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Driving Forces of China’s Energy and Emission Growths Between 2007 and 2010:

A Structural Decomposition Analysis

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Abstract

The Eleventh Five-Year Plan (between 2006 and 2010) is significant for China's economic development, energy consumption, and CO_2 emissions. In 2006, China surpassed the USA to become the world's largest CO_2 emitter, which led to widespread discussions about China's role in climate change negotiations. The global financial crisis in 2008 resulted in the one and only downturn in China's exports since 2000. To sustain the country's economic growth, the government made an investment of four trillion Yuan on infrastructure construction and social welfare improvements. In 2009, China became the greatest energy-consuming country in the world. Therefore, it is important to understand the main drivers of China's energy consumption and CO_2 emission growth in this period.

Using an input–output structural decomposition analysis, this paper analyses the key drivers of China's energy consumption and CO_2 emissions growth between 2007 and 2010. Results show that growth in GDP per capita contributed over 20 per cent of the growth in both energy consumption and CO_2 emissions, though this was partly offset by efficiency gains. From a demand perspective, capital formation contributes most to the changes in energy consumption and CO_2 emissions in China; this is followed by urban household consumption. Furthermore, the contribution of exports to both energy consumption and CO_2 emissions declined in both absolute and relative terms. Despite the increase in urban household consumption, structural changes (as indicated in the Eleventh Five-Year Plan) that aimed at encouraging consumption and adjusting the share of investment may need a longer term to reach fulfilment.

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Introduction

The Eleventh Five-Year Plan period[1] (between 2006 and 2010) has proven to be remarkable for China's economic development, energy consumption, and CO_2 emissions. Nominal GDP increased from 21,631 billion Yuan to 40,151 billion Yuan; this made China overtake Japan to become the second-largest economy in the world. Given the deep integration of the Chinese economy into the international market since the late 1970s, the global financial crisis in late 2008 resulted in a significant downturn in China's international trade. Total exports decreased from 10,039 billion Yuan in 2008 to 8,203 billion Yuan in 2009. At the same time, total imports decreased from 7,953 billion Yuan to 6,862 billion Yuan (National Bureau of Statistics, 2014). Following this, China's economic growth rate dropped from 10.6 per cent in the third quarter of 2008 to 6.6 per cent in the first quarter of 2009. In order to sustain economic growth in China, the government invested four trillion Yuan[2] (equivalent to about 15 per cent of total GDP in 2007), on infrastructure construction and social welfare improvement between the fourth quarter of 2008 and the end of 2010. The economy quickly bounced back and reached a high level of annual growth in 2010 (10.4 per cent). Despite the short-term shock experienced during the global financial crisis (between late 2008 and 2009), the Chinese economy still maintained an average annual growth rate of 11.2 per cent during the period of the Eleventh Five-Year Plan.

This rapid economic growth led to a significant increase in China's energy consumption. The country's total primary energy consumption reached 3,249 million tonnes of coal equivalent (Mtce) in 2010, making China surpass the USA to become the world's largest energy consumer. Rapid growth in energy consumption, together with over-dependence on fossil fuels (especially coal), made China the world's largest CO_2 emitter from 2006 onwards and by the end of 2010, China accounted for a quarter of total global CO_2 emissions.

Using an input–output structural decomposition analysis (IO–SDA), this study aims to analyse the key drivers of China's energy consumption growth and CO_2 emissions growth between 2007 and 2010.[3] This research makes two key contributions:

1) it updates the previous IO–SDA on China with the most recent 2010 input–output table. The years between 2007 and 2010 can be of particular interest to an economy-in-transition while experiencing economic crisis;
2) it deals with both energy consumption and CO_2 emissions.

In previous studies, the key drivers of energy consumption and emissions growth were estimated individually. This is key, because while energy consumption causes CO_2 emissions, the actual amount of emissions depends on the energy mix. For instance, a nation with a high proportion of low-carbon energy sources may consume more energy but still produce lower levels of emissions in comparison to nations reliant on fossil fuels. The same also applies to different industries. It is possible for industries that use coal as their main energy source to produce more CO_2 emissions while consuming less energy than others that use nuclear or hydro as their main energy sources. Therefore, there is a need to address both indicators.

The report is organized as following: Section 2 provides a description of China's economic growth, energy consumption, and CO_2 emissions growth during the Eleventh Five-Year Plan period. Section 3 briefly introduces the input–output analysis and structural decomposition analysis. Section 4

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[1] The Five-Year Plan is the strategic planning of five consecutive years of economic development in China. For example, the Eighth Five-Year Plan is from 1991 to 1995, the Ninth Five-Year Plan is from 1996 to 2000, the Tenth Five-Year Plan is from 2001 to 2005, and so on.

[2] This action is known as the 'four trillion Yuan stimulus package'. The exchange rate in September 2008 was about US$1 ≡ 6.83 Yuan (IMF, 2015). 4 trillion Yuan is equivalent to US$586 billion.

[3] The selection of years depends on the availability of input–output tables. See Section 4.2 Data source for details.

introduces the research method (input–output structural decomposition analysis) in detail. This section also includes an explanation of the data sources and data compilation method. The results, including the main forces contributing to the changes in energy consumption and CO_2 emissions, are presented in Section 5. Results are also interpreted by final demand categories and at sectoral level. Discussions of research findings are given in Section 6.

The main findings of this research include:

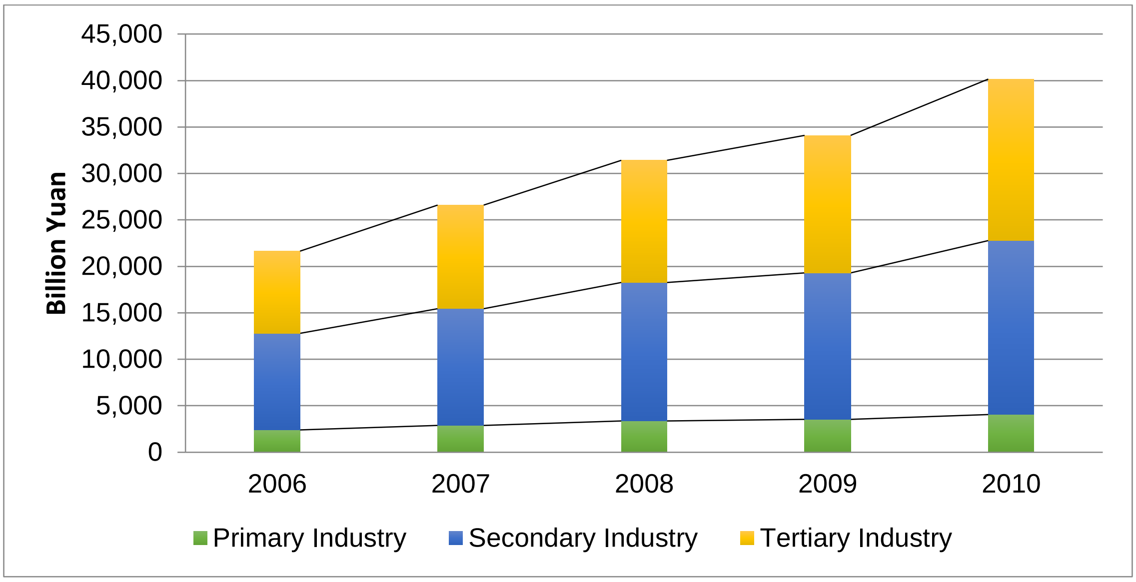
- Growth in GDP per capita is the largest contributor to the growth of energy consumption and CO_2 emissions between 2007 and 2010, while improvements in energy efficiency largely offset this growth;
- The four trillion Yuan stimulus package was successful in sustaining China's economic growth at a relatively high level during the global financial crisis, but it came at a cost – in terms of soaring energy consumption and CO_2 emissions;
- The economic rebalancing towards a consumption-led economy will need longer to reach fulfilment, as the process of investment-driven economic growth was reinforced during the period between 2007 and 2010;
- There are positive signals from household consumption during this period, as the share represented by service industries in total household consumption experienced significant growth.

2. China between 2006 and 2010: the Eleventh Five-Year Plan period

2.1 Economy

China's GDP almost doubled between 2006 and 2010, experiencing an annual average growth rate of 11.2 per cent. Primary industry accounted for 11.1 per cent of total GDP in 2006, declining by one percentage point to 10.1 per cent in 2010. The share represented by secondary industry in total GDP declined from 47.9 per cent in 2006 to 46.7 per cent in 2010. One of the primary targets in the Eleventh Five-Year Plan was to shift China's economic structure from a manufacturing-based to a service-based economy. This resulted in a steady growth of tertiary industry, which represented 40.9 per cent of total GDP in 2006, increasing to 43.2 per cent in 2010 (see Figure 1).

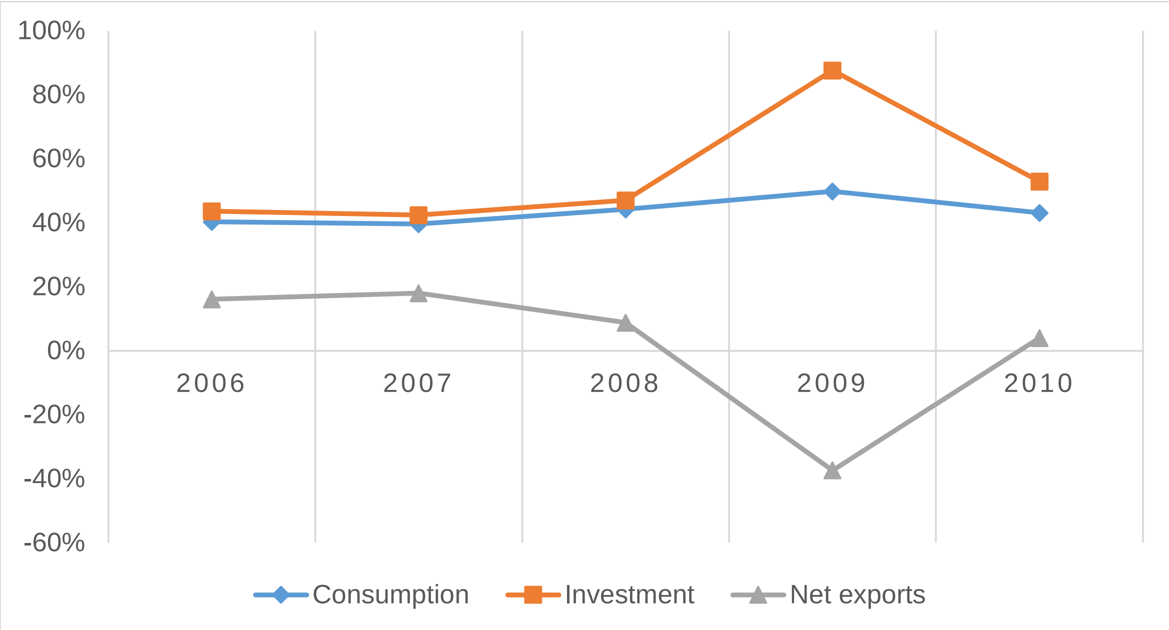
Figure 1: China's GDP growth between 2006 and 2010



Source: author's calculation. Data from: National Bureau of Statistics (2013).

Using the expenditure measure of GDP, the share of consumption, investment, and net exports to GDP growth were relatively stable between 2006 and 2007. A sharp fall in net exports was seen in the fourth quarter of 2008. The share of investment in GDP growth reached a very high level (88 per cent) in 2009, in response to the plunge in net exports (decreasing from 2,086 billion Yuan in 2008 to 1,341 billion Yuan in 2009). Although net exports gradually recovered in 2010, their contribution to GDP growth remained at low levels (4 per cent) compared to the contributions of investment (53 per cent) and consumption (43 per cent) (see Figure 2).

Figure 2: Contributions to GDP growth by expenditure measures from 2006 to 2010



Source: author's calculation. Data from: National Bureau of Statistics (2013).

The rapid rise in investment resulted from the central government's four trillion Yuan stimulus package, which aimed to mitigate the adverse impacts of the global financial crisis on the Chinese economy. Massive spending on housing, rural infrastructure, transportation network construction, and social welfare was undertaken by the central government between 2008 and 2010. Table 1 lists the main components of the four trillion Yuan stimulus package.

Table 1: A breakdown of the four trillion Yuan stimulus package

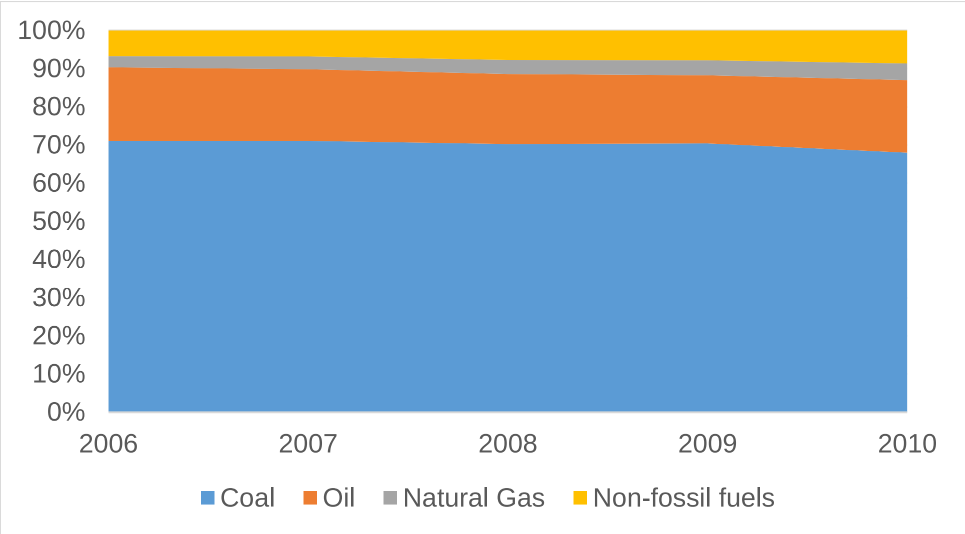
Sector	billion Yuan
Construction of houses for low-income urban households	400
Increased spending on rural infrastructure and boosting rural incomes	370
Expenditures in transportation network construction	1500
Increased investment in medical services, culture, and education	150
Increased spending on ecological protection	210
Technical innovation and economic restructuring	370
Sichuan post-earthquake reconstruction	1000
Total	**4000**

Source: NDRC (2009).

2.2 Energy

Energy has played a vital role in China's double-digit GDP growth during the Eleventh Five-Year Plan period. According to the National Bureau of Statistics (2013), China's total energy consumption increased from 2,587 Mtce in 2006 to 3,249 Mtce in 2010, with an annual growth rate of 6.6 per cent. Coal dominated this energy consumption, accounting for around 70 per cent of China's energy consumption over this period. Other fossil fuels, such as oil and natural gas, also made up a significant proportion (about 20 per cent). The share of non-fossil fuels (including hydropower, nuclear power, wind power, and so on) has been increasing, but remains small in total primary energy consumption (approximately 10 per cent) (See Figure 3).

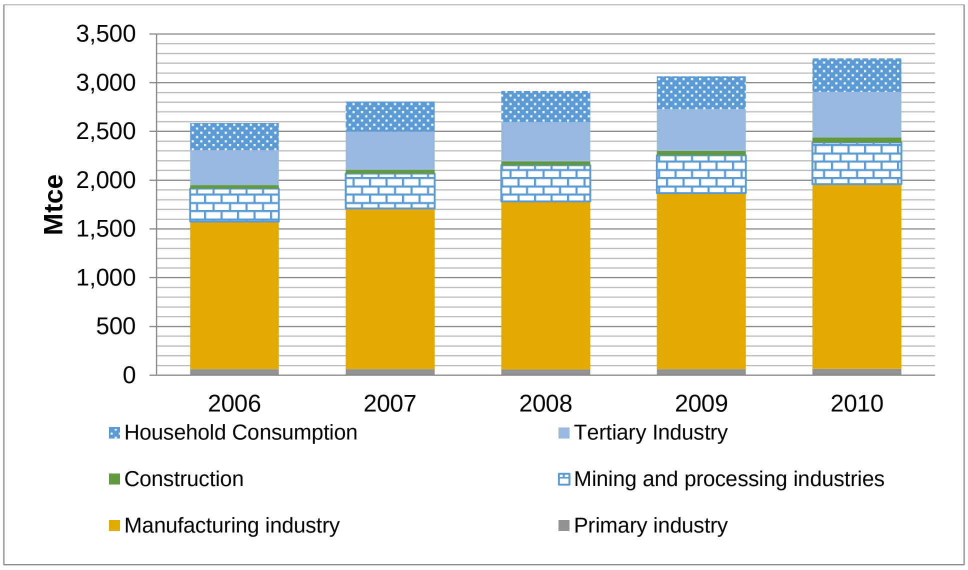
Figure 3: Share of energy sources in total energy consumption



Source: author's calculation. Data from: National Bureau of Statistics (2013).

The bulk of energy (over 70 per cent) was consumed in secondary industries such as mining and processing, manufacturing, and construction. The share represented by tertiary industry (services) and household consumption in total energy consumption increased slightly over this period, together accounting for a quarter of total energy consumption. The share of primary industry remained stable at around 2 per cent (See Figure 4 for details).

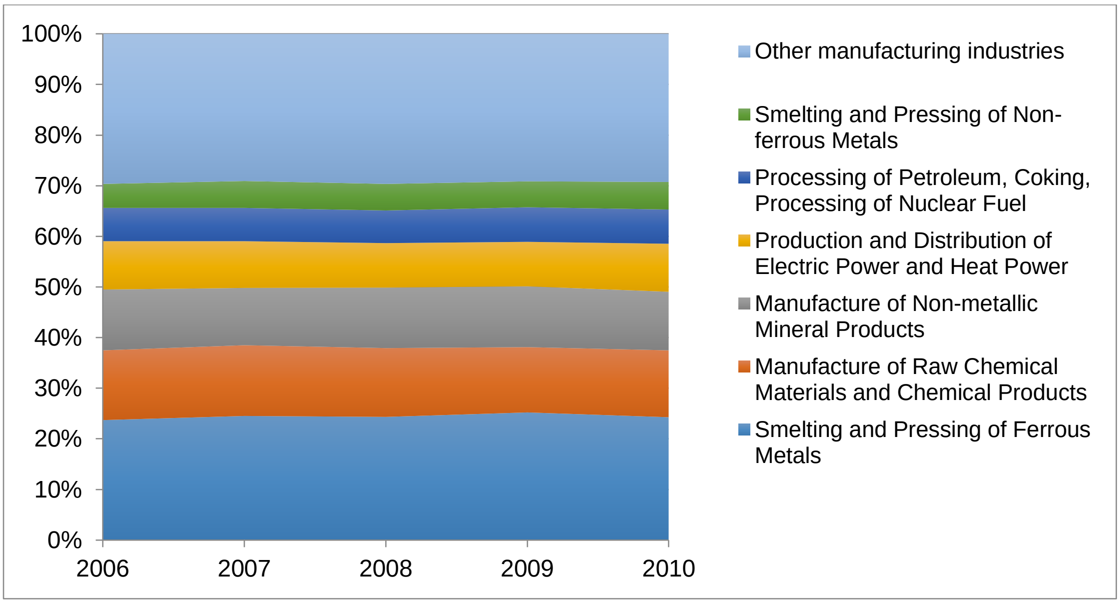
Figure 4: Total energy consumption by sector between 2006 and 2010



Source: author's calculation. Data from: National Bureau of Statistics (2013).

Within the category of secondary industries, six energy-intensive industries accounted for over 70 per cent of the energy consumed in the manufacturing sector. For example, in 2010, smelting and processing of ferrous metals (24.2 per cent), manufacture of raw chemical materials and chemical products (13.2 per cent), manufacture of non-metallic mineral products (11.6 per cent), production and distribution of electric power and heat power (9.5 per cent), processing of petroleum, coking, and nuclear fuel (6.8 per cent), and smelting and processing of non-ferrous metals (5.4 per cent) together accounted for 70.7 per cent of total energy consumption in manufacturing. Figure 5 shows the contributions of energy-intensive industries to total energy consumption in manufacturing.

Figure 5: Contribution of energy-intensive industries to the total energy consumed in manufacturing between 2006 and 2010



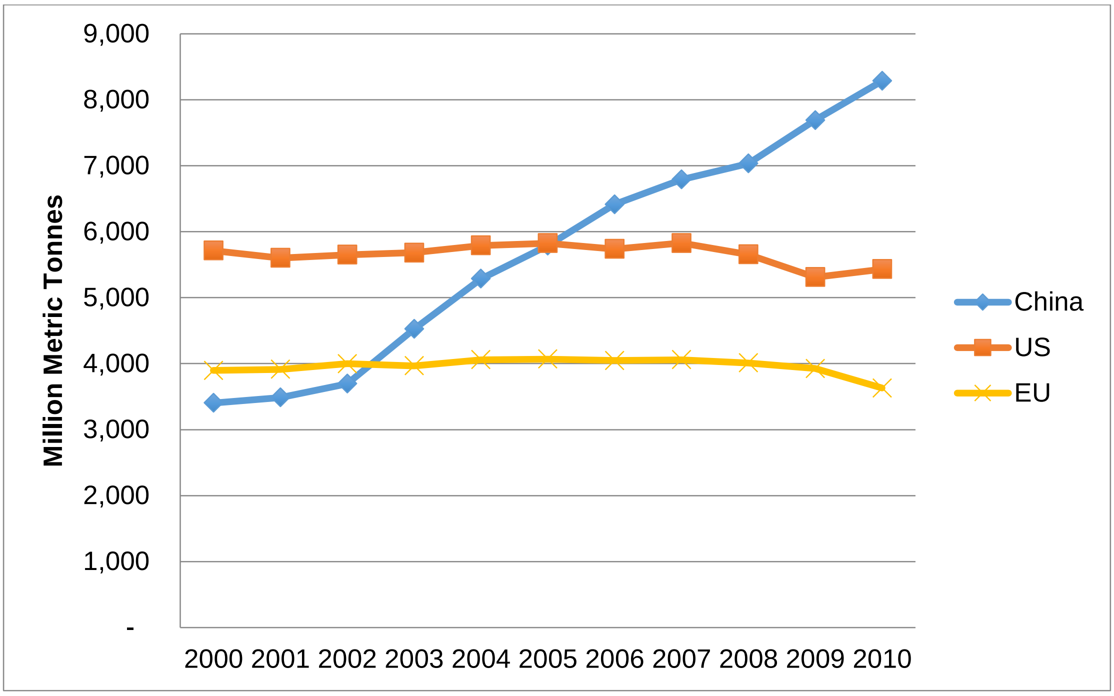
Source: author's calculation. Data from: National Bureau of Statistics (2013).

2.3 CO_2 emissions

In the early 2000s, China's CO_2 emissions increased slightly from 3,405 million tonnes (MT) in 2000 to 3,694 MT in 2002. After overtaking the EU in 2003, China quickly approached the emission level of the USA in 2005. In 2006, China's CO_2 emissions reached 6,414 MT, exceeding the total emissions of the USA (5,738 MT). At the end of 2010, China's CO_2 emissions were 8,287 MT; this accounted for approximately a quarter of the world's total CO_2 emissions. Figure 6 compares CO_2 emissions in China, the USA, and the EU between 2000 and 2010.

The world rankings for per capita CO_2 figures are somewhat different from those for total emissions. CO_2 emissions per capita in China were 6.2 MT in 2010; this figure is slightly lower than that for the UK (7.9 MT) and is only about 35 per cent of the figure for the USA (17.6 MT) (the World Bank, 2014).

Figure 6: CO_2 emissions in China, the USA, and the EU between 2000 and 2010



Source: the World Bank (2014).

The United Nations Framework Convention on Climate Change (UNFCCC) emphasizes the significance of mitigating greenhouse gas (GHG) emissions, the majority of which are energy-related CO_2 emissions, in order to avoid extreme weather conditions (UN, 1992). As the world's largest CO_2 emitter, China's contribution to CO_2 emission reduction will be vital to meeting the target of limiting the global temperature rise to 2°C. In response, China published a National Climate Change Programme in 2007 (NDRC, 2007) which outlines the principles, objectives, policies, and measures needed to address climate change in China. In 2008, a White Paper on China's actions and strategies on climate change was published by the State Council (the State Council, 2008). In 2009, China committed to reduce its CO_2 emissions per unit of GDP by 40–45 per cent (compared to the 2005 baseline) by 2020 (Xinhua, 2009). China had also been keen on developing non-fossil fuel power generation technology between these years. For example, wind power, hydropower, and nuclear power accounted for 24.5 per cent, 22 per cent, and 17 per cent of the total investment in power generation facilities (approximately 364.1 billion Yuan or US$53.5 billion) in 2010 (Nature, 2011).

3. Input–output analysis and structural decomposition analysis

3.1 Input–output analysis

Input–output (IO) analysis (interpreting the flows of goods and services within a specific economy) is considered to be one of the most effective tools for examining interrelationships between economic sectors for a given time period.[4]

The foundation of an IO analysis is the IO table, which is compiled from primary data collected, or estimated by using partial survey or non-survey techniques. The IO table demonstrates the flow of goods and services from one industry to all other industries (described in rows) and the inputs required by an industry to produce its outputs (described in columns) in detail. The major components and their common notations in an IO table include:

- Intermediate transaction (x_{ij}): describes the intermediate deliveries of product from one sector to all sectors (including itself). For example, x_{ij} represents the delivery of product x from sector i to sector j.
- Final demand (y_i): shows the sales of product to end-users. Sales can be made to household purchases, government spending, and foreign purchases (exports), and also considered in terms of inventory increase.
- Value added (w_i): represents the other inputs to the production, including employees' compensation and tax.

The basic layout of an IO table is given in Table 2.

Table 2: An example of IO table

		Economic sectors	Final demand	Total output
		1 ⋯ j ⋯ n		
Economic sectors	1 ⋮ i ⋮ n	x_{ij}	y_i	x_i
Value added		w_i		
Total input		x_i		

IO analysis is based on several assumptions. The first assumption is that one sector produces a single product and any by-product is treated as part of the main product. It can be represented mathematically in the following equation, as:

$$x_i = x_{i1} + \cdots + x_{ij} + \cdots + x_{in} + y_i \quad \textbf{Equation 1}$$

[4] The original idea of IO analysis can be traced back to the 'Tableau Économique' (or Economic Table), which was developed by a French economist, François Quesnay, in 1758. One of the most significant contributions of Quesnay's work is that it provides an analytical foundation to product flows in an economy (Miller and Blair, 2009). In the late eighteenth century, another Frenchman, Léon Walras, developed a general equilibrium theory in economics. A set of production coefficients was introduced; these are similar to the technological coefficients in the later IO model. In 1936, Wassily Leontief simplified the Walras model and published the first article on IO analysis; it was entitled 'Quantitative Input and Output Relations in the Economic Systems of the United States' (Leontief, 1936). Later on, Leontief applied the IO model to assess the economic structure of the USA in his book *The Structure of the American Economy: 1919–1939* and provided an IO model that was appropriate for empirical research (Leontief, 1951).

where:

x_i represents the total output of sector *i*;

x_{ij} (*j* = 1, 2, 3, …, *n*) depicts the flows of goods and services from sector *i* to sector *j*;

y_i represents the final demand of sector *i.*

The second assumption made in IO analysis is that the ratio of input to output remains constant within a specific time period in an economy. It is defined by Leontief as the 'technical coefficient' (a_{ij}). This coefficient states the requirement of sector *i* to produce one monetary unit of product of sector *j*, which is calculated by dividing x_{ij} by x_j, where x_j represents the total output of sector *j* (see Equation 2)

$$a_{ij} = \frac{x_{ij}}{x_j} \qquad \textbf{Equation 2}$$

Replacing x_{ij} by $a_{ij} \times x_j$, Equation 1 can be rewritten as Equation 3.

$$x_1 = a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n + y_1 \qquad \textbf{Equation 3}$$

Equation 3 can be written in matrix form as Equation 4.

$$(I - A)\, x = y \qquad \textbf{Equation 4}$$

where:

I represents the identify matrix;

A represents *n* × *n* matrix of technical coefficients;

x is the total output vector;

y is the final demand vector.

If (*I – A)* is not equal to zero, then Equation 4 can be rewritten as Equation 5.

$$x = L\ y \qquad \textbf{Equation 5}$$

$L = (I - A)^{-1}$ is known as the Leontief inverse matrix – representing the production structure. It describes that, as *L* remains constant for a specific period of time, the changes in total output depend on the changes in final demand. The implication of this equation is that sector *i* needs to generate corresponding amounts of product to fulfil changes in final demand *y*. Therefore, the outputs from other sectors to meet the additional requirements from sector *i* are also taken into account. In other words, it produces a mapping between the final demand vector and the inputs.

For an introduction to the extensions of input–output analysis, please refer to Appendix A.

3.2 Structural decomposition analysis

Structural Decomposition Analysis (SDA) refers to a decomposition analysis based on input–output analysis. It is defined as an '*analysis of economic change by means of a set of comparative static changes in key parameters in an input–output table*' (Rose and Casler, 1996 page 34).

The rationale of SDA is to disaggregate an identity into several components. Thus, it is possible to quantify the changes of different components and their contributions to the total changes of the identity. SDA presents a feasible way of examining the key drivers behind changes in an economy. For example, early applications of SDA decomposed economic growth into three components: technical change, production structure, and level of final demand (these components are usually considered to be the underlying causes of changes in economic growth) and examined their contributions to economic growth.

The following gives a simple example of SDA: assuming the total output of car manufacturing increases by the amount Δx from year 0 to year 1. Based on Equation 5, it can be described as

$$\boldsymbol{x^1} - \boldsymbol{x^0} = \Delta \boldsymbol{x} = \boldsymbol{L^1 y^1} - \boldsymbol{L^0 y^0} \quad \textbf{Equation 6}$$

where the superscripts represent different years (year 0 and year 1). The increase might be explained by changes in production structure (ΔL) through either improved efficiency in production (using less steel per unit of car production) or the use of cheaper materials; or by changes in final demand (Δy) from commercial or private consumers.

Given that: $L_1 = L_0 + \Delta L$

and: $y_1 = y_0 + \Delta y$

Equation 6 can be rewritten as:

$$\Delta x = \Delta L\, y^1 + L^0\, \Delta y$$

and also

$$\Delta x = L^1 \Delta y + \Delta L\, y^0$$

There could be decomposition forms that include changes of more than one factor. For example, Equation 6 can be written as: $\Delta x = L^0 \Delta y + y^0 \Delta L + \Delta L \Delta y$. However, this lacks a straightforward explanation regarding the meaning of the multiplication ($\Delta L \Delta f$) (Miller and Blair, 2009). As suggested by Dietzenbacher and Los (1998), averaging all possible measures has become common practice, and has been used in a number of SDA studies (Guan et al., 2014, Minx et al., 2011). Furthermore, production structure could be explored to see which sector is the source of improvements in efficiency. Similarly, changes in final demand could be decomposed into different categories such as: household purchases, government spending, capital formation, and foreign purchases (exports). The decomposition is not constrained by contributory factors, which means that one can select the number of factors that determine the changes. In addition, the applications of IO to energy, environment, and socioeconomic studies have also extended the use of IO–SDA on these research areas in recent years. Thus, the number of determinants varies between three and 10 in recent IO–SDA studies.

4. Research Method

4.1 Input–output structural decomposition analysis

The foundation of SDA analysis is input–output analysis, which has been used widely in energy and environmental analysis. Adding a matrix *F*, which represents energy consumption or CO_2 emissions per unit of total output, the economy-wide impacts (*f*) can be calculated as:

$$\boldsymbol{f} = \boldsymbol{FLy} \quad \textbf{Equation 7}$$

A simple structural decomposition analysis was introduced in Section 3.2. Total changes in economic outputs (Δx) are subject to changes in production structure (ΔL) and changes in final demand (Δy). In this research, the examination of changes in energy consumption and CO_2 emissions are decomposed into five driving forces (See Equation 8).

$$\boldsymbol{f} = \boldsymbol{p} * \boldsymbol{F} * \boldsymbol{L} * \boldsymbol{y_s} * \boldsymbol{y_v} \quad \textbf{Equation 8}$$

where:

p represents total population;
F is the matrix representing energy consumption or CO_2 emissions per unit of total output;
L is the Leontief Inverse representing the production structure;
y_s represents the ratio of sectoral consumption to total consumption; and
y_v is the total volume of consumption divided by total population.

Given that $y = p * y_s * y_v$, Equation 8 and Equation 7 are equal.

Thus, changes in total energy consumption and CO_2 emissions between year 0 and year 1 can be represented as following:

$$\Delta \boldsymbol{f} = \boldsymbol{f}^{1} - \boldsymbol{f}^{0} = (\boldsymbol{p}^{1} * \boldsymbol{F}^{1} * \boldsymbol{L}^{1} * \boldsymbol{y}_s^{1} * \boldsymbol{y}_v^{1}) - (\boldsymbol{p}^{0} * \boldsymbol{F}^{0} * \boldsymbol{L}^{0} * \boldsymbol{y}_s^{0} * \boldsymbol{y}_v^{0}) \qquad \textbf{Equation 9}$$

One of the decomposition forms is shown below,

$$\begin{aligned} \Delta f = {} & \Delta p * F^1 * L^1 * y_s^1 * y_v^1 \\ & + p^0 * \Delta F * L^1 * y_s^1 * y_v^1 \\ & + p^0 * F^0 * \Delta L * y_s^1 * y_v^1 \\ & + p^0 * F^0 * L^0 * \Delta y_s * y_v^1 \\ & + p^0 * F^0 * L^0 * y_s^0 * \Delta y_v \end{aligned}$$

Equation 10

Keeping all other variables constant, each term on the right hand side of Equation 10 represents the contribution of one of the driving forces to a change in energy consumption and CO_2 emissions. For example, the first term represents the contribution of changes in total population (Δp) to changes in energy consumption or CO_2 emissions (Δf); the second term represents the contribution of changes in energy/emission intensities (ΔF) to the changes in total environmental repercussions (Δf); and so on.

One of the challenges when performing SDA is the existence of equally acceptable decomposition forms; this is referred to as non-uniqueness in SDA. As mentioned above (Section 3.2), there are two possible solutions in the case with two determinants, each of which is equally acceptable. In this research, an equivalent decomposition form to Equation 10 is:

$$\begin{aligned} \Delta f = {} & \Delta p * F^0 * L^0 * y_s^0 * y_v^0 \\ & + p^1 * \Delta F * L^0 * y_s^0 * y_v^0 \\ & + p^1 * F^1 * \Delta L * y_s^0 * y_v^0 \\ & + p^1 * F^1 * L^1 * \Delta y_s * y_v^0 \\ & + p^1 * F^1 * L^1 * y_s^1 * \Delta y_v \end{aligned}$$

Equation 11

As was introduced in Dietzenbacher and Los (1998), the number of decomposition forms is the number of permutations of a set of *n* elements, which is given by (*n*!). For example, five determinants are considered in this research. The number of different decomposition forms is the number of permutations of a set of 5 elements, which is given by (5!). As a result, there are 120 decomposition forms, each of which is equally acceptable. Equation 10 and Equation 11 are termed 'polar decompositions' because they work through the ordering from left to right and from right to left, respectively.[5] Here we only consider changes of one factor and its contribution to the total changes in one formula.

4.2 Data source

The SDA requires two datasets: the IO table and the CO_2 emissions and energy consumption data at sectoral level. China has published benchmark IO tables every five years since 1987. From 2005, IO tables have been updated on non-benchmark years (three years after the benchmark IO table is published). For a brief introduction of the IO table compilation, refer to Appendix B. This study uses the 2007 IO table and the most recent 2010 IO table which were compiled by the National Bureau of Statistics (NBS) in 2009 and 2013, respectively.

The Chinese IO table has several categories of final demand including: rural and urban household consumption, government consumption, fixed capital formation, inventory increase, exports, and imports. Energy data is from the NBS.[6] It provides total energy consumption data at sectoral level. The unit of NBS data is 10,000 tonnes of coal equivalent; this is converted to 1 million tonne of coal equivalent (Mtce) in this study. However, the energy consumption data cannot be used to generate CO_2 emissions data as they are in an aggregated form and therefore only the total amount of energy consumption is given. Therefore, CO_2 emissions data are compiled following the method introduced by Peters et al. (2006) using the energy balance from Energy Statistical Yearbooks (ESY) (See Appendix C for details).

However, there is always incompatibility between IO tables and energy/CO_2 data because of the differences in industrial classification when compiling these two datasets. In this study, the sectoral classification of IO tables is also different between the selected two years: the 2007 IO table has 135 sectors and the 2010 IO table has 65 sectors. In addition, the energy and CO_2 emissions data have 43 sectors. Two approaches are used to reconcile the incompatibility between IO data and energy/CO_2 data: aggregate the IO data to the level that matches the energy/environment data or disaggregate the energy/CO_2 data to the level that matches the IO data. The former approach refers to simple addition of values in similar sector categories (e.g. 'special machinery manufacturing' and 'other machinery manufacturing' can be added to 'machinery manufacturing'). The latter approach is subject to some assumptions. For instance, one of the common assumptions is that similar industries have similar energy/CO_2 intensities.

The choice of sector classification is dependent on the availability of economic and energy/emission data. Theoretically, a higher level of sector disaggregation is preferable, as it produces information in more detail than that from a lower level of sector disaggregation. Nevertheless, there is no consensus about what level of sector classification would be most likely to produce reliable results. Su et al. (2010) went some way towards examining the effect of different levels of sector aggregation by examining the impact on estimation of CO_2 emissions embodied in trade. Using China and Singapore as examples, their study concludes that the minimum level of sector classification, which is least likely to affect the overall results, is 40 sectors. However, the sectoral results can be quite different and very sensitive to the choice of sector classification. This study aggregates the two IO tables into a uniform sector classification with 43 sectors, which is identical to the sectoral classification of the available energy/environmental indicators.

Removing imports from intermediate and final consumption

The compilation of Chinese IO tables treats imports as competitive imports, which means the consumption of imported products can be replaced by that of domestic products, and vice versa. It implies that imports are not only presented in the final demand category as a vector, but are also distributed in the other final demand sectors (such as household consumption and capital formation)

[5] For a more detailed explanation of SDA, refer to Chapter 13 'Structural Decomposition, Mixed and Dynamic Models' in Miller and Blair (2009).

[6] Data is available from: http://data.stats.gov.cn/workspace/index?m=hgnd.

as well as in intermediate inputs. Imports are not always included in the examination of one country's energy consumption (and CO_2 emissions) as they are not produced within the territory under consideration. Weber et al. (2008) introduced an approach to strip imports from both intermediate and final consumption. This approach assumed that intermediate inputs and final demand categories consumed the same proportion of domestic products and imported products. For a more comprehensive removal of imported goods, one should compile an import matrix, which represents the imported products for specific sectors. However, the compilation of an import matrix would require very detailed import data. This research adopts the approach introduced in Weber et al.'s study.

5. Results

5.1 Changes in energy consumption between 2007 and 2010

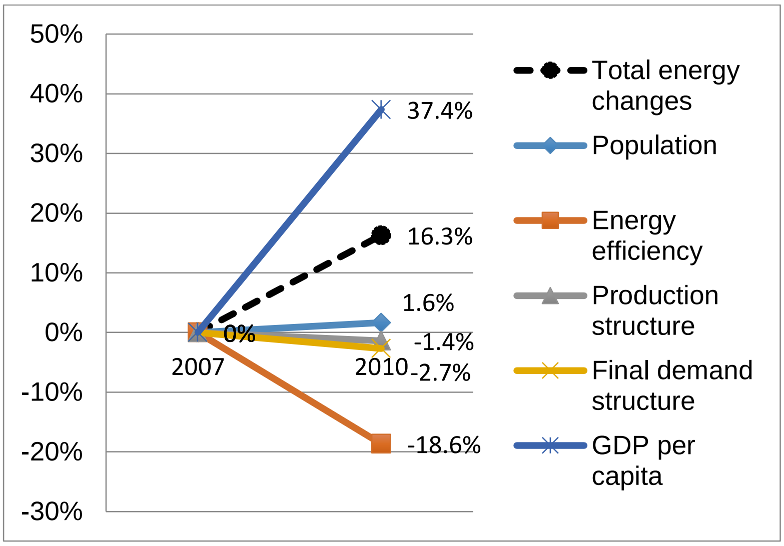
Between 2007 and 2010, China's energy consumption related to production[7] increased by 16.3 per cent from 2,497 million tonnes of coal equivalent (Mtce) to 2,904 Mtce. Figure 7 shows the changes in total energy consumption between 2007 and 2010 and the key contributing factors behind this increase.

- Increase in GDP per capita contributed 37.4 per cent (or 933 Mtce) of the total increase in energy consumption, all other factors remaining constant.
- Population growth contributed to a small change in energy consumption, estimated at 1.6 per cent (or 41 Mtce). This was expected, as total population remained relatively stable during this period (1,318 million in 2007 vs. 1,334 million in 2010).

The remaining drivers contributed to a decline in energy consumption growth:

- Energy efficiency improvement has offset the increase in energy consumption by 18.6 per cent (466 Mtce).
- Changes in the production and final demand structure contributed to minor decreases in energy consumption by 1.4 per cent (34 Mtce) and 2.7 per cent (67 Mtce), respectively.

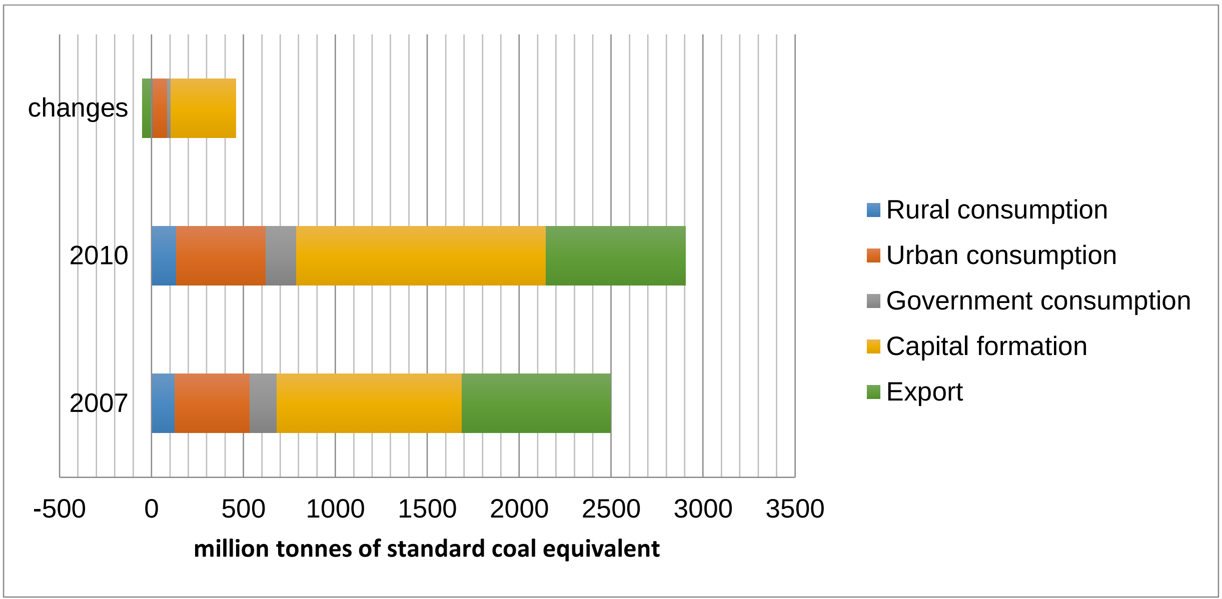
Figure 7: Changes in energy consumption and contributions of key drivers to total changes between 2007 and 2010



[7] Household energy consumption is deducted from total energy consumption to calculate production-related energy consumption.

Figure 8 shows the contributions of final demand categories to the increment in production-related energy consumption between 2007 and 2010. The most significant growth is attributed to capital formation,[8] which consumed 1,360 Mtce of energy in 2010, compared to 1,006 Mtce in 2007. It accounted for 38.5 per cent and 44.4 per cent of the total energy consumption in 2007 and 2010, respectively. The second-largest contribution to the increment was made by changes in urban consumption, which represented 16.8 per cent (or 487 Mtce) of the total energy consumption in 2010, compared to 16.3 per cent or 407 Mtce in 2007. It is interesting to note that all final demand categories experienced growth in energy consumption, except export. Energy consumption related to export activity decreased from 809 Mtce in 2007 to 758 Mtce in 2010, reducing its share in total energy consumption from 32.4 per cent in 2007 to 26.1 per cent in 2010.[9]

Figure 8: Contributions of final demand categories to total energy consumption between 2007 and 2010

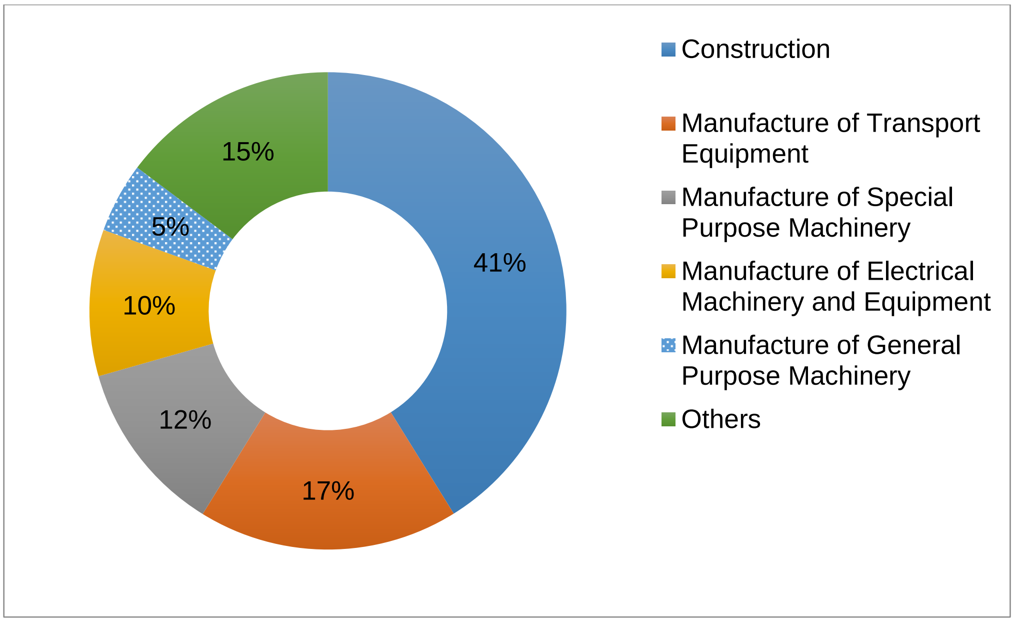


As mentioned above, capital formation contributed the most to production-related energy consumption growth. Of the 354 Mtce increment, construction-related activities accounted for 145 Mtce or 41 per cent. This is mainly due to the 2008 four trillion Yuan stimulus package, which resulted in massive investment on infrastructure such as roads, railways, and so on. For example, China's railway network quickly expanded in length from 78,000 km in 2007 to 91,000 km in 2010, compared to a steady growth from 68,000 km in 2000 to 77,000 km in 2006 (National Bureau of Statistics, 2014). At the same time, the manufacture of transport equipment and the manufacture of special purpose machinery accounted for 60 Mtce (17 per cent) and 42 Mtce (12 per cent) of the changes in energy consumption, respectively. An example of the substantial increase in manufacture of transport equipment is the increase of road transportation vehicles. The number of vehicles that are used for goods and passenger transport (excluding private cars) increased by 2.8 million from 2007 to 2010, compared to an increase of 1 million between 2000 and 2006. Figure 9 shows the contribution of sectors to energy consumption in capital investment.

[8] For a better interpretation of the results, fixed capital formation and inventory increase are added together to derive capital formation.

[9] Also, rural consumption increased from 128 Mtce to 134 Mtce; government consumption increased from 148 Mtce to 165 Mtce, over the period.

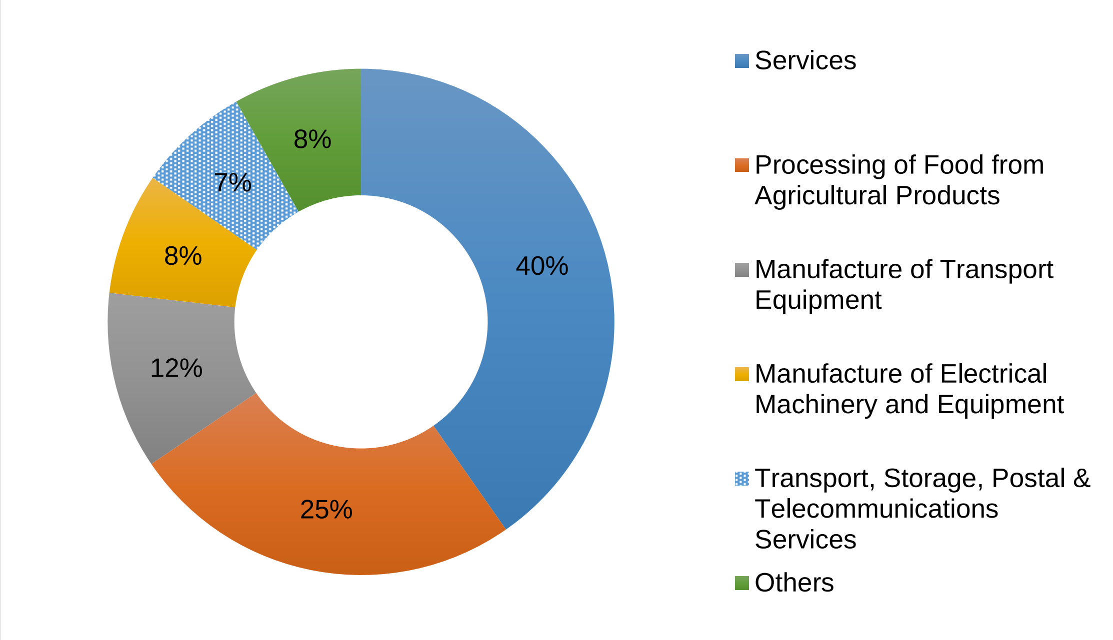
Figure 9: Sectors Responsible for the Increase in Energy Consumption by Capital Formation from 2007 to 2010



Urban household consumption is another significant contributor to the growth of China's energy consumption. Between 2007 and 2010, urban household consumption was responsible for 80 Mtce of China's energy consumption growth. The services [10] sectors was responsible for the largest contribution to this increase (40 per cent), followed by strong growth in processing of food from agricultural products (25 per cent), and manufacture of transport equipment (12 per cent). Private car ownership grew significantly over recent years. For example, the total number of private vehicles increased from 28.8 million in 2007 to 59.4 million in 2010. Figure 10 shows the main sectors that are responsible for the increase in energy consumption by urban households.

[10] The services sectors include: wholesale, retail, and postal services, financial, insurance, and real estate services, education, and health care.

Figure 10: Sectors Responsible for the Increase in Energy Consumption by Urban Households from 2007 to 2010



Exports experienced a decrease in energy consumption between 2007 and 2010, despite their large share in total energy consumption in these two years. Although some industries (such as the manufacture of electrical machinery and equipment, the manufacture of communication equipment and computers, and the manufacture of plastics) experienced significant growth, a decline in other industries (such as the smelting and processing of ferrous and non-ferrous metals, and the manufacture of textiles) has largely offset the energy consumption growth in exports (See Table 3). In other words, the decline in energy consumption related to export activity was due to significant decline in the export of energy-intensive goods and textile products between 2007 and 2010. For example, the total volume of iron exported decreased from 62.7 million tonnes in 2007 to 42.6 million tonnes in 2010 (National Bureau of Statistics, 2014). The decline in the export of goods also resulted in a decline in the shipments of goods. Thus, transport-related energy consumption decreased by 8.6 Mtce over the period.

Table 3: Top and Bottom Sectors Responsible for the Changes in Energy Consumption Triggered by Export from 2007 to 2010

Sectors	Changes in energy consumption (Mtce)
Manufacture of Electrical Machinery and Equipment	12.6
Manufacture of Communication Equipment and Computers	10.1
Manufacture of Plastics	7.5
Manufacture of Transport Equipment	6.7
Processing of Timber, Manufacture of Wood, Bamboo, and others	4.1
Manufacture of Metal Products	–7.1
Smelting and Processing of Non-ferrous Metals	–8.6
Transport, Storage, Postal & Telecommunications Services	–8.6
Manufacture of Textiles	–11.5
Smelting and Processing of Ferrous Metals	–31.2

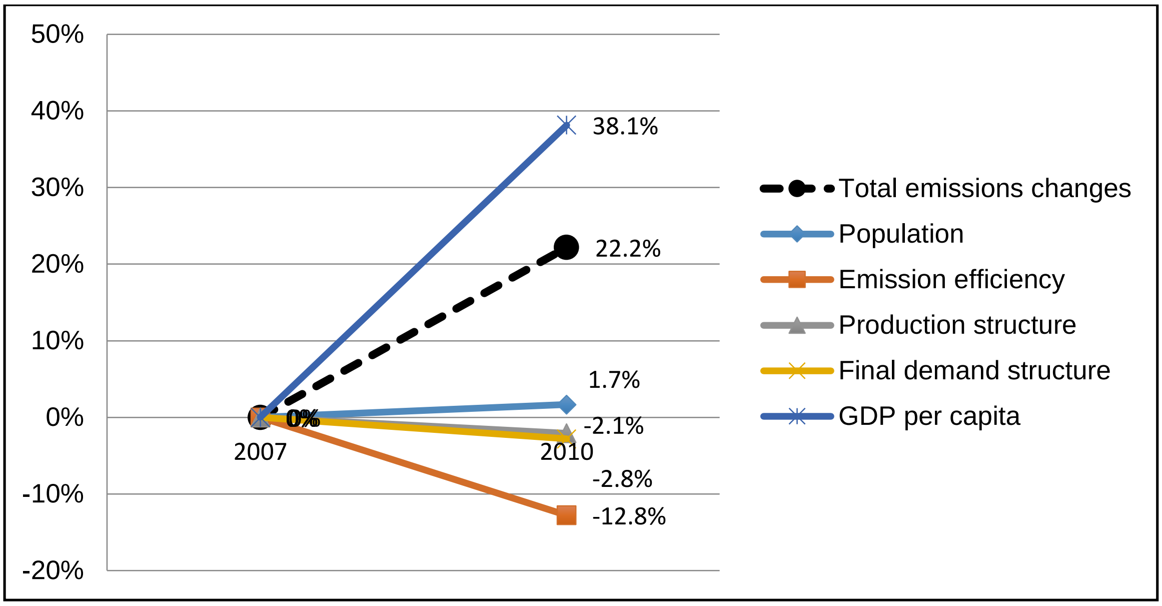
5.2 Changes in CO_2 emission between 2007 and 2010

Growth in CO_2 emissions follows a similar trend to that of energy consumption. Total CO_2 emissions increased by 22.2 per cent or 1,338 million tonnes (MT) between 2007 and 2010:

- GDP per capita contributed most to the growth in emissions; this amounted to 2,301 MT (or 38.1 per cent), other driving forces remaining constant.
- By contrast, emission efficiency improvements (measured by CO_2 emissions per unit of total output) led to a reduction of 12.8 per cent of the total emissions (771 MT).
- Population growth contributed to a minor increase in CO_2 emissions (1.7 per cent or 101 MT) as total population increased by 1.2 per cent between 2007 and 2010.
- Other key drivers, such as changes in production structure (technology) and final demand structure, contributed to a minor decline in CO_2 emissions, by 125 MT (2.1 per cent) and 169 MT (2.8 per cent), respectively.

Figure 11 shows the contribution of each key driving force to the changes in total emissions.

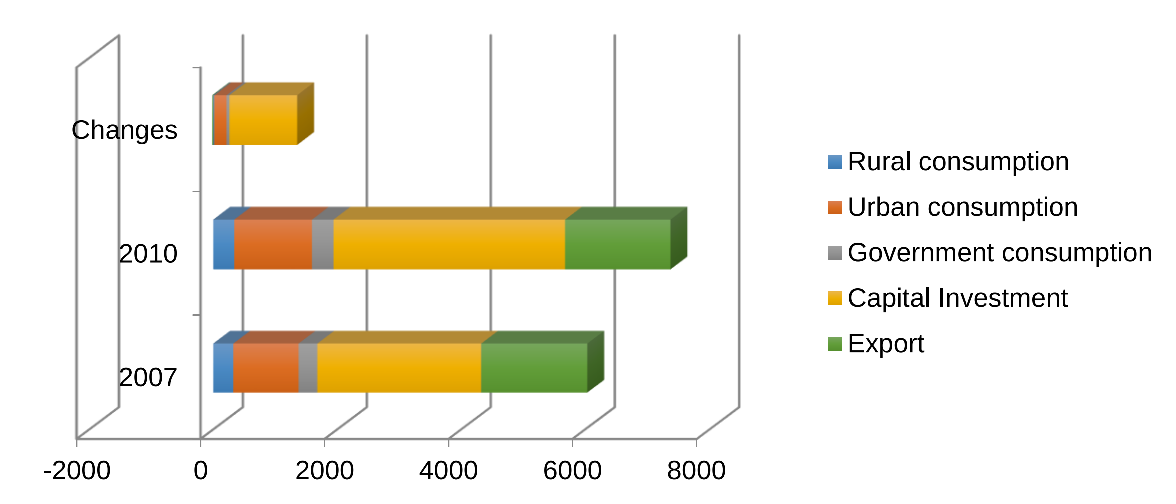
Figure 11: Changes in CO_2 emission and contributions of key drivers to total changes between 2007 and 2010



As expected, capital formation contributed to the majority of the CO_2 emission growth between 2007 and 2010 (Figure 12). It contributed 43.8 per cent (2,645 MT) of total emissions in 2007, increasing to 50.7 per cent (3,737 MT) in 2010. This result is similar to the Peters et al. (2007) study, which finds that capital formation contributed 45 per cent of total CO_2 emissions in 1992 and 52 per cent in 2002. However, the increase of emissions accounted for by capital formation which is seen in the current study accounts for 81.6 per cent (1,092 MT) of the total 1,338 MT emission growth; this contrasts with 56 per cent or 712 MT between 1992 and 2002 in the Peters study.

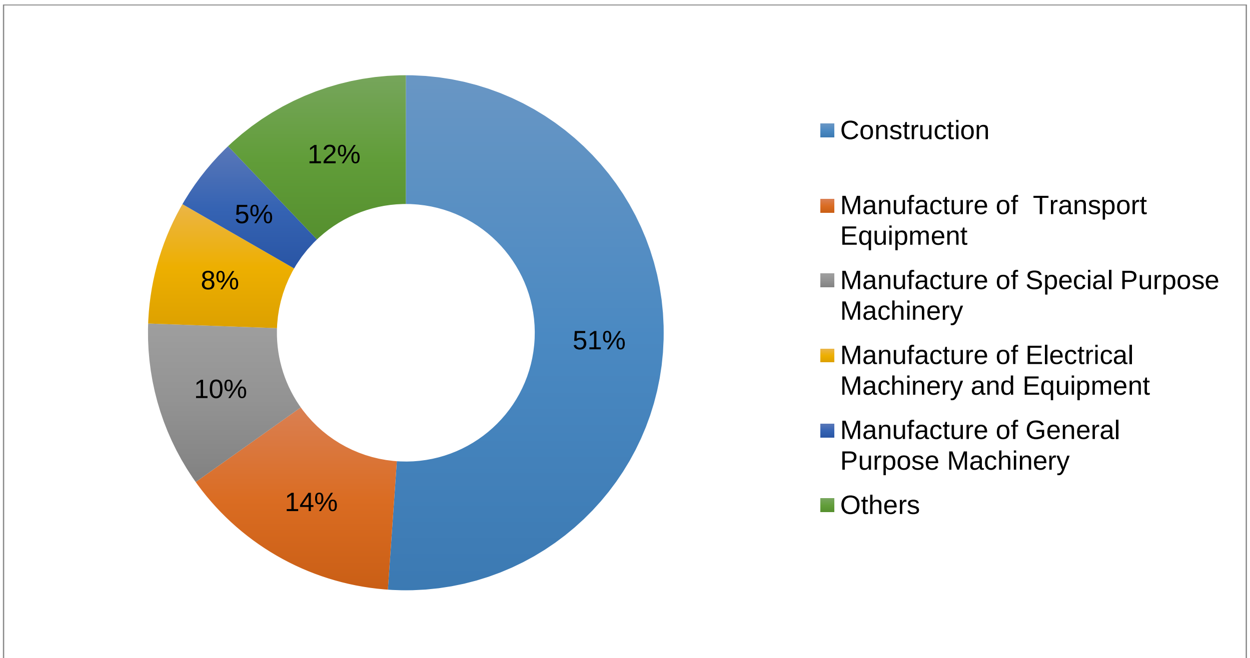
Household consumption – comprising urban (14.9 per cent) and rural (1.2 per cent) household consumption – was responsible for 215 MT (16.1 per cent) of the increase in CO_2 emissions, while 46 MT of CO_2 emissions growth was due to government consumption. The only final demand category that experienced a decline in CO_2 emissions was exports, which decreased from 1,709 MT in 2007 to 1,694 MT in 2010.

Figure 12: Contributions of final demand categories to total CO_2 emissions between 2007 and 2010



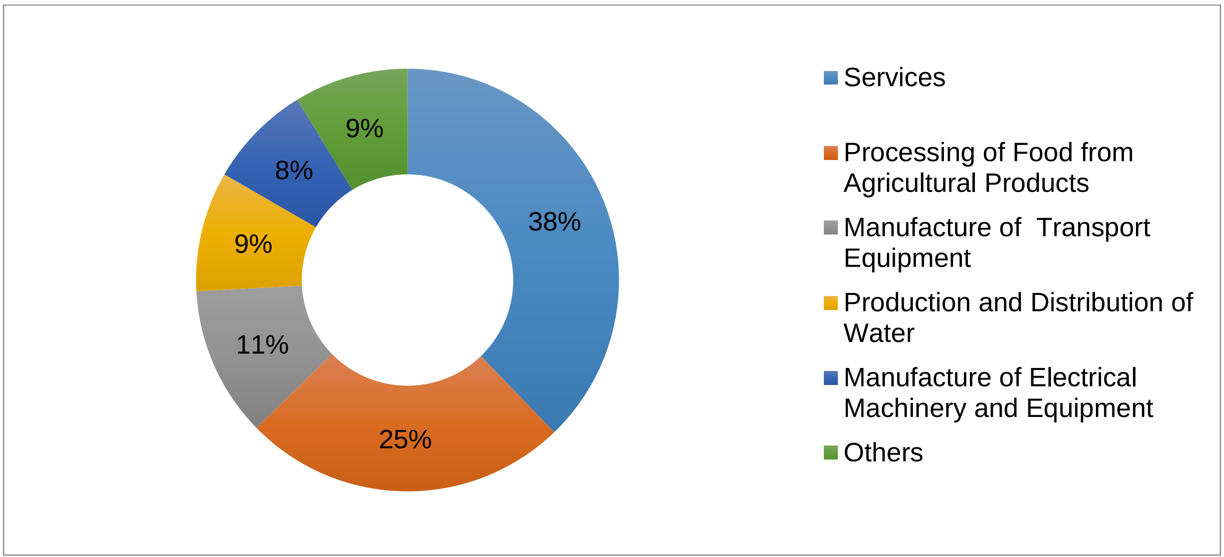
Of the 1,092 MT of additional CO_2 contributed by growth in capital formation, construction accounted for 51 per cent or 558 MT. According to the definition of construction by the National Bureau of Statistics, construction includes: housing construction, civil engineering, equipment installation (pipes, glass, floors, etc.), decoration, and other construction-related services. Among these, the total area of housing under construction increased from 4.8 billion m^2 in 2007 to 7.1 billion m^2 in 2010. Total construction output almost doubled from 5.1 trillion Yuan to 9.6 trillion Yuan over this period. Manufacture of transport equipment and manufacture of special purpose machinery accounted for 153 MT and 114 MT of the changes in CO_2 emissions, respectively. Figure 13 shows the contribution of sectors to CO_2 emissions by capital formation.

Figure 13: Sectors Responsible for the Increase in CO_2 emissions by Capital Formation from 2007 to 2010



Urban household consumption was the second-largest contributor to the growth in CO_2 emissions between 2007 and 2010. This is due to a 38.6 per cent increase in total household disposable income – from 13,786 Yuan to 19,109 Yuan between these years. Services accounted for 38 per cent (75 MT) of the total CO_2 emissions growth in urban household consumption, while processing of food from agricultural products contributed 25 per cent (50 MT). According to the National Bureau of Statistics (2014), expenditure on urban household food products increased from 3,628 Yuan per capita in 2007 to 4,805 Yuan per capita in 2010. In addition, car ownership per 100 households increased from 6.1 to 13.1 between 2007 and 2010, resulting in a significant increase in CO_2 emissions from the manufacture of transport equipment, which increased by 23 MT. Figure 14 shows the contribution of sectors to growths in CO_2 emission in urban household consumption.

Figure 14: Sector Contributions to CO_2 Emission Growth in Urban Household Consumption



Corresponding to the case of energy consumption seen above, the contribution of exports to CO_2 emissions declined between 2007 and 2010. This result is in contrast to previous SDA studies, which found that exports had contributed a significant proportion of the growth in CO_2 emissions for the period between 2002 and 2005, for example see Guan et al. (2009). Although some industries (such as the manufacture of communication equipment and computers, the manufacture of electrical machinery and equipment, and the manufacture of transport equipment) experienced significant growth in CO_2 emissions, the decline in other industries (such as the smelting and processing of ferrous and non-ferrous metals, and the manufacture of textiles) has largely offset the CO_2 emission growth in exports (see Table 4). This decline in CO_2 emissions resulted from a decline in exports of energy-intensive goods between 2007 and 2010. For example, the total volume of exported iron decreased from 62.7 million tonnes in 2007 to 42.6 million tonnes in 2010 (National Bureau of Statistics, 2013).

Table 4: Top and Bottom Sectors Responsible for the Changes in Energy Consumption Triggered by Export from 2007 to 2010

Sectors	Changes in CO_2 emission (MT)
Manufacture of Communication Equipment and Computers	37.4
Manufacture of Electrical Machinery and Equipment	35.7
Manufacture of Transport Equipment	18.5
Manufacture of Plastics	16.6
Manufacture of General Purpose Machinery	13.4
Manufacture of Artwork and Other Manufacturing	–12.8
Transport, Storage, Postal & Telecommunications Services	–14.3
Smelting and Processing of Non-ferrous Metals	–16.4
Manufacture of Textile	–18.5
Smelting and Processing of Ferrous Metals	–62.5

5.3 Carbon emission intensity

Paradoxically, results show that the increase in energy consumption (16.3 per cent) is slower than that of CO_2 emissions (22.2 per cent) between 2007 and 2010. This implies an increase in the carbon emission intensity (measured by CO_2 emissions per unit of energy consumption). This is inconsistent with the fact that the share of non-fossil fuels in primary energy consumption increased from 8.1 per cent in 2007 to 10.3 per cent in 2010. At the same time, the share of coal in primary energy consumption decreased from 69.3 per cent in 2007 to 67.4 per cent, while renewable energy sources were increasing their share in total energy consumption. In fact, based on the changes in the energy mix, production-related CO_2 emission growth would be expected to be slower than production-related energy consumption growth.

There can be several reasons to explain such a counterfactual result. One key factor relates to the fact that the current study uses different data sources for energy consumption and carbon emissions. The figures for energy consumption (total energy consumption at sectoral level) are extracted from the National Bureau of Statistics. By definition, China's total energy consumption is the sum of final consumption, transformation, and losses; this is equivalent to total primary energy consumption (Fridley et al., 2011). However, these sectoral energy consumption data are not suitable for use in the compilation of CO_2 emissions data as they are at a very aggregate level (energy consumption data in each sector is available in the unit of 10,000 tonnes of coal equivalent, which does not classify the type and amount of energy source consumed). Therefore, the compilation of CO_2 emissions data uses the energy balance from the energy statistical yearbooks, which provide energy consumption data in greater detail at sectoral level (See Appendix C for details about the description of data). A number of studies have used this method to compile China's CO_2 emissions data (such as Guan et al., 2012, Feng et al., 2012).

In addition, data from the NBS for total energy consumption show that China's total energy consumption increased from 2,805 Mtce in 2007 to 3,249 Mtce in 2010.[11] It worth noting that figures from other sources (such as the BP Statistical Review and the World Bank) are different for the same period (see Table 5).

[11] Note: these figures are different from those related to energy data mentioned above. The NBS energy data figures include figures for residential consumption; residential consumption figures are neglected in this study because they are not considered as production-related energy consumption.

Table 5: A comparison of energy consumption in China by different sources

Source	2007 Mtce	2010 Mtce	Growth between 2007 and 2010
BP*	2,686	3,342	24%
The World Bank*	2,921	3,595	23%
NBS	2,805	3,249	16%

Source: BP Statistical Review of World Energy (2014); The World Bank (2014); National Bureau of Statistics (2014)

Note: *BP and World Bank data are presented in million tonnes of oil equivalent (Mtoe). They are converted to Mtce by using the conversion of 1 Mtoe ≡ 1.4285 Mtce.

The inclusion of process emissions in compiling CO_2 emissions in some datasets may also help explain the discrepancies. The IPCC (1996) has suggested that industrial process emissions need to be included in accounting for total emissions. Industrial process emissions result from combustion of fuel feedstock in petrochemical plants and other energy-intensive plants (such as cement production plant). While fuel feedstock is not used for energy purposes but for the manufacture of products, some fuel feedstock is inevitably, converted to energy during the process. In order to calculate the emissions associated with such industrial processes, the IPCC proposed an approach: this multiplies the total quantity of products (such as cement) produced by an associated emission factor. In this study, process emissions (due to production of cement[12] and soda ash) accounted for 19.5 per cent (261 MMT) of the CO_2 emissions growth between 2007 and 2010.

5.4 Discussions and conclusions

In short, the above results suggest that population growth contributed to a minor increase in both energy consumption and CO_2 emissions. China's population growth rate has been lower than the world average since the mid-1970s. The annual growth rate was about 0.6 per cent between 2007 and 2010, compared to 1.2 per cent for the world average. The slow growth rate can be attributed to China's family planning policy.[13] Indeed, Nolan (2014) argued that China's family planning policy is much more effective than any low-carbon technologies in cutting CO_2 emissions. According to the United Nations (2012), the population growth rate in China will be even slower in the next 15 years and will see negative growth after 2030. Therefore, the impact of population growth on energy consumption and CO_2 emissions growth will remain low.

By contrast, GDP per capita increased by 47.9 per cent between 2007 and 2010; this is the main driver of growth in energy consumption (37.4 per cent) and CO_2 emissions (38.1 per cent). The finding is similar to Guan's study, which focused on China's growth in CO_2 emissions between 2002 and 2005 (Guan et al., 2009), and found that changes in GDP per capita contributed to 37 per cent of the total CO_2 emission growth between 2002 and 2005. Data from the World Bank suggest that China's GDP per capita growth rate was among the highest in the world during the past 20 years. By the end of 2013, China's figure for GDP per capita was US$6,807, which made China an upper-middle-income nation according to the income-level classification by the World Bank. Despite a recent slowdown in GDP growth rate, China is expected to join the high-income nations by 2030. By then, China's GDP per capita figure is expected to exceed US$12,000, which is almost double the figure for 2013. Therefore, the growth of GDP per capita will continue to be a major driving force in China's future energy consumption and CO_2 emissions growth.

The improvement in energy efficiency has largely offset the growth in energy consumption and emissions, which is consistent with the government's policies aimed at improving energy efficiency. For example, China's Top-1000 Energy-Consuming Enterprises Program, which aimed at reducing the energy consumption and improving the energy efficiency of the largest energy consuming

[12] Cement production increased from 1,361 million tonnes in 2007 to 1,882 million tonnes in 2010.
[13] Not solely limited to the one child policy in the 1980s but also to other policies before that. See Hesketh et al. (2005) for details.

enterprises in China, was implemented in 2006. The programme helped these enterprises to reduce total energy consumption by 150 Mtce between 2006 and 2010, which exceeded the official target of 100 Mtce (Ke et al., 2012). During the Twelfth Five-Year period (2010–2015), a number of government policies were released, aiming at energy efficiency improvements. For instance, the Twelfth Five-Year Development Plan on Energy sets a target of reducing energy consumption per unit of GDP by 16 per cent between 2010 and 2015; the Twelfth Five-Year Development Plan on Industrial Energy Savings sets a target of 21 per cent energy consumption reduction per unit of value added by 2015, based on the 2010 level. Nevertheless, as measured by the IEA (2015), China's primary energy consumption per unit of GDP in 2012 is 0.64 tonnes of oil equivalent per US$1,000 based on the 2005 price level, which is much higher than the United Kingdom (0.08), Japan (0.1), and the USA (0.15) – it is even higher than the figure for India (0.57). Thus, there is still significant potential for China to improve its energy efficiency in the future.

Using the expenditure measures, the contribution of urban household consumption to energy consumption and CO_2 emissions growth had been increasing continuously between 2007 and 2010. Expenditures on service industries represent the most significant growth; this shows that China's economic rebalancing from an industrial-based economy to a service-based economy is in progress. Urban household consumption can present a growing trend in the near future as the process of urbanization continues. As stated in the National New-Type Urbanization Plan (2014–2020), China plans to increase its urbanization rate from 53.7 per cent in 2013 to 60 per cent in 2020. The figure can be further increased to 70 per cent by 2030 (about one billion people), according to the World Bank and Development Research Centre (2014).

Exports contributed negatively to China's energy consumption and CO_2 emissions growth in the period under study mainly due to the global financial crisis, which resulted in the decline of export activity. By contrast, capital formation contributed most to both the increase in energy consumption and CO_2 emissions growth, mainly driven by the four trillion yuan stimulus package. The short-term effects of large-scale investments are visible. For instance, He et al. (2009) estimated the employment effect of the stimulus package and found that the higher investment generated between 18 and 20 million new jobs in non-farming sectors in 2009. However, this increase comes at the expense of rapid growth of both energy consumption and CO_2 emissions, and also of a slowing down of the process of China's economic rebalancing in the long run. The World Bank and Development Researech Center (2013) have projected the share of consumption and investment in total GDP to reach 66 per cent and 34 per cent by 2030, respectively. In turn, the service industry is expected to account for 60 per cent of the country's total GDP by 2030, compared to 43 per cent in 2010. This is generally referred to as 'economic rebalancing' – from an investment-led manufacturing-based economy towards a consumption-led service-based economy in China.

The rebalancing of the Chinese economy is motivated by the structural challenge represented by heavy reliance on investment and manufacturing industries. It could have significant implications on China's energy consumption patterns,[14] energy mix, and CO_2 emissions. In addition, the shift from a manufacturing-based economy to a service-based economy could have an impact on energy consumption at both the sectoral level and as a whole. On the other hand, the majority of the stimulus package is centred on investment in infrastructure such as: railway, road, and airport construction, low-income housing provision, and rural infrastructure (irrigation facilities, power grid extension, and paved roads). This investment in infrastructure drove a quick expansion in the production capacity of

[14] For example, Fattouh and Sen (2014) argue that, between 2000 and 2010, diesel consumption in China grew significantly due to the soaring demand in industries (such as coal mining, steel manufacturing, cement manufacturing, and power generation) and transportation (trucks and rail), with an average growth rate of 8.7%. Efforts to rebalance the economy away from heavy industries have resulted in a lower demand for diesel after 2010. The annual growth rate of diesel has declined to 3.5% since then. At the same time, demand for gasoline has increased by 10.6% on average since 2010. The key driving factors of rising gasoline consumption come from the increasing ownership of private cars, which is expected to grow through to 2020. Thus, the economic rebalancing is likely to shift oil consumption patterns from diesel-driven to gasoline-driven in China.

energy-intensive industries such as: cement, glass, steel, and iron. In 2010, China consumed 53 per cent of global cement production, 48 per cent of iron ore, 45 per cent of steel and lead, 39 per cent of copper, and 35 per cent of nickel (Nolan, 2014). However, following the implementation of the stimulus package, these production capacities cannot be fully utilized, which has also led to overcapacity of these industries in recent years. Thus, despite the increase in urban household consumption, structural changes (as indicated in the Eleventh Five-Year Plan), which aimed at encouraging consumption and adjusting the share of investment, may need a longer term to reach fulfilment. In other words, the way in which the stimulus package works is not sustainable: it solves the short-term pain by causing long-term sickness.

It is not surprising, then, that China is reluctant to implement a similar stimulus package in the future, even with a lower level of GDP growth. In 2014, economic indicators, such as industrial production and GDP growth rate, fell to record lows for the period since the global financial crisis in 2008. Under the pressure of slowing growth, Premier Li Keqiang re-stated the central government's priority at the Tianjin Davos conference:

> *... we won't be distracted by short-term fluctuations in individual economic indicators and will maintain focus on structural adjustments and dealing with long-term issues* (Foreign & Commonwealth Office, 2014).

This does not mean that the government will loosen its grip on the economy. Instead, the government is opting for small-scale stimulus. For example, in April 2014, the State Council initiated tax cuts for small and micro enterprises, aiming at job creation. Furthermore, there are significant pressures on CO_2 emissions mitigation. China's participation will be both necessary and vital to achieving the global emission reduction target. It is expected that this will happen around 2030, according to President Xi Jinping. It would therefore be difficult, for the sake of both the environment and energy consumption, for China to implement another large-scale stimulus, similar to the four trillion Yuan stimulus package, in the future.

Last but not least, our results show that China's energy consumption and CO_2 emissions growth are largely driven by construction, although the direct environmental impacts of construction are low. Similar conclusions can be found in previous studies, such as Peters et al. (2007) and Guan et al. (2009). Liu et al. (2012) indicated that indirect energy consumption from the construction sector is substantial. It has argued that an integrated energy policy should not only focus on the direct energy consumption of energy-intensive industries but should also address energy consumption along their supply chains. Thus, both direct energy consumption and embodied energy consumption should be taken into account in energy policy making.

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Appendix A: Input–output analysis and its extensions

During the past few decades, IO analysis has been further developed in numerous studies and applied in various research areas. For example, the oil crisis of the 1970s stimulated the development of **energy IO analysis**. Energy IO studies usually examine the impacts of energy in a specific economy; such studies include net energy analysis (Bullard et al., 1978), energy cost of goods and services (Hendrickson et al., 2006, Crawford, 2009), structural change and its energy implications (Lin and Polenske, 1995), and so on.

The analytical approach began with adding a set of linear energy coefficients to the traditional Leontief framework. Each of the elements represents the amount of energy consumed per unit of industrial output. Thus, the total energy consumption of a given economy can be represented by

$$\boldsymbol{f} = \boldsymbol{E}\boldsymbol{x} \qquad \textbf{Equation A1}$$

Where *f* is the vector of energy consumption; *E* is the matrix of energy consumption coefficients. Combining Equation 4 with Equation A1, we can get

$$\boldsymbol{f} = \boldsymbol{E}\,(\boldsymbol{I}-\boldsymbol{A})^{-1}\,\boldsymbol{y} \qquad \textbf{Equation A2}$$

In an energy input–output analysis, total energy impacts can be expressed as:[15]

$$f = Ex = Ey + EAy + EA^2y + EA^3y + \ldots.. + EA^ny = E(I-A)^{-1}y$$

where:

Ey is the direct energy impacts due to final demand expenditure;

EAy is the first round of indirect energy impacts due to intermediate requirements;

EA^2y is the second round of indirect energy impacts; and so on.

In order to explain energy use per unit of output, a number of studies applied this approach to estimate the energy consumption of a specific economy (Tiwari, 2000, Liang et al., 2007, Liu et al., 2009). Although this approach has been widely used in energy IO studies, limitations exist because of the assumption of uniform energy price, in which case energy consumption in physical units is not accurately reflected. To overcome this barrier, a hybrid unit approach was introduced by Bullard and Herendeen (1975); it was further developed by Blair (1980), Han and Lakshmanan (1994), and Dietzenbacher and Stage (2006) to deal with limitations of the approach.

Similar to energy IO models, **environmental IO analysis** started with adding a set of linear environmental coefficients to the traditional Leontief framework. Thus the total environmental impacts can be estimated by replacing the energy coefficient matrix in Equation A1 with an environmental coefficient matrix. In recent years, one of the most significant contributions of environmental IO analysis has been its application to the quantification of environmental impacts in trade, especially those related to CO_2 emissions.

The application of environmental IO analysis to trade originated from the UNFCCC framework that used territory-based emissions accounting as the basic method of accounting for national CO_2 emissions. This accounting approach was questioned by some studies, which regarded national CO_2 emission reduction policies as being insufficient if imported products accounted for a significant proportion of a country's consumption (Wyckoff and Roop, 1994). For example, over 70 per cent of exports from developing countries are used to satisfy the needs of developed countries. Production of exported goods results in CO_2 emissions in exporting countries(Peters and Hertwich, 2006). This

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[15] $(I-A)(I+A+A^2+A^3+\ldots+A^n) = (I-A^{n+1})$. All elements of A are smaller than or equal to 1.
If $n \to \infty$, $A^{n+1} \to 0$, we can get $(I-A)(I+A+A^2+A^3+\ldots+A^n) = I$.
Thus, $(I+A+A^2+A^3+\ldots+A^n) = (I-A)^{-1}$.

phenomenon suggests that a different approach should be adopted – depending on whether on whether producers (in which case, production-based emission analysis would be appropriate) or consumers (consumption-based emission analysis) should be held responsible for these emissions. The application of IO analysis to the quantification of environmental impacts in trade is significant for planning national or global environmental policies, as it provides an alternative to existing methods of territory-based emissions accounting.

One alternative to territory-based emissions accounting is consumption-based emissions accounting. Two approaches are commonly used in estimating consumption-based emissions; (Peters et al., 2011, Peters, 2008) provide detailed description of the two approaches. A brief introduction is provided here. The first approach considers the emissions embodied in bilateral trade (EEBT). For example, the emissions embodied in exports between region *r* and region *s* (f^{rs}) can be estimated as:

$$f^{rs} = E^{r} (I - A^{rr})^{-1} k^{rs}$$

where:

E^{r} is the matrix of emission coefficients of region *r*,

A^{rr} is the technical coefficient matrix of region *r* (assuming imports from all other regions have been removed), and

k^{rs} denotes the amount of exports from region *r* to region *s*. Likewise, the emissions embodied in imports between region *r* and region *s* can be estimated as:

$$f^{sr} = E^{s} (I - A^{ss})^{-1} k^{sr}$$

where:

E^{s} is the matrix of emission coefficients of region *s*,

I is the identity matrix,

A^{ss} is the technical coefficient matrix of region *s*, and

k^{sr} denotes the amount of exports from region *s* to region *r*. The figure for total emissions resulting from the production of a unit of final demand consumption (f^{rr}) is calculated as:

$$f^{rr} = E^{r} (I - A^{rr})^{-1} y^{rr}$$

where, y^{rr} is the vector of final demand in region *r.* Using the EEBT approach, consumption-based and production-based emissions of region *r* can be calculated as:

$f_c = f^{rr} + f^{sr}$ and $f_p = f^{rr} + f^{rs}$, respectively.

The second approach further decomposes exports from region *s* to region *r* by separating exports into intermediate consumption and final consumption; in other words, k^{rs} is decomposed into Z^{rs} and y^{rs}, as:

$$k^{rs} = Z^{rs} + y^{rs}$$

where:

$Z^{rs} = A^{rs} x^{s}$ is the intermediate consumption of exports from region *r* to region *s*; and

y^{rs} represents the final consumption of exports from region *r* to region *s*. Thus, the total outputs of region *r* can be calculated as:

$$x^{r} = A^{rr} x^{r} + y^{rr} + \sum_{s \neq r} A^{sr} x^{s} + \sum_{s \neq r} y^{rs}$$

This type of research is usually implemented in **multiregional input–output** (MRIO) analysis. MRIO is an extension of traditional regional input–output analysis that focuses on the economic activity in a single region. The matrix form of the above equation is obtained:

$$\begin{pmatrix} x^1 \\ x^2 \\ x^3 \\ \vdots \\ x^n \end{pmatrix} = \begin{pmatrix} A^{11} & A^{12} & A^{13} & \cdots & A^{1n} \\ A^{21} & A^{22} & A^{23} & \cdots & A^{2n} \\ A^{31} & A^{32} & A^{33} & \cdots & A^{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A^{n1} & A^{n2} & A^{n3} & \cdots & A^{nn} \end{pmatrix} \begin{pmatrix} x^1 \\ x^2 \\ x^3 \\ \vdots \\ x^n \end{pmatrix} + \begin{pmatrix} \sum_r y^{1r} \\ \sum_r y^{2r} \\ \sum_r y^{3r} \\ \vdots \\ \sum_r y^{nr} \end{pmatrix}$$

Where: the diagonal block matrix represents the domestic production activity; the non-diagonal matrix represents trade between regions. For example, A^{11} is the technical coefficient matrix of region 1 which includes all economic sectors in the region. A^{12} represents exports from region 1 to region 2 (or region 2's imports from region 1) which are used in intermediate consumption in region 2. Within the MRIO framework, consumption-based emissions for region *r* can be calculated as

$$f_c^r = H\,(I - A)^{-1} c^r$$

where:
H represents emissions per unit of industry output for all regions;
A is the block matrix in the equation above; and
y^r is the vector of each sector's outputs produced in all other regions and consumed in region r. Thus,

$$y^r = \begin{pmatrix} y^{1r} \\ y^{2r} \\ y^{3r} \\ \vdots \\ y^{mr} \end{pmatrix}$$

Production-based emissions (f_p^r) for region *r* can be calculated as:

$$f_p^r = H\,(I - A)^{-1} p^r$$

in which $p^r = y^{rr} + \sum_s y^{rs}$ (where $p^r$is the final production in region *r*);
y^{rr} is the final consumption produced and consumed domestically,
y^{rs} is the total final consumption produced in r and consumed in all other regions.

Appendix B: Compilation of input–output tables

The work of compiling input–output tables in most countries has adopted the Systems of National Accounts make-use model. Systems of National Accounts (SNA) take into account all activities in an economy including: production and consumption of goods and services, accumulation of capital, imports and exports, and government expenditure. They present the aggregated productive output of the national economy. The principle goal of SNA is:

> ... to provide a framework within which the statistical information needed to analyse the economic process in all of its many aspects could be organized and related. (Miller and Blair, 2009, page 122).

By expanding the national economic accounts to include information at industry and commodity level, we can assemble input–output accounts. (Such information is usually collected through ad hoc surveys or a census of all economic activities of establishments or firms involved in the economy.)

The SNA make-use model first compiles the make table and the use table and then converts the make-use table to the symmetric IO table. In the use table each row represents a commodity that is consumed by industry, household, government, investment, and export, (represented in columns). The make table provides information on the production of commodities by each industry, with rows representing industries and columns representing commodities. The advantage of using a commodity–industry format is that it takes into account secondary products and by-products, which are neglected in the Leontief model.

The conversion from the make-use table to the industry-by-industry table (symmetric IO table) is based on two assumptions: the industry–technology assumption (ITA) and the commodity–technology assumption (CTA). ITA assumes that all product in one producing sector has the same input structure; CTA assumes that each product has a unique input structure which is independent of the producing sector (Guo et al., 2002). A number of countries have compiled their industry-by-industry table by using the make-use table as a foundation.

One of the other approaches to compiling the symmetric IO table is the use of an ad hoc survey. China adopts the latter approach, as its basic statistical unit is enterprise rather than industrial activity. The compilation of make and use tables using data at enterprise level would induce inaccurate results because enterprises usually produce more than one product, and these would have distinctive input structures. A direct decomposition method is used in the compilation of China's IO table. Enterprises classify their products according to the industrial classification introduced by the statistical bureau and then decompose the total costs into industries which represent their products. Combining all data provided by each enterprise, the NBS compiles the IO table. Here, only enterprises above a designated size (annual sales income over 5 million Yuan[16]) are included. For all other enterprises, random sampling is used to collect relevant information.

Appendix C: Compilation of CO_2 emissions

Step 1: Construct final energy consumption data by sector in physical units

Table 6 gives a description of energy data; it includes data source, energy type, sector classification, and so on. Energy data[17] is used as the foundation for the compilation of CO_2 emission data.

[16] The new standard increased the figure for annual sales income from 5 to 20 million Yuan in 2011. Since the latest IO table is from 2010, the new standard does not apply to the existing IO tables.

[17] The energy data used for compiling CO_2 emissions are different from the energy data used for calculating energy consumption. The former are derived from the energy balance that includes some energy sources in physical units (such as tonnes for raw coal and cubic metres for natural gas). The latter gives total energy consumption in tonnes of coal equivalent.

Table 6: Energy Data for 2007 and 2010

Data source	Data used	Note
Energy Statistical Yearbook (ESY) 2008, Table 4-2	Energy Balance of China; Total Final Consumption	20 energy sources; 7 economic sectors (primary, residential, construction)
ESY 2008, Table 5-2	Final energy consumption by industrial sectors	20 energy sources; 39 industrial sectors
ESY 2011, Table 5-1	Energy Balance of China; Total Final Consumption	30 energy sources 7 economic sectors (primary, construction, residential)
ESY 2011, Table 4-2	Final Energy consumption by industrial sectors	27 energy sources; 39 industrial sectors;

Note: National Bureau of Statistics (2008) for ESY 2008; National Bureau of Statistics (2011) for ESY 2011.

Step 2: Data manipulation

For ease of calculation and due to shortage of data (such as net calorific value for some energy sources), energy sources in ESY 2011 are aggregated into 20 energy sources – the same classification as ESY 2008 Table 5-2. These 20 energy sectors are: raw coal, cleaned coal, other washed coal, briquettes, coke, coke oven gas, other gas, other coking products, crude oil, gasoline, kerosene, diesel oil, fuel oil, LPG, refinery gas, other petroleum products, natural gas, heat, electricity, and other energy.

The aggregation (in all 2010 tables) includes:

1. Summation of blast furnace gas, converter gas, and other gas to form 'other gas'.
2. Redistribution of the volume of briquettes in industrial sectors according to consumption proportion in 2007. Consumption information for briquettes is only available in total value (Table 5-1, Energy Statistical Yearbook 2011). Sectoral consumption is not given.
3. Summation of naphtha, lubricants, petroleum waxes, white spirit, bitumen, petroleum, coke, and other petroleum products to form 'other petroleum products'.
4. Summation of natural gas and LNG to form 'natural gas'. Conversion factor: 1 tonne LNG = 1,360 m^3 NG (according to BP).

Step 3: Data conversion

This step involves the conversion of energy from physical units to thermal units (e.g. from tonnes to petajoules). Net calorific values (NCVs) from a number of sources are used to ensure the accuracy of conversion. Most of the conversion factors are obtained from the Energy Statistical Yearbook. If not, other sources, such as the Intergovernmental Panel on Climate Change (IPCC) reference approach, are also used for reference.

Step 4: Accounting for losses, non-energy use, transformation, and processing emissions.

Losses: energy losses during transportation, transmission, etc. are accounted for. Most such losses occur in crude oil, natural gas, heat, and electricity.

Non-energy use: significant amounts of energy are used for purposes (such as the manufacture of chemical products – plastics, rubber, medicines, etc.) other than energy generation. Figures for these non-energy uses should be deducted from those for energy use, to avoid overestimation of energy use, and subsequently of CO_2 emissions. Non-energy use mostly occurs in chemical sectors, and also in the use of coke in metals smelting and pressing; such consumption is removed in this calculation.

Transformation: to avoid double counting, the amount of heat and electricity generated by fossil fuels should be removed, as it has already been counted. The remaining figure represents generation by non-fossil fuel sources – including hydropower, wind, nuclear, and so forth.

Processing emissions: this study considers the processes suggested by Peters et al. (2006) in the estimation of China's emissions inventory. These processes include:

- Raw chemicals: ammonia production, soda ash use.
- Non-metal mineral products: cement production.
- Smelting and pressing of ferrous metals: iron and steel, coke as a reducing agent.
- Smelting and pressing of non-ferrous metals: coke as a reducing agent.

Step 5: Summarize total energy consumption (*E*) in thermal unit

Energy consumption is finally compiled by adding losses, transformation, and by removing non-energy use.

Step 6: CO_2 conversion

The final results for sectoral CO_2 emissions are calculated by multiplying *E* with the default carbon content (tC/Tj), the default carbon oxidation factor (%), and the C to CO_2 conversion factor (44/12).