

# Structural Decomposition Analysis of China's Industrial Energy Consumption Based on Input-Output Analysis

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**Abstract.** China is now at a stage of accelerated industrialization and urbanization, with energy-intensive industries contributing a large proportion of economic growth. In this study, we examined industrial energy consumption by decomposition analysis to describe the driving factors of energy consumption in China. Based on input-output (I-O) tables from the World Input-Output Database (WIOD) website and China's energy use data from 1995 to 2011, we studied the sectorial changes of energy efficiency during the examined period. The results showed that all industries increased their energy efficiency. Energy consumption was decomposed into three factors by the logarithmic mean Divisia index (LMDI) method. The increase in production output was the leading factor that drives up China's energy consumption. World Trade Organization accession and financial crises had great impact on the energy consumption. Based on these results, a series of energy policy suggestions for decision-makers has been proposed.

## 1. Introduction

With increasing energy demands arising from China's industrialization, China has been the largest energy consumer in the world since 2010[1]. Coal is the major energy source in China, making up about 70% of China's total energy use [2-3]. As a consequence, China emits large volumes of greenhouse gases as well as dust, raising serious domestic and global concerns [4-5]. Industrial sectors are the biggest energy consumers, with over 70% of China's total energy consumption [6]. In addition, the compound growth rate of China's industrial added value increased dramatically from 1995 to 2011. Meanwhile, energy consumption increased greatly as well, with an average increase of 6.3% per year. Compared to major developed countries, China's energy utilization efficiency is still at a relatively low level.

Decomposition analysis is a useful tool for distinguishing the intrinsic driving forces of changes in energy efficiency. Index decomposition analysis (IDA) and structural decomposition analysis (SDA) are two common types of decomposition methods. IDA is a type of analytical framework using direct energy data. Numerous studies have established IDA frameworks to analyse the driving force for energy consumption and its environmental impact, including industry energy use [7], residential energy consumption [8-9], CO<sub>2</sub> emission [10-14], etc. SDA is based on input-output analysis, using both direct and indirect energy consumption data. SDA is also applied to analyse environmental



impacts such as CO<sub>2</sub> emissions [15-16], material consumption [17], and footprint evolution [18]. Compared to IDA, SDA has its advantage to reveal indirect energy consumption concealed in the material flows among industrial sectors, therefore being widely and increasingly adopted for such studies. More details about the differences between IDA and SDA can be found in Ref. [19].

China is of particular interests to the international community due to its scale of economy, energy use and emissions. Many studies [20-21] have focused on China's energy intensity by tracing the data back to each sector and using national level statistics. In order to understand the rapid growth of China's energy consumption and energy productivity, a group of researchers [22-23] used production-theoretical decomposition analysis and IDA to investigate the driving force behind changing energy data. A study based on an energy input-output model and SDA analysis [24] found that the main challenge for China is that of the final demand structure. Previous SDA work used only gap years and failed to give continuous analysis on the driving factors of energy use. This paper proposes to use SDA and continuous data to reveal the driving factors of energy use change in China. The main method, including input-output analysis and the logarithmic mean Divisia index (LMDI) method, is described in Section 2, along with descriptions of the data sources and preliminary process. Section 3 describes the results. Section 4 contains a discussion of the implications of the results from Section 3.

## 2. Methods and Data

### 2.1. Methods

Input-output analysis was first introduced by Leontief [25]. It is widely used to study the interdependent relationships between sectors in an economic system, and to systematically analyse the internal complex transactions among various industries [26]. An economic-energy input-output (EEIO) table is a table in which the monetary energy flows in the original I-O table are replaced by physical energy flows. The formula can be expressed as follows:

$$c_{kj} = d_{kj} + \sum_{s=1}^n d_{ks} a_{sj} + \sum_{s=1}^n \sum_{l=1}^n d_{ks} a_{sl} a_{lj} + \dots \quad (1)$$

$$d_{kj} = \frac{E_{kj}}{x_j} \quad (2)$$

Table 1 showed the implication of each variable. Equation (1) also can be expressed in a matrix form:

$$C = D(I - A)^{-1} = D \cdot L \quad (3)$$

where  $C$  and  $D$  represent the matrixes of  $c$  and  $d$ .  $(I - A)^{-1}$  is known as the Leontief inverse matrix, and  $(I - A)^{-1} = L$ .

In this paper, the driving force of energy use in industry is decomposed into three elements by the LMDI method. The LMDI method is called the perfect decomposition technique that can process data equal to or smaller than zero and generate no residual [27]. The three decomposed elements are production effect, structure effect, and intensity effect. The total energy consumption is formulated as follows:

$$E_{i,t} = f(X_{i,t}, S_{i,t}, C_{i,t}) \quad (4)$$

By using LMDI methods, equation (4) can be derived into equation (5):

$$dE_{i,t} = \frac{\partial E_{i,t}}{\partial X_{i,t}} dX_{i,t} + \frac{\partial E_{i,t}}{\partial S_{i,t}} dS_{i,t} + \frac{\partial E_{i,t}}{\partial C_{i,t}} dC_{i,t} \quad (5)$$

which can be also expressed as follows:

$$\Delta E_t = E_t - E_o = \Delta E_x + \Delta E_s + \Delta E_c \quad (6)$$

Finally, the production effect, structure effect, and intensity effect of the change in energy use can be formulated as follows:

$$\Delta E_{t,x} = \sum_i \frac{E_{i,t} - E_{i,o}}{\ln E_{i,t} - \ln E_{i,o}} \ln(X_{i,t} / X_{i,o}) \quad (7)$$

$$\Delta E_{t,s} = \sum_i \frac{E_{i,t} - E_{i,o}}{\ln E_{i,t} - \ln E_{i,o}} \ln(S_{i,t} / S_{i,o}) \quad (8)$$

$$\Delta E_{t,c} = \sum_i \frac{E_{i,t} - E_{i,o}}{\ln E_{i,t} - \ln E_{i,o}} \ln(C_{i,t} / C_{i,o}) \quad (9)$$

**Table 1.** Implication of each variable in Section 2.1.

Variable	Meaning
$c_{kj}$	the complete inputs required from energy k for sector j to generate one unit value added
$d_{kj}$	the direct inputs required from energy k for sector j to generate one unit value added
$a_{sj}$	the direct inputs required from sector s for sector j to generate one unit value added
$E_{kj}$	the total inputs required from energy k for sector j
$x_j$	total amount of energy consumed in sector j
$E_{i,t}$	total amount of energy consumed by sector i in year t
$X_{i,t}$	total amount of economic output in sector i in year t
$S_{i,t}$	the proportion of total output for sector i in year t
$C_{i,t}$	the complete energy consumed coefficient of sector i in year t
$\Delta E_t$	total effect from year 0 to year t
$\Delta E_x$	production effect from year 0 to year t
$\Delta E_s$	structure effect from year 0 to year t
$\Delta E_c$	intensity effect from year 0 to year t

## 2.2. Data

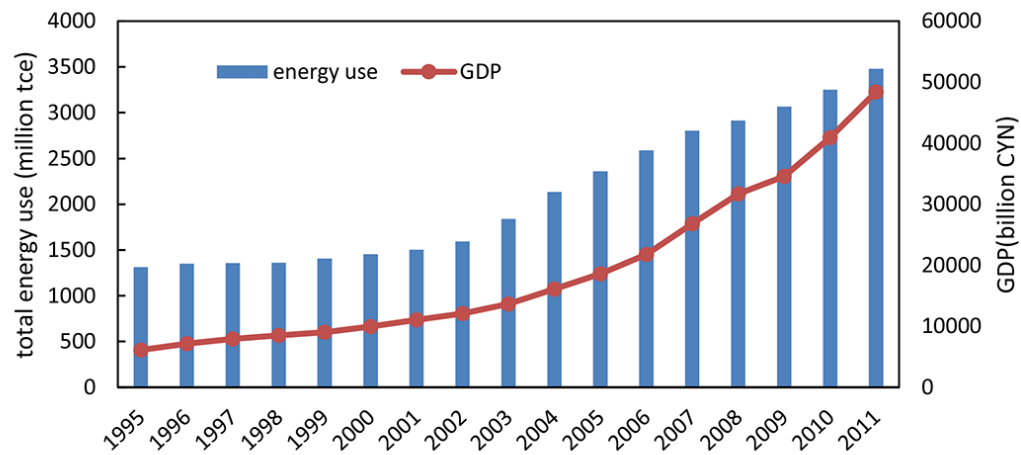
All data for this analysis were obtained from open public databases. China's monetary I-O tables were obtained from the World Input-Output Database (WIOD), including 34 sectors. Industrial energy consumption data were obtained from China Energy Statistical Yearbooks, containing 36 sectors. We consolidated some of the industries into 21 sectors to coordinate the two different sectorial classifications and formed 17 EEIO tables (1995–2011).

## 3. Results

### 3.1. Energy efficiencies of different sectors

China's economy began its rapid growth in 1978, and its energy consumption also showed an analogous growth at the same time (Figure. 1). China's gross domestic product (GDP) has a significant positive linear relation with total energy consumption ( $R^2 = 0.946$ ,  $P < 0.001$ ). However,

there is no evidence that the inflection point of the environmental Kuznets curve (EKC) will appear in the near future [28].



**Figure 1.** The changes in total energy use and GDP in China from 1995 to 2011.

Table 2 shows the statistics of all sectors. The value of DV (the difference in energy coefficient between 1995 and 2011) was positive in all sectors, indicating the total improvement of energy saved per unit output. The DV/AC values indicate that most industrial sectors had remarkable improvements in efficiency. Sector H20 had a relatively low DV/AC value, possibly because the sector is highly dependent on transportation. By contract, the improvement of energy efficiency with regard to vehicles and trains was not as significant as that of industrial sectors [29].

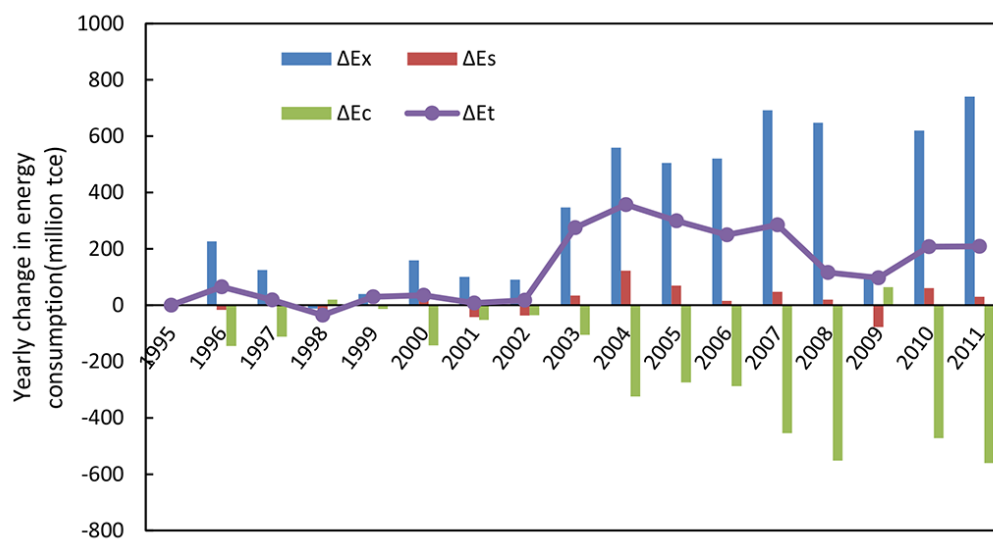
**Table 2.** The change in energy consumption coefficients of industrial sectors during the period from 1995–2011. AC: average energy coefficient; RAC: rank of the AC; DV: difference in energy coefficient between 1995 and 2011; DV/AC: ratio between DV and AC.

NO.	Industry	AC (tce/1000 USD)	RAC	DV (tce/1000 USD)	DV/AC
H1	Agriculture, Hunting, Forestry, and Fishing	0.432	21	0.632	1.46
H2	Mining and Quarrying	1.954	6	3.442	1.76
H3	Food, Beverages, and Tobacco	0.604	17	0.957	1.58
H4	Textiles and Textile Products	0.774	15	1.02	1.32
H5	Leather, Leather, and Footwear	0.54	18	0.72	1.33
H6	Wood and Products of Wood and Cork	0.697	16	0.907	1.30
H7	Pulp, Paper, Printing, and Publishing	1.003	11	1.33	1.33
H8	Coke, Refined Petroleum, and Nuclear Fuel	2.247	2	3.79	1.69
H9	Chemicals and Chemical Products	2.074	4	3.452	1.66
H10	Rubber and Plastics	1.096	9	1.498	1.37
H11	Other Non-Metallic Mineral	1.963	5	2.358	1.20

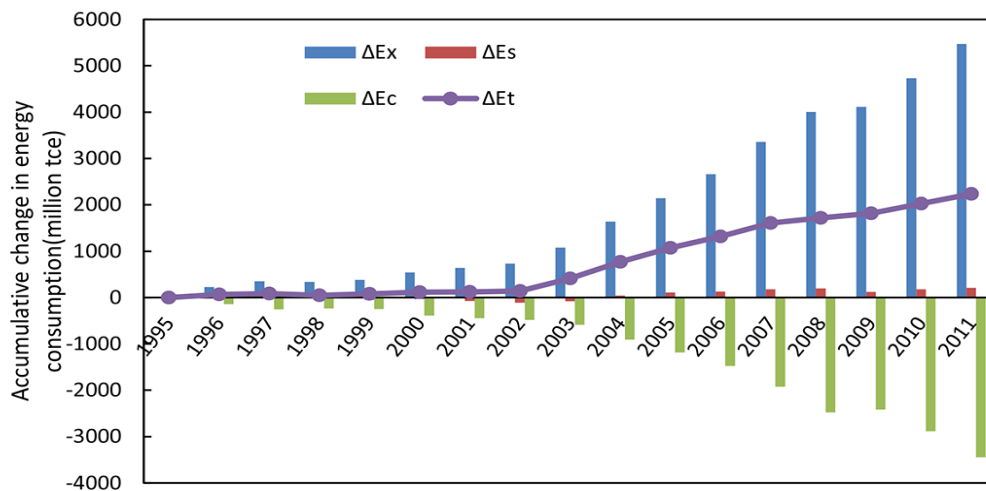
<b>H12</b>	Basic Metals and Fabricated Metal	2.351	1	3.343	1.42
<b>H13</b>	Machinery, n.e.c. <sup>a</sup>	1.024	10	1.367	1.33
<b>H14</b>	Electrical and Optical Equipment	0.774	14	1.005	1.30
<b>H15</b>	Transport Equipment	0.898	13	1.148	1.28
<b>H16</b>	Manufacturing, n.e.c; Recycling	1.241	7	1.979	1.59
<b>H17</b>	Electricity, Gas, and Water Supply	2.176	3	3.292	1.51
<b>H18</b>	Construction	1.21	8	1.912	1.58
<b>H19</b>	Wholesale and Retail Trade, Hotels, and Restaurants	0.457	20	0.663	1.45
<b>H20</b>	Transport, Storage, and Post	0.938	12	0.678	0.72
<b>H21</b>	Others	0.533	19	0.813	1.53

<sup>a</sup> [not elsewhere classified]

### 3.2. Decomposition of China's total energy consumption



**Figure 2.** Decomposition of China's yearly energy consumption during the period from 1996 to 2011.



**Figure 3.** The accumulative effects during the period from 1996 to 2011 (Base year: 1995).

As to the production effect, its variation was rather small before 2002 as Figure 2 and Figure 3 depicted. During this period, the production effect contributed positively to the total energy consumption, except in 1998. Possibly, the outbreak of Asian financial crisis in 1998 caused decline in exports, which in turn influenced the industrial outputs. As the consequence, the production effect presented a negative contribution in 1998, equivalent to -6.32 million tce. During 2003-2008, the outputs of industrial sectors dramatically increased with an annual growth rate at 18.3% due to China's entry into the World Trade Organization (WTO), which created a large foreign demand for industrial products and manufacturing capacities from China. Consequently, the production effect also increased significantly as Figure 2 showed. The 2008 crisis caused the recession of outputs and the production effect (-8.27 million tce). Generally, the production effect was the largest effect and contributed positively to the energy consumption increase.

Structure effect was insignificant compared to the other two effects. As a result, energy consumption relatively concentrated to the energy intensive sectors, and the structure effect became unfavourably positive. This trend was also very clear in Figure 3. The accumulative structure effects kept larger than zero, which reflected China failed to transform its economy structure into an energy saving one as it promised.

Energy intensity effect contributed negatively to the total energy consumption in general during 1996-2011. Suppressed production demand and excessive energy supply might desert their renovation projects and investments for energy saving technologies.

### 3.3. Sectorial energy consumption decomposition

The contribution of each effect for industrial sectors' energy consumption was diverse. Table 3 showed the effects of contributions and their rankings at sectorial level. The structure effects were positive together with the production effect in these sectors, implying their share for economy output enlarged in the past 16 years and contributed the largest part for the undesirable structure change. H1 was a special case with negative accumulative total effect.

The accumulated production effect of each sector was positive and played a major role on the energy consumption growth. Besides, the rank of accumulated production effect presented a high positive unsupervised correlation with the rank of total energy consumption. That means high energy intensive sectors often had high production effect, implying the economy growth based on the expansion of large industrial energy consumers. Sectors with high accumulative production effect basically also had very large accumulative energy intensity effect in absolute term. Two reasons might explain this phenomenon. One is, the elimination of backward production capacity especially the energy intensive technologies indirectly promoted the energy efficiency of industrial sectors. The

other is, the newly built production capacity driven by the expanding needs after 2002 often used the new technologies and devices with high energy efficiency, guaranteed by the policy makers through the strict examination and approval system for high energy sectors. However, the accumulative energy intensity effect of each and all sectors could not compensate the increment of the accumulative production effect. H1 had the closest two effects, with a gap about 11.10 million tce, or 8.4% of the accumulative production effect. Comparatively, H12 had the largest absolute gap about 510.29 million tce, and H20 had the largest relative gap about 61.2%. Thus, to achieve the favourable decoupling status between energy consumption and the economy, much still can be do to minimize the gaps for each industrial sector.

The accumulative structure effects for industrial sectors were much complicated. Half of sectors had positive effect. Unfortunately, these sectors were mostly energy intensive, such as H12, H17, H2, H8, and H9. These five sectors only consisted of 19.55% of the economy output, but contributed 206.6% of the accumulative structure effect. In other words, these undesirable expansions were biased towards energy intensive sectors, and lead to energy consumption increase. Other sectors had negative accumulative structure effect, mainly due to their shrinking share of total economy outputs. The structure change of H1 together with the energy efficiency improvement had cancelled out all the increment of the production effect. As a result, H1 became the only sector that had negative total effects.

**Table 3.** Accumulated effects of each sector (million tce; TE: total effect; PE: accumulative production effect; SE: accumulative structure effect; IE: cumulative energy intensity effect; R: the ranking of each effect)

NO.	TE	R	PE	R	SE	R	IE	R
H12	63515.12	1	131036.54	1	12485.80	1	-80007.22	1
H17	33508.35	2	51909.32	3	10990.06	2	-29391.02	4
H9	30595.97	3	77241.58	2	4839.97	5	-51485.59	2
H2	20681.59	4	47221.07	4	8420.60	3	-34960.08	3
H8	15870.03	5	34131.94	6	6479.90	4	-24741.81	6
H20	14786.71	6	33115.67	7	-5490.54	20	-12838.42	8
H21	10757.88	7	24364.60	8	647.33	8	-14254.04	7
H18	5674.39	8	9767.00	14	1514.56	6	-5607.17	14
H14	5030.46	9	7384.23	16	894.78	7	-3248.54	19
H13	4679.18	10	10804.84	12	-94.50	12	-6031.16	13
H11	4207.08	11	44032.03	5	-10867.87	21	-28957.08	5
H15	3538.05	12	6811.92	17	189.53	9	-3463.41	16
H10	2557.54	13	5864.05	18	65.50	10	-3372.01	17
H4	2446.51	14	12296.64	11	-1943.92	18	-7906.21	11
H19	2203.74	15	10448.08	13	-1071.15	15	-7173.19	12
H3	2040.23	16	12350.40	10	-1128.62	16	-9181.55	10
H7	1532.23	17	7557.28	15	-1206.80	17	-4818.25	15
H6	1098.50	18	2397.27	20	3.31	11	-1302.08	20
H16	714.70	19	4484.98	19	-440.70	14	-3329.59	18
H5	48.75	20	709.70	21	-176.71	13	-484.23	21
H1	-2078.54	21	13276.70	9	-3188.82	19	-12166.42	9

#### 4. Discussion



There is still room to improve in catching up with developed countries. Basically, these sectors could reduce their energy use by innovating their production processes through cleaner production audits. In addition, updated energy saving technologies, such as waste heat conversion technology, heat storage technology, and high temperature air combustion (HTAC) technology, have great potential for application in these sectors and for reducing their energy use in terms of efficiency improvements [30–32]. Further policymaking and funding should encourage these energy intensive sectors to decouple their energy use and economy output.

The industry structure effect exhibited a weakening trend in comparison to the production effect and intensity effect. Two industries including non-metallic minerals, and transport, storage, and post contributed a large share of favourable structure effect. These two sectors reached –108.68 and –54.91 million tce of the cumulative structure effect, respectively. In contrast, China's economy is still highly reliant on high energy intensive sectors such as metal-processing, electric power, and mining, whose structure effects caused an unfavourable rise in the total energy consumption growth. Therefore, more attention should be focused on adjusting the industrial structure. Low energy intensive industries such as H21 and H19 should be carefully supported to further establish an energy saving economic structure.

Although there was no difference in decomposition results, regardless of the type of energy used, it is obvious that China's energy consumption has been dominated by coal, which has caused terrible carbon and dust emissions. However, China's international pledge to the United Nations Framework Convention on Climate Change (UNFCCC) is to achieve a peak of carbon dioxide emissions around 2030, making its best efforts to peak at an early date, to lower carbon dioxide emissions per unit of GDP by 60% to 65% of the 2005 level, and to increase the share of non-fossil fuels in primary energy consumption to around 20%. The general public also has a vision set out to improve the environment. There is no denying the fact that China urgently needs to optimize and upgrade its energy structure, and to use more clean energy, such as solar power, hydropower, and nuclear power [33].

## 5. Conclusion

China's energy utilization efficiency greatly improved over the study period. The chemical industry has shown the most marked change. The structural decomposition results showed that an increase of the production effect, as the dominant driving force, had been raising the consumption of energy significantly after 2002. The energy intensity effect also grew impressively in terms of absolute value, and cancelled out most of the production effect. The structure effect was the least dominant effect; however, it was revealed that China's industry structure adjustment had an unfavourable result. Sectorial decomposition indicated that the increment of production effect and the structural effect mainly came from the energy intensive sectors, although these sectors also contributed the largest share of decrement of energy intensity effect. Future policymaking should focus on the energy intensive sectors through technology and device renovation, and economic structure readjustment.

## 6. Acknowledgments

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