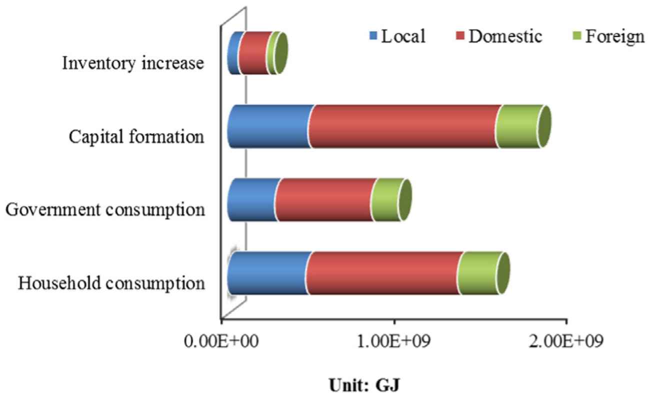

Fig. 5. Energy related mercury emissions embodied in trade balance.

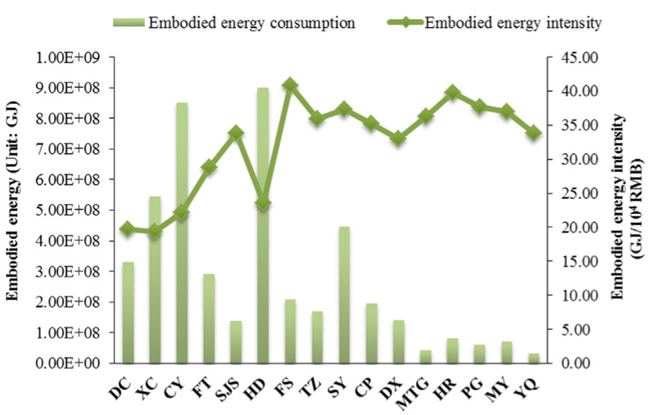

Fig. 6. The embodied energy consumption by each district.

top final consumer of embodied energy, to which the local, domestic and global scale contributed 28.14%, 56.06% and 15.81%, respectively. From the perspective of sectors, Sector 26 (*Construction*) is the largest contributor to the energy embodied in capital formation. This sector alone is responsible for about a quarter to the total final embodied energy consumption among all the 42 sectors. It should be noted that rural embodied energy consumption is just about one tenth that of urban consumption, reflecting the striking gap between living standards of rural and urban residents.

3.4. Embodied energy consumption of each district

It is assumed that all the districts within Beijing have the same sectoral embodied energy intensities. Thus, the embodied energy consumption by each district is obtained and shown in Fig. 6.

Haidian District has the largest embodied energy consumption, with an amount of 8.99E+08 GJ. Secondary industry and tertiary industry is responsible for 0.08%, about 33% and 66%, respectively; while the fraction of the primary industry is less than 1%. Followed are Chaoyang District and Xicheng District, with the second and third largest embodied Energy consumption of an amount of 8.52E+08 and 5.45E+08 GJ, respectively. In contrast, Mengtougou District, Pinggu District and Yanqing County are the three regions with the smallest embodied energy consumption. The sum of the three smallest ones only takes a percentage of 3% of the total. Notably, the embodied energy consumption by urban districts is higher than that of suburban districts.

Embodied GHG emission intensity of each district is illustrated in Fig. 6. Fangshan District has the highest embodied energy intensity (40.80 GJ/10^4 RMB) while Xichen has the lowest one (19.34 GJ/10^4 RMB). Generally, the urabn districts have lower embodied energy intensity, owing to the low embodied energy intensive tertiary dominant economy, compared with the suburban districts. However, there is one exception among the urban districts. Shijingshan District's energy intensity is as high as 33.76 GJ/10^4 RMB, which should attribute to the higher share of more energy-intensive energy industry in its economy.

Table 2
Regulation cost.

District	AP	ISP	ASP	DIP	DAP
DC	0.02	0.01	0.02	0.01	0.00
XC	0.00	0.00	0.00	0.00	0.00
CY	0.00	0.00	0.00	0.00	0.00
FT	0.49	0.45	0.49	0.46	0.43
SJS	0.37	0.37	0.37	0.37	0.36
HD	0.00	0.00	0.00	0.00	0.00
FS	0.11	0.11	0.11	0.11	0.11
TZ	0.56	0.55	0.56	0.55	0.56
SY	0.00	0.00	0.00	0.00	0.00
CP	0.48	0.48	0.48	0.48	0.48
DX	0.71	0.57	0.71	0.56	0.65
MTG	0.76	0.26	0.76	0.36	0.75
HR	0.34	0.34	0.34	0.34	0.34
PG	0.93	0.49	0.93	0.58	0.93
MY	0.77	0.54	0.77	0.61	0.77
YQ	0.75	0.01	0.75	0.08	0.70

3.5. Abatement scenarios

Presented in Table 2 are the sub-regional directional distance functions under different alternatives when energy regulation exists. For AP, ISP and DAP scenarios, Pinggu is the most impacted district, with potential losses of over 90%, respectively. Daxing suffers most in the scenario ISP, with a percentage of 57.19%. For DIP scenario, Miyun is the most impacted district and its potential loss is 60.55%.The impacts on Yangqing in various scenarios are noticeably different. For scenarios AP, ASP and DAP, Yanqing is featured as one of the most impacted districts, while for other two scenario Yanqing suffers slight potential losses. Dongcheng suffers no impact for Scenario DAP, and the potential losses for other scenarios are also in a very small amount. Notably, the potential losses of Fangshan and Shijingshan stay stable under each regulation scenario, maintaining at the levels of 11% and 37%, respectively, suggesting that all kinds of regulation have the same impacts on these two district. It should be noted that no matter under which scenario, Xicheng, Chaoyang, Haidian, and Shunyi have no potential output loss. While Tongzhou, Fengtai, Miyun and Changping are witnessed to lose half or even more of their potential outputs under each regulation scenario, indicating that they will be strongly impacted no matter under which scenario.

Table 3 provides the losses of nominal output potential among districts in different scenarios. The situation for nominal output losses is different from that of potential losses. In all of the five scenarios, Fengtai is the most influenced district and has the largest nominal output loss, followed by Daxing and Changping. TongZhou, Shijingshan, Mengtougou, Huairou and Miyun also suffer varying degrees of smaller regulation costs. It can be implied that Fengtai's economic development has the closest relationship to embodied energy consumption, among all the districts. By summing up all the losses of each district in each scenario, it was found that both scenarios AP and ASP cause the largest amount of nominal output losses while scenario ISP results in the smallest nominal output losses. As a consequence, scenario ISP the optimal energy regulation scenario for Beijing.

Table 3
Regulation cost of nominal output (Unit: Billion RMB).

District	AP	ISP	ASP	DIP	DAP
DC	2.22	1.01	2.22	1.05	0.00
XC	0.00	0.00	0.00	0.00	0.00
CY	0.00	0.00	0.00	0.00	0.00
FT	36.07	33.24	36.07	33.53	31.27
SJS	10.98	10.99	10.98	10.99	10.75
HD	0.00	0.00	0.00	0.00	0.00
FS	3.98	3.97	3.98	3.97	3.97
TZ	19.28	18.97	19.28	18.98	19.28
SY	0.00	0.00	0.00	0.00	0.00
CP	19.30	19.30	19.30	19.30	19.30
DX	22.12	17.84	22.12	17.33	20.38
MTG	6.53	2.25	6.53	3.09	6.49
HR	5.01	5.00	5.01	5.00	5.01
PG	11.00	5.74	11.00	6.80	11.00
MY	10.90	7.61	10.90	8.57	10.91
YQ	5.04	0.06	5.04	0.53	4.72

4. Discussion

The results obtained by the current work are consistent with our earlier findings for Beijing embodied GHG emissions [36]. Chen et al. [36] highlighted Beijing as a typical urban economy benefiting from developed tertiary industry sectors, which enable the region to achieve stunning economic output while keeping the direct GHG emissions at a relatively low level. However, the fact behind the low direct emissions is that indirect emissions, which are several times the direct emissions, are ignored by the direct accounting. Our study verified this point from the perspective of embodied energy consumption. As shown by the calculated results in this study, direct energy input was only equal to a small fraction of the overall embodied energy consumption. As energy is major source for GHG emissions, the current study explains that the neglecting of the indirect energy consumption, which dominates Beijing's overall energy consumption, caused the GHG emission leakage. Moreover, according to Zhang et al. [13], most of the economic sectors within Beijing show a tendency: an increase in indirect energy consumption while a decrease in direct energy consumption. Moreover, the ongoing urbanization and growing weight of tertiary industry in Beijing will expand the gap between the direct and indirect energy consumption. Therefore, the conventional way of focusing direct energy consumption only will cause precious information loss and is far from sufficient to support a robust energy strategy. From our findings, it can be implied that the declining direct energy consumption in Beijing was attributed to the transfer of energy use to other regions. The results in this study also suggests that one important reason to explain why China failed to control its growing energy consumption even under so strict energy regulation is because those energy conservation strategies in the five-year plans neglect the indirect effect and embodied energy transfer between regions.

The present study also expands our knowledge on regional energy consumption. From the viewpoint of embodied energy consumption, economic sectors such as construction and some tertiary industry sectors are much more energy intensive as they were assumed to be. Compared with the small amount of direct energy input, their consumption of industrial products and services induces much more energy consumption embodied in the upstream activities. Therefore, this work also provides us a new angle for evaluating current policy for Beijing. Beijing has devoted significant efforts to control direct energy consumption. Driven by the mandatory energy abatement targets and the ambitious to become a low carbon city, Beijing is seeking to change its economic structure by reducing the heavy industry in favor of increasing the service sectors. In this context, measures like simply displacing the energy-intensive industries such as manufacturing to other regions and replacing electricity from local coal power plants by imported electricity from other provincial regions have been implemented. However, as our analysis suggests, there is potential for overall energy consumption rise behind these measures. That is because the manufacturing industries are usually reallocated to less developed regions where the regulation is weaker and technological level is lower. For example, to smelt 1 t steel, steel factories in Beijing may require 30 kWh of electricity while those in Shanxi need to use 40 kWh. That means 10 kWh extra electricity will be consumed for per tonnes from Shanxi used by Beijing to replace the local produced steel. The measure for increasing electricity imports as alternative for local power will result in a growth in China's total energy consumption in the same way.

Furthermore, it can be implied that Beijing's overall embodied energy abatement is subject to the whole nation’s energy consumption reduction, as the energy embodied in domestic import contributed the majority of Beijing's embodied energy consumption as well as the embodied energy intensity. This can be understood that the nature of Beijing's economy, which heavily relies on the commodities produced outside its territory. As Beijing lacks the indigenous energy resources and manufacturing industries are gradually moved out the city boundary, it is easily predicted that to sustain the rising living standard of the growing population as well as the economy, Beijing's reliance on domestic imported commodities will be even heavier in the future. Consequently, the amount of indirect energy consumption by Beijing will become larger and larger along with the growing imports of domestic commodities. As a result, energy abatement for China as a whole is vital for Beijing to achieve its own energy abatement goal. Nevertheless/In spite of this, it does not mean there is no potential for Beijing to reduce its own embodied energy consumption. The government should break through the traditional limitations in direct energy input focused energy policies and broad their eyesight to all the resources, goods and services. To rationally consume all the commodities means to save energy, the government is encouraged to enhance the rates of commodity utilization efficiency. Meanwhile, the development of circular economy is also a strategic choice for solving these problems and keeping sustainable economic growth in Beijing.

In the 11th and 12th five-year plans [7,8], Beijing is assigned a fixed energy reduction task by China's central government and the municipal government allocated the mandate task to each district under its jurisdiction. That means if one district within Beijing was assigned less energy reduction, some other districts had to take heavier energy abatement pressure. Subsequently, the district under lighter pressure may produce higher output as it faces less energy constraints and vice versa. Therefore, the relative economic structure of the region concerned will be reorganized as the abatement allocation of energy consumption changed the economic relation between different Decision Making Units [22]. However, the results presented in the current study showed that the economic structure will experience changes with different degrees. For districts like Haidian and Chaoyang, the costs of energy regulation did not offset the economic growth in Beijing. These results indicate that a win–win opportunity for economic growth and energy abatement in these districts. On the contrary, for other districts such as Pinggu and Fengtai, their economies will be significantly influenced under the mandatory pressure. The difference between the districts' industrial structure is the principal cause. Additionally, according to the nominal output losses under different scenarios based on embodied energy information, it indicates that the current mechanism of abatement responsibility assignment in both national and local five-year plans is not appropriate. For example, the current weight of responsibility for each district in Beijing is the equivalent. Then it was found out that the potential output loss is the largest under AP scenario, indicating that this scenario will cause the largest absolute cost of abatement. Therefore, to help Beijing and the whole nation to achieve its abatement goal at the lowest price, it is necessary to address the factors such as industrial structure and the absolute potential cost when facilitating the abatement strategies.

5. Conclusions

Based on a three-scale input–output analysis, this paper analyzed the impacts of domestic and foreign trade on a specific region's embodied energy consumption by using the case of Beijing. The results show that Beijing provides a stark illustration of the significant implications of multi-scale analysis for energy related policy assessment. As calculated, the overall embodied energy consumption by Beijing in 2010 is 4.62E+09 GJ. Domestic imports contribute the majority of Beijing's overall energy consumption rather than local energy inputs. The directional distance function was also employed to figure out an optimal regulation strategy for Beijing by evaluating the economic loss of five energy abatement scenarios. The calculated results reveal that intensity share scenario is the optimal energy abatement strategy among all the five scenarios.

The analysis obtained by this study conveys significant information to decision-makers. The results indicate that the conventional way of investigating regional energy consumption, which solely pays attention on local energy input and ignores the complex energy flows embodied in trade between different regions in our national development plans, is not appropriate for formulating comprehensive energy policy. Moreover, this study reveals that local efforts like controlling the direct energy consumption only may result in perverse incentives and overall increase. Therefore, energy abatement and energy efficiency improvement measures should not only focus on local energy consumers, but also pay greater attention to large embodied energy consumers along the supply chain.

A broader message that comes from the case study of Beijing's embodied energy consumption is related to the allocation of energy abatement tasks in China. For more developed regions like Beijing, it is easier for them to fulfill the abatement tasks as the energy-intensive production factories are moved to some developing regions. At the same time, the direct energy consumption has also been displaced to other regions when the developed regions consume the commodities imported from the developing regions. Moreover, the developing regions in China are usually places which are rich in energy resources and supply developed regions with energy products such as electricity. This will result in lower reported energy use in those developed regions even their consumption increases. Thus, the current production-oriented responsibility assignment mechanism is regarded as arguably unjust as it makes those developed regions able to avoid scrutiny. As implied by this study, to fulfill the energy abatement tasks at each scale, each region should break limits of self-centered perceptions and multi-governance for more appropriate responsibility assignment is in urgent need.

Acknowledgments

This research was supported by the National Natural Science Foundation of China, China (Grant no. 71573021) and National Key Program for Basic Research (973 Program, no. 2010CB950904).

Appendix

See Table A1 and A2

Table A1
Embodied energy intensity for domestic scale (Unit: GJ/10^4 Yuan).

Sector code	Embodied energy intensity	Sector code	Embodied energy intensity	Sector code	Embodied energy intensity
1	14.55	15	43.56	29	12.12
2	676.01	16	34.56	30	11.76
3	143.63	17	31.51	31	20.52
4	47.57	18	31.95	32	11.33
5	37.47	19	20.79	33	5.49
6	20.95	20	25.05	34	23.27
7	27.28	21	33.07	35	19.16
8	26.29	22	5.33	36	18.37
9	28.48	23	145.43	37	20.75
10	29.91	24	162.64	38	21.30
11	197.08	25	37.18	39	16.81
12	62.22	26	43.22	40	14.19
13	63.75	27	36.84	41	17.52
14	62.78	28	20.12	42	16.55

Note: The Chinese input–output table has 41 sectors as Sector 27 (Transport and Storage) and 28 (Post) are merged into one sector. To be consistent with Beijing table, these two sectors are considered as having the same embodied energy intensity

Table A2
Embodied energy intensity for global scale (Unit: GJ/10^4 Yuan).

Sector code	Embodied energy intensity	Sector code	Embodied energy intensity	Sector code	Embodied energy intensity
1	16.11	15	20.01	29	6.45
2	27.19	16	16.33	30	9.09
3	14.61	17	14.39	31	6.08
4	25.23	18	15.35	32	4.45
5	25.23	19	13.87	33	1.23
6	15.36	20	15.35	34	6.08
7	18.91	21	16.33	35	11.72
8	13.75	22	16.33	36	11.72
9	13.69	23	129.87	37	7.37
10	20.38	24	42.66	38	7.37
11	123.63	25	20.99	39	11.72
12	37.94	26	12.71	40	11.72
13	41.62	27	55.53	41	11.72
14	42.39	28	6.45	42	7.37

Note: The embodied energy intensities are derived from Chen and Chen (2013).

Embodied energy intensities

At the urban scale, the direct energy input data are derived from the energy balance table in the Beijing Statistics Yearbook 2011(BSY, 2011). The input–output table of Beijing economy 2010 is compiled by the Beijing Statistical Bureau. It divides Beijing economy into 42 sectors. Sector 1 is the primary industry, Sector 2–26 belong to secondary industry and the rest are characterized as tertiary industry.

At the domestic scale, the direct energy input data are derived from China Energy Statistical Yearbook (CESY, 2011) and the corresponding economic the national input–output table of Chinese economy compiled by Chinese Input–Output Association (CIOA, 2014). The embodied energy intensity dataset is listed in Table A1 in Appendix. It should be noted that the embodied energy intensity for global economy comes from the existing study conducted by our research group. The global dataset is obtained based on the year of 2007 (Chen and Chen, 2013). Assuming that there is no significant change between the year of 2007 and 2010, the global dataset which covers 57 sectors is adopted by the current study.

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