

# Socioeconomic determinants of China's growing CH<sub>4</sub> emissions

## Abstract

Reducing CH<sub>4</sub> emissions is a major global challenge, owing to the world-wide rise in emissions and concentration of CH<sub>4</sub> in the atmosphere, especially in the past decade. China has been the greatest contributor to global anthropogenic CH<sub>4</sub> emissions for a long time, but current understanding towards its growing emissions is insufficient. This paper aims to link China's CH<sub>4</sub> emissions during 2005-2012 to their socioeconomic determinants by combining input-output models with structural decomposition analysis from both the consumption and income perspectives. Results show that changes in household consumption and income were the leading drivers of the CH<sub>4</sub> growth in China, while changes in efficiency remained the strongest factor offsetting CH<sub>4</sub> emissions. After 2007, with the global financial crisis and economic stimulus plans, embodied emissions from exports plunged but those from capital formation increased rapidly. The enabled emissions in employee compensation increased steadily over time, whereas emissions induced from firms' net surplus decreased gradually, reflecting the reform on income distribution. In addition, at the sectoral level, consumption and capital formation respectively were the greatest drivers of embodied CH<sub>4</sub> emission changes from agriculture and manufacturing, while employee compensation largely determined the enabled emission changes across all industrial sectors. The growth of CH<sub>4</sub> emissions in China was profoundly affected by the macroeconomic situation and the changes of economic structure. Examining economic drivers of anthropogenic CH<sub>4</sub> emissions can help formulate comprehensive mitigation policies and actions associated with economic production, supply and consumption.

Keywords: China's CH<sub>4</sub> emissions; Consumption-based accounting; Income-based accounting; Input-output analysis; Structural decomposition analysis

# 1 Introduction

China is one of the countries most vulnerable to the adverse impacts of climate change. However, it is also the largest CO<sub>2</sub> emitter in the world (Li et al., 2016). China's rapidly increasing CO<sub>2</sub> emissions have prompted the measures to address climate change and to achieve emission mitigation. The country's government has pledged to lower its CO<sub>2</sub> emissions per unit of GDP by 60-65% relative to the 2005 level and committed to peak its CO<sub>2</sub> emissions by around 2030. A series of energy and climate policies have been developed and implemented to ensure such mitigation targets. Nevertheless, most of these policies and actions have focused on the reduction of CO<sub>2</sub> emissions.

Methane (CH<sub>4</sub>) is the second largest greenhouse gas (GHG) after CO<sub>2</sub>, but is more active than the latter. For a time horizon of 20 years, CH<sub>4</sub> has greater short-term climate impacts than CO<sub>2</sub> with a Global Warming Potential 84 times larger than CO<sub>2</sub> (IPCC, 2014), while it is responsible for nearly one fifth of global warming (Montzka et al., 2011). In the recent decade, the atmospheric concentration of CH<sub>4</sub> has witnessed a disturbing surge (Saunois et al., 2016) to the extent that it has more than doubled compared with the level before the Industrial Revolution. The growth of CH<sub>4</sub> levels in the atmosphere has been largely driven by increasing emissions from human activities such as agricultural activities and fossil fuel extraction, and then mitigation of anthropogenic CH<sub>4</sub> emissions can generate direct effects on its atmospheric concentration (e.g., Ghosh et al., 2015; Nisbet et al., 2016).

China is the world's largest contributor of anthropogenic CH<sub>4</sub> emissions. To date, there are three national GHG inventories including CH<sub>4</sub> emissions reported by the Chinese government (CCDNDRC, 2017; Zhang et al., 2018a). According to the last official national GHG inventory, which was published in the first Biennial Update Report (BUR) on Climate Change submitted to the UNFCCC (CCDNDRC, 2017), China's total CH<sub>4</sub> emissions amounted to 55.9 Tg in 2012. Even by the lower GWP value of 21, this amount was equal to 1174 Mt CO<sub>2</sub>-eq, much larger than the CO<sub>2</sub> emissions in some developed countries such as England and Japan. In view of the importance of CH<sub>4</sub> in the whole GHG emission inven-

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4 tories, China's significant CH<sub>4</sub> emissions have attracted considerable research in inventory  
5 compilation and analysis over the last decade. Some researchers and international institu-  
6 tions have published their own estimates for China's CH<sub>4</sub> emissions at the national scale  
7 (e.g., USEPA, 2012; Yang et al., 2014; Zhang and Chen, 2014; Zhang et al., 2014; Peng  
8 et al., 2016; Janssens-Maenhout et al. 2017). All unanimously reported that China's CH<sub>4</sub>  
9 emissions had witnessed dramatic increases over the past three decades (Zhang, 2011; Peng  
10 et al., 2016). Recently, the EDGAR database provided a consistent series of China's CH<sub>4</sub>  
11 emissions inventory covering 1970-2012 (EDGAR, 2017). Existing emission inventories have  
12 identified the surge in livestock, energy and waste-related CH<sub>4</sub> emissions in China, especially  
13 since 2005, as well as how this fast growing trend is unlikely to be reversed in the near pe-  
14 riods (Yao et al., 2016). Given the severe challenges that increasing CH<sub>4</sub> emissions poses in  
15 mitigating GHG emissions, more attention should be paid to understanding and quantifying  
16 China's CH<sub>4</sub> emissions and to propose potential mitigation measures.  
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32 In China, CH<sub>4</sub> emissions are directly related to economic production such as energy  
33 extraction and supply (Zhang et al., 2014), rice cultivation and livestock farming (Wang et  
34 al., 2017b), and waste management services (Du et al., 2017, 2018b). Besides mitigating  
35 CH<sub>4</sub> emissions on the production side, it is essential to understand the role of socioeconomic  
36 activities in anthropogenic emissions and reveal the opportunities available for mitigation  
37 (Zhang et al., 2015; Zhou et al., 2018). It is widely acknowledged that resource extraction and  
38 environmental emissions are induced by final consumption demand (Liu et al., 2010; Wu and  
39 Chen, 2017; Tang et al., 2018). Environmentally extended input-output analysis (EEIOA)  
40 facilitates a deeper appreciation of sector-specific direct/visible and indirect/hidden emission  
41 requirements (Miller and Blair, 2009). By using the Leontief demand-driven input-output  
42 models, a series of studies have been performed to measure consumption-based accounting  
43 of GHG emissions at different scales (Feng et al., 2015; Hawkins et al., 2015). An increasing  
44 amount of literature has focused on China's CO<sub>2</sub> emissions embodied in final consumption  
45 and international trade (e.g., Chen and Zhang, 2010; Feng et al., 2012; Yuan et al., 2018).  
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4 Particularly, Zhang and his colleagues (Zhang and Chen, 2010; Zhang et al., 2015, 2018a)  
5 have conducted a series of studies on the embodiment analysis of CH<sub>4</sub> emissions in China.  
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7 Environmental emissions can also be driven by primary inputs. Higher income translates to  
8 higher consumption capacity and greater demands for environmental resource inputs. The  
9 Ghosh supply-push input-output model can capture the linkages of value-added with primary  
10 inputs, which has been used to estimate the enabled emissions of CO<sub>2</sub> and air pollutants  
11 driven by the value added using the income-based accounting method (e.g., Liu et al., 2010;  
12 Zhang, 2010; Marques et al., 2013; Liang et al., 2016a,b; Liu and Fan, 2017). Furthermore,  
13 the method of structural decomposition analysis (SDA) enables researchers to examine the  
14 driving forces of resources, emissions and other physical quantities (e.g., Hoekstra and Van  
15 Den Bergh, 2002; Su and Ang, 2012, 2017; Arto and Dietzenbacher, 2014; Malik et al., 2016;  
16 Deng and Xu, 2017; Wang et al., 2017a). By using this method, energy, air pollutants and  
17 carbon emissions in China have been widely analyzed (e.g., Kagawa and Inamura, 2004;  
18 Peters et al., 2007; Guan et al., 2008, 2009, 2014; Zhang, 2009; Xu et al., 2011; Zhang and  
19 Qi, 2011; Feng et al., 2012, 2017; Xie, 2014; Zeng et al., 2014; Deng et al., 2016; Yuan and  
20 Zhao, 2016; Jiao et al., 2017; Liu and Liang, 2017; Mi et al., 2017a, 2017b; Shi et al., 2017;  
21 Wei et al., 2017; Zhao et al., 2017; Du et al., 2018a; Zhang et al., 2018b). Despite of the  
22 existing literature on GHG emissions accounting, the current understanding of China's CH<sub>4</sub>  
23 emissions from both consumption- and income-based perspectives is insufficient.  
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26 Exploring and explaining the socio-economic drivers behind China's growing anthro-  
27 pogenic CH<sub>4</sub> emissions is of critical importance for three reasons. First, China has not only  
28 been the largest CH<sub>4</sub> emitter in the world, its level of emissions has also increased constantly.  
29 Identifying major emission drivers provides guidance on further mitigation. Second and more  
30 importantly, the world-wide rise in CH<sub>4</sub> emissions over the last decade is poorly understood.  
31 Unlike CO<sub>2</sub> emissions, there is an ongoing dispute over the determinants of the surging at-  
32 mospheric CH<sub>4</sub>. Various sources have been suggested to be responsible for this increase,  
33 such as agricultural activities in Asia (Schaefer et al., 2016), feedback effects from tropical  
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4 wetlands (Nisbet et al., 2016), and declines in hydroxyl radicals (Turner et al., 2017), yet  
5 no consensus has been reached. Surprisingly, explaining CH<sub>4</sub> emission growth with socio-  
6 economic factors barely draws any attention from researchers, even though atmospheric CH<sub>4</sub>  
7 is closely associated with human activities. Third, CH<sub>4</sub> monitoring is especially inadequate.  
8 Although some developed countries have refined their CH<sub>4</sub> measurement equipment to mon-  
9 itor emissions from various sources, upgrading to better equipment for monitoring individual  
10 sources is costly for developing countries. Therefore, analyzing the socio-economic drivers of  
11 CH<sub>4</sub> emissions and their corresponding mitigation potentials is not only meaningful but is  
12 also a practical option for most developing countries with limited resources.  
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23 This paper aims to shed light on the issue of China’s anthropogenic CH<sub>4</sub> emissions, and  
24 explore the socioeconomic determinants of its growing emissions from 2005 (the baseline for  
25 China’s emission reduction commitment) to 2012 based on the EEIOA and SDA methods.  
26 Key sectors and driving forces for embodied and enabled CH<sub>4</sub> emissions in China are identi-  
27 fied by using income-based accounting and consumption-based accounting, where the former  
28 involves a supply-side SDA and the latter a demand-side SDA. The main contribution of our  
29 work is to reveal the supply- and demand-side impacts on anthropogenic CH<sub>4</sub> emissions aris-  
30 ing from structural changes in the economy. Finally, we discuss the development of emission  
31 trend and future mitigation policies, especially in the economic “new normal”.  
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## 44 **2 Methodology and data sources**

### 45 **2.1 Consumption-based accounting and structural decomposition** 46 **analysis** 47

48 Consumption-based accounting covers the embodied CH<sub>4</sub> emissions caused by final demand  
49 (e.g., rural and urban consumption, government consumption, investment and export) and  
50 relocates the emission responsibility to final consumers. Performing structural decomposi-  
51 tion on embodied emissions can provide a comprehensive understanding towards the socioe-  
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4 conomic determinants of CH<sub>4</sub> emissions from the demand side. According to the principle  
5 of EEIOA model,  $e$  denotes a row vector of sector-level CH<sub>4</sub> emissions and  $x$  denotes the  
6 sector-level output vector, the CH<sub>4</sub> emissions embodied in final demand,  $u$ , can be calculated  
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$$10 \quad u = (e'\hat{x}^{-1})(I - Z\hat{x}^{-1})^{-1}\hat{y} \quad (1)$$

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12 where  $Z$  is the inter-sectoral transaction matrix denoting the monetary relationship among  
13 different sectors of the economy;  $y$  is the vector of final demand for each sector; and the  
14 operator  $\hat{\cdot}$  represents a diagonalizing matrix. The term  $e'\hat{x}^{-1}$  stands for a vector of sector-  
15 level CH<sub>4</sub> emission intensities, and  $(I - Z\hat{x}^{-1})^{-1}$  is the Leontief inverse matrix. Since  $y$   
16 represents the final demand,  $(I - Z\hat{x}^{-1})^{-1}\hat{y}$  can be interpreted as the inputs from each sector  
17 to produce the final demand. Thereafter, embodied CH<sub>4</sub> emissions induced by any given  
18 final demand category such as consumption, can be obtained through Equation (1).  
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21 We consider five factors, i.e. population, production efficiency, production input struc-  
22 ture, consumption structure and absolute consumption volume, for analyzing the deter-  
23 minants of embodied CH<sub>4</sub> emissions. Consequently, the CH<sub>4</sub> emissions embodied in final  
24 demand can be decomposed into five terms by rewriting Equation (1) into:  
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$$30 \quad u = F \times L \times \hat{p} \times \hat{y}_s \times \hat{y}_v \quad (2)$$

31 where  $F = e'\hat{x}^{-1}$  is the emission intensity which represents production efficiency, and  
32  $L = (I - Z\hat{x}^{-1})^{-1}$  represents the linkage between final demand and total output, therefore  
33 suggesting the production input structure of the economy. The final demand is decomposed  
34 into three terms  $y = \hat{p} \times \hat{y}_s \times \hat{y}_v$ . Here  $p$  is a scalar denoting total population;  $y_s$  represents  
35 per capita consumption patterns; and  $y_v$  stands for per capita consumption of each final  
36 demand category.  
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Performing a structural decomposition analysis on Equation (2) yields:

$$\begin{aligned} \Delta u = & \Delta F \times L \times \hat{p} \times \hat{y}_s \times \hat{y}_v + F \times \Delta L \times \hat{p} \times \hat{y}_s \times \hat{y}_v + F \times L \times \Delta \hat{p} \times \hat{y}_s \times \hat{y}_v \\ & + F \times L \times \hat{p} \times \Delta \hat{y}_s \times \hat{y}_v + F \times L \times \hat{p} \times \hat{y}_s \times \Delta \hat{y}_v \end{aligned} \quad (3)$$

where  $\Delta x$  denotes the change in  $x$ . Each of the five components with  $\Delta x$  in the right hand side of the equation represents the contribution to CH<sub>4</sub> emission changes triggered from the changes of  $x$ , where all other components remain constant.

The structural decomposition analysis on the input-output model is subject to the non-uniqueness problem since there are 120 alternatives for any decomposition with 5 factors. To address this issue, we follow Dietzenbacher and Los (1998) and Hoekstra and Van Den Bergh (2002) to use the average of all possible first-order decomposition alternatives as the contribution of each component.

## 2.2 Income-based accounting and structural decomposition analysis

Income-based accounting evaluates the downstream CH<sub>4</sub> emissions enabled by primary inputs (e.g., supplies of labor forces and capital), which accounts for the emissions embodied in the value-added chain. Besides the demand function, the value-added function can be employed to capture the functioning of the EEIOA model from the perspective of income-based accounting. The value-added enabled emissions can be measured as

$$d = \hat{v}(I^{-1} - \hat{x}^{-1}Z)^{-1}(\hat{x}^{-1}e) \quad (4)$$

where  $v$  is the vector of value-added, and  $(I^{-1} - \hat{x}^{-1}Z)^{-1}$  is the Ghosh inverse matrix that links value-added with primary inputs. Therefore, the right-hand side of Equation (4) amounts to the enabled CH<sub>4</sub> emissions triggered by intermediate input demand.

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4 Because the difference between consumption-based and income-based measure is the emis-  
5 sion induced by either final demand or intermediate input demand, the quantity of gross  
6 emissions remains unchanged, i.e.  $\sum e_i = \sum u_i = \sum d_i$ .  
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10 The structural decomposition on enabled emissions can further identify the socioeco-  
11 nomic determinants of China's increasing CH<sub>4</sub> emissions from the supply side. Similarly,  
12 we decompose the income-based measure into five terms in terms of total population, per  
13 capita income, the input structure, production output structure and production efficiency,  
14 as follows  
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$$20 \quad d = \hat{p} \times \hat{v}_s \times \hat{v}_d \times G \times F \quad (5)$$

21 where  $G = (I^{-1} - \hat{x}^{-1}Z)^{-1}$  and  $\hat{v} = \hat{p} \times \hat{v}_s \times \hat{v}_d$ . The scalar  $p$  again denotes total population;  
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24  $v_s$  stands for the input structure vector, whose element  $v_{s_i}$  indicates the share of sector  $i$ 's  
25 inputs to gross income;  $v_d$  stands for per capita income; the matrix  $G$  denotes production  
26 output structure; and  $F$  represents production efficiency.  
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32 The structural decomposition form of Equation (5) can be written as:  
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$$35 \quad \Delta d = \Delta \hat{p} \times \hat{v}_s \times \hat{v}_d \times G \times F + \hat{p} \times \Delta \hat{v}_s \times \hat{v}_d \times G \times F + \hat{p} \times \hat{v}_s \times \Delta \hat{v}_d \times G \times F \\ 36 \quad + \hat{p} \times \hat{v}_s \times \hat{v}_d \times \Delta G \times F + \hat{p} \times \hat{v}_s \times \hat{v}_d \times G \times \Delta F \quad (6)$$

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42 We use the same approach by calculating the average of all possible first-order decompo-  
43 sitions to tackle with the non-uniqueness problem.  
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## 48 2.3 Data sources

49 The empirical design involves two kinds of dataset: time-series input-output tables and  
50 sector-level CH<sub>4</sub> emissions. We obtain the deflated national IO tables for 2005, 2007, 2010  
51 and 2012 from Mi et al. (2017a). They employed double deflation method to deflate the  
52 input-output tables. More specifically, they used price indices from China Statistical Year-  
53 book to deflate input-output tables. The real value-added was calculated by the difference  
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4 between real output and real intermediate inputs to balance the IO tables. Based on the  
5 deflated results, all the data of input-output tables were aggregated into 20 economic sec-  
6 tors. Sectoral aggregation provides the convenience of presenting and analyzing empirical  
7 results, meanwhile it has limited impacts on our decompositions, because CH<sub>4</sub> emissions  
8 are largely concentrated in three sectors (Agriculture, Mining and Other service), and little  
9 heterogeneity exists among the merged sectors. Detailed procedures to illustrate the compi-  
10 lation process of the input-output tables at 2012 constant prices can be referred to Mi et al.  
11 (2017a).  
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21 In this study, the inventories of China's anthropogenic CH<sub>4</sub> emissions from the EDGAR  
22 4.3.2 database (EDGAR, 2017; Janssens-Maenhout et al., 2017) are adopted directly. The  
23 time-series emission inventories make it possible for a more systematic study on China's  
24 CH<sub>4</sub> emissions via the methods of EEIOA and SDA with more strength consistency. We  
25 use the time series CH<sub>4</sub> inventories from the EDGAR database to link the industrial sectors  
26 of input-output tables directly. The emissions of CH<sub>4</sub> originate from a wide variety of  
27 anthropogenic sources, including enteric fermentation, manure management, rice cultivation,  
28 coal mining, oil and gas system leakage, fuel combustion, landfills, wastewater treatment,  
29 etc. The EDGAR database reports China's detailed CH<sub>4</sub> emissions for more than 80 sources.  
30 We merge them into related economic sectors and obtain the sector-level CH<sub>4</sub> emissions.  
31 It is worth noting that the uncertainties of input-output analysis can be affected by the  
32 accuracy of emission data, especially for developing countries with limited official national  
33 GHG inventories. Authoritative time-series inventories of GHG emissions at the national  
34 level in the future will improve the performance of EEIOA and SDA models and reduce the  
35 uncertainties.  
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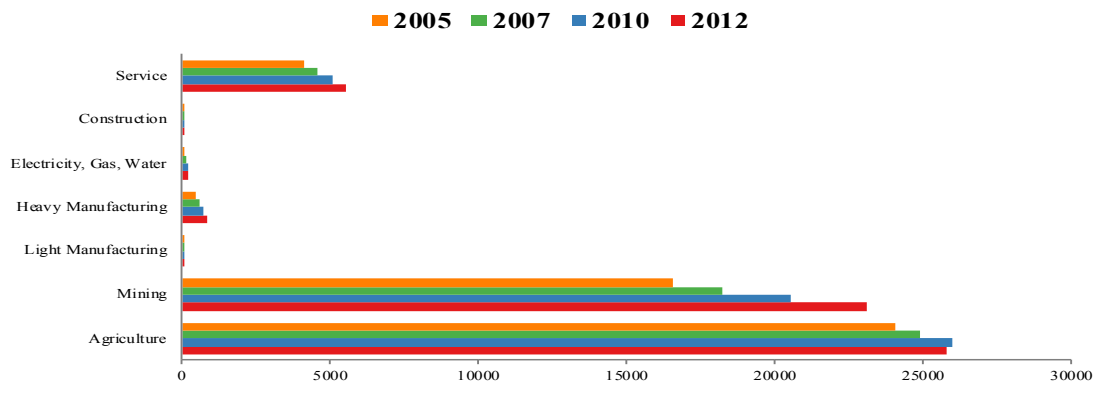
## 3 Results

### 3.1 Direct and indirect CH<sub>4</sub> emission features

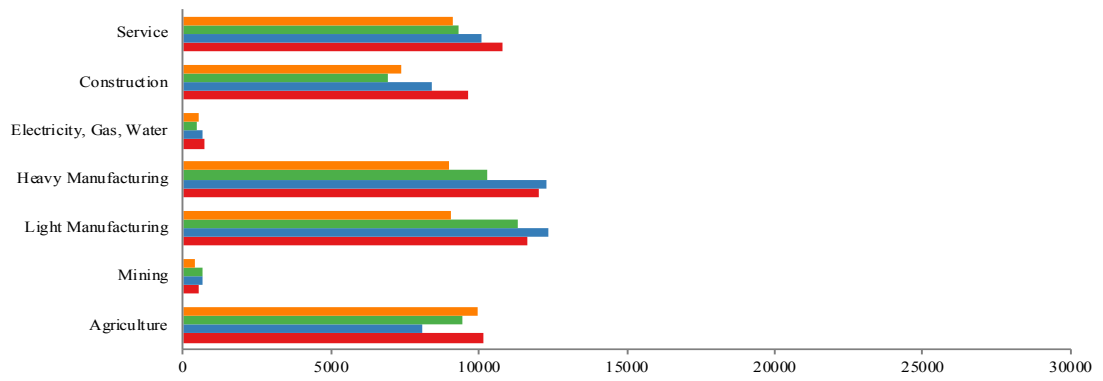
In Figure 1, we employ production-based, consumption-based and income-based accounting to quantitatively analyze the dynamics of CH<sub>4</sub> emissions in different sectors. The 13 manufacturing sectors are classified into light and heavy industry sectors for the convenience of presenting the dynamic patterns. The aggregate CH<sub>4</sub> emissions were 45370 Gg in 2005 and grew to 55440 Gg in 2012. Agriculture was the greatest direct contributor to CH<sub>4</sub> emissions, accounting for 47% of national emissions in 2012, although its emissions grew at a moderate rate (7%). Mining was the second largest CH<sub>4</sub> direct emitter, whose emissions grew nearly 40% (from 16576 Gg to 20371 Gg) over the same period. Another important contributor was the service sector, and its direct emissions grew steadily from 3858 Gg to 5020 Gg. These three sectors altogether accounted for 97% of the total national emissions. Other sectors had negligible direct CH<sub>4</sub> emissions.

For consumption-based accounting, the contribution of Agriculture was significantly smaller, only accounting for 18% of the total emissions in 2012. More than half of the emissions from this sector are transferred to the production processes of Light Manufacturing and Service as primary material inputs, which highlights the crucial role of Agriculture in providing food, fiber and other plant or animal products for the intermediate use in other industrial sectors. The contribution of Mining decreased to almost zero, suggesting that the Mining sector was more important as a direct emitter of CH<sub>4</sub> emissions than final consumer that induced upstream emissions. Meanwhile, the Manufacturing sectors claimed to be the largest contributor of consumption-based emissions, accounting for 43% of the total emissions in 2012. For both heavy and light manufacturing sectors, their embodied emissions experienced dramatic increase from 2005 to 2010 and slightly decreased in 2012. The production processes of manufacturing required CH<sub>4</sub>-intensive intermediate inputs from the Agriculture and Mining sectors. Construction was another major embodied CH<sub>4</sub> emission

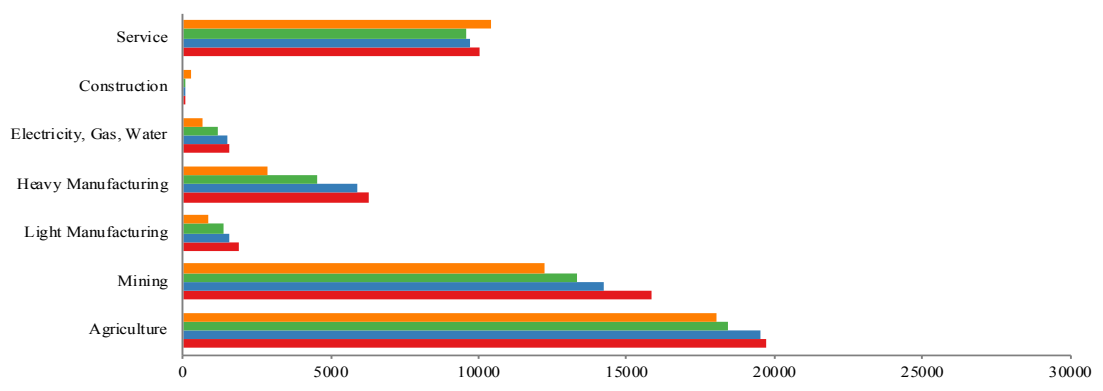
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(a) Production-based CH<sub>4</sub> emissions (Gg)



(b) Consumption-based CH<sub>4</sub> emissions (Gg)



(c) Income-based CH<sub>4</sub> emissions (Gg)

Figure 1: Direct, embodied and enabled CH<sub>4</sub> emissions of 7 general sectors

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4 sector. It can be explicated that construction sector has high demand for cement, steel,  
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6 wood and other building materials, which incurs large indirect CH<sub>4</sub> emissions.  
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9 In terms of income-based accounting, Agriculture regained its dominant role as a major  
10 CH<sub>4</sub> emitter, despite that it contributed less to total enabled emissions compared with its  
11 direct emissions. Furthermore, the two different emission measures for Agriculture shared  
12 similar moderate growth trends. Mining also remained the second largest income-based  
13 emission sector and grew at a steady rate from 12220 Gg to 15850 Gg. Although the  
14 enabled emissions of Manufacturing sectors were increasing over time, their contribution  
15 to aggregate income-based emissions was significantly smaller than the consumption-based  
16 emissions, suggesting the CH<sub>4</sub> emissions of manufacturing sectors were mainly incurred by  
17 final demands instead of intermediate inputs. For the Construction sector, it had negligible  
18 income-based emissions. This again emphasizes the role of construction sector as a final  
19 consumer instead of primary supplier. No matter what accounting approaches are used,  
20 the Service sector accounted for 10% to 20% of the national total enabled or embodied  
21 emissions, indicating that Service played equally important roles as primary suppliers and  
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38 Overall, Figure 1 not only displays the constantly increasing trend of CH<sub>4</sub> emissions in  
39 China, but also highlights the sharp distinction in consumption- and income-based measures,  
40 which further underlines the importance of conducting decomposition analysis from both  
41 demand and supply sides.  
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### 48 **3.2 Structural changes in consumption-based CH<sub>4</sub> emissions**

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51 Figure 2 presents the determinants of consumption-based emission changes. The aggregate  
52 CH<sub>4</sub> emissions increased more than 20% from 2005 to 2012, with an annual growth rate  
53 about 3%. The greatest driver of this aggregate emission change was the change in per  
54 capita consumption, which increased emissions almost 50% during the study period. China  
55 kept a rapid economic growth rate with an annual average at 10.7%, and national house-  
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hold consumption grew even more aggressively, i.e. 150% from 2005 to 2012. This surging residential consumption drove up embodied emissions in two ways. On the one hand, the increasing food consumption boosted the growth of CH<sub>4</sub> emissions since Agriculture was the major CH<sub>4</sub> direct emitter. On the other hand, the consumption of other commodities and services also escalated the growth rate of CH<sub>4</sub> emissions, because production of other commodities required intermediate inputs from direct CH<sub>4</sub>-intensive sectors (i.e. Agriculture and Mining).

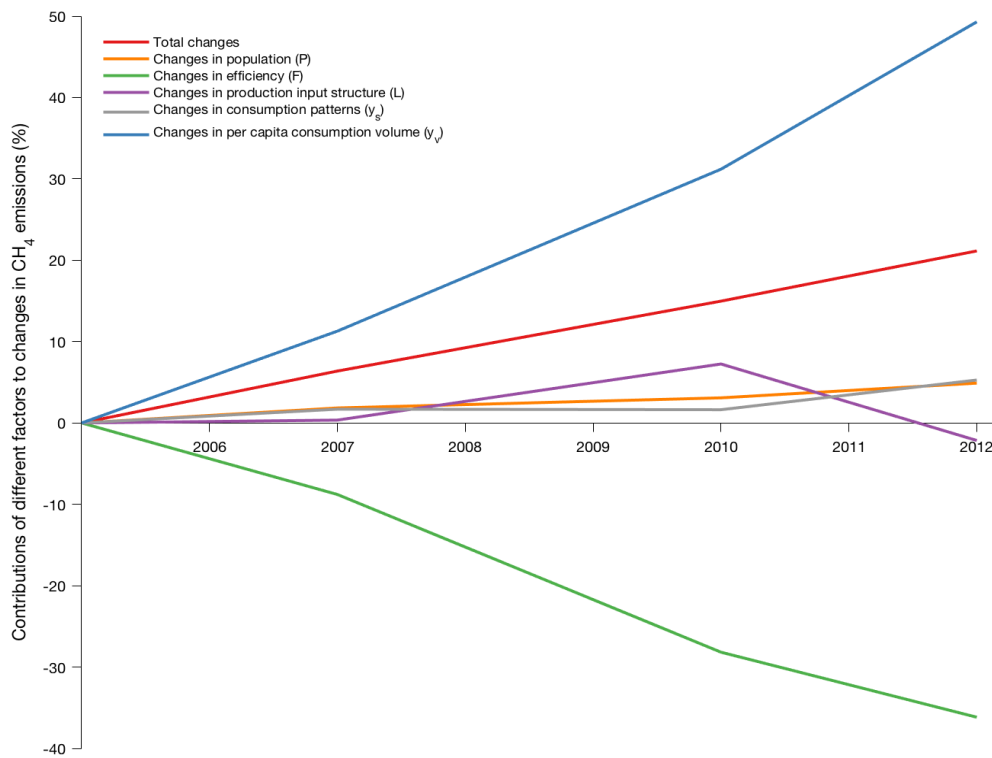


Figure 2: Contributions of different factors to changes in embodied CH<sub>4</sub> emissions

Meanwhile, the efficiency gains offset a large magnitude of CH<sub>4</sub> emission growth (about 35%). Technology progress significantly increased productivity, which suggests firms were able to use fewer inputs to produce the same amount of outputs, therefore inducing fewer CH<sub>4</sub> emissions. Other factors were less important in driving the emission growth. Population changes only increased 5% of CH<sub>4</sub> emissions from 2005 to 2012. The impacts of production input structure on the emission growth were increasing until 2010. After that, its impacts

diminished to negative in 2012. This structural change coincided with the “new normal” period during which China put more emphasis on transforming economic development mode and restructuring the economy for balanced and sustainable development. Furthermore, for the consumption structure, it increased at a rather small rate before 2010 and then at a faster pace, reflecting the shift in household consumption towards more CH<sub>4</sub> intensive goods.

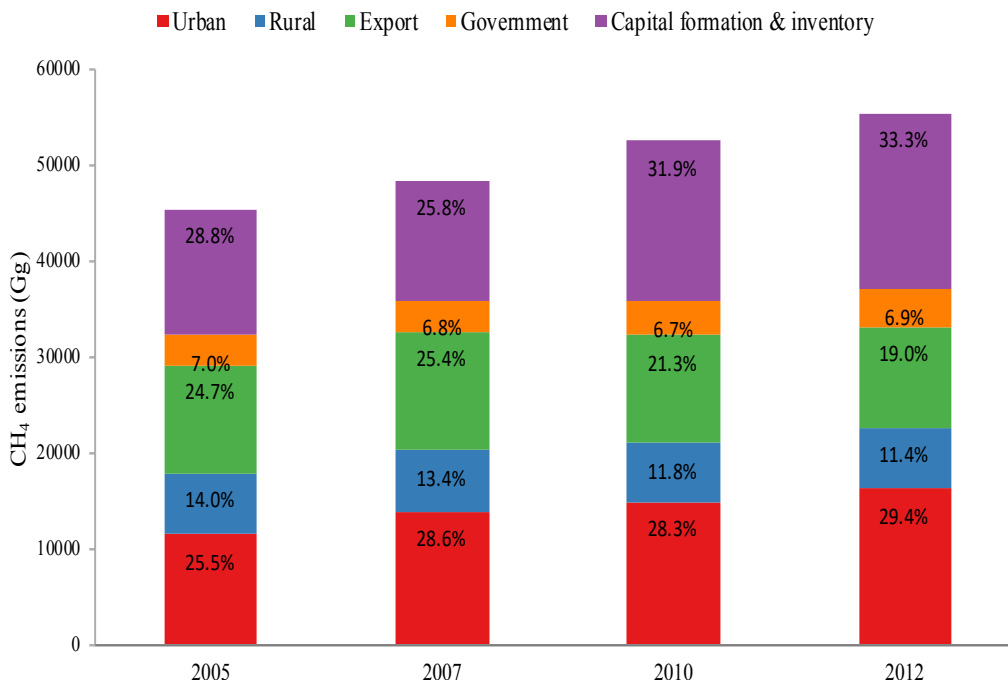


Figure 3: Embodied CH<sub>4</sub> emissions induced by final demand

To present more detailed descriptions on the forces behind the dynamics of embodied CH<sub>4</sub> emissions, we decompose them into five different final users in the perspective of consumption-based accounting, as displayed in Figure 3. The contribution of urban household consumption was increasing from 25.5% in 2005 to 29.4% in 2012, while the contribution of rural household consumption was decreasing over time. This is consistent with the urbanization process of China. From 2005 to 2012, the ratio of urban population to the total population increased 22%, and the ratio of rural population decreased 17% (NBSC, 2013). The share of CH<sub>4</sub> emissions induced by export also decreased after 2007. This decline can be attributed to two reasons. First, the global financial crisis sharply decreased China’s export

volume after 2007, hereby dragging down embodied CH<sub>4</sub> emissions. Second, to deal with the dramatic decline in exports, the Chinese government adjust export structure by reducing the exports of farm products and minerals, and increasing manufactured goods. This structural change leads to decrease in the embodied CH<sub>4</sub> emission intensity of exporting goods. Meanwhile, the contribution of capital formation increased dramatically after 2007 and became the greatest contributor hereafter, coinciding with the national economic stimulus plan during the financial crisis to maintain the economic growth. The four trillion investments were mainly made on infrastructure construction, which incurred higher demands for CH<sub>4</sub>-intensive intermediate inputs. As for government consumption, it accounted for only 7% of CH<sub>4</sub> emissions and remained quite stable during the sample period.

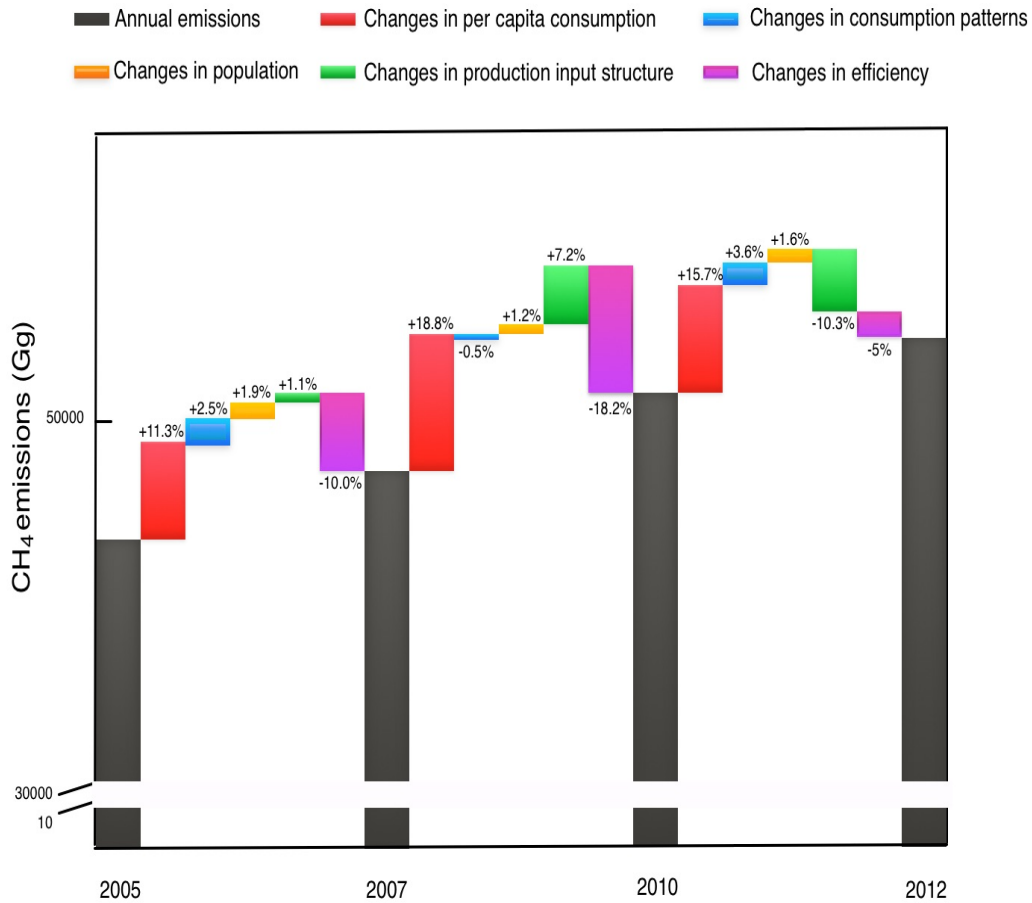


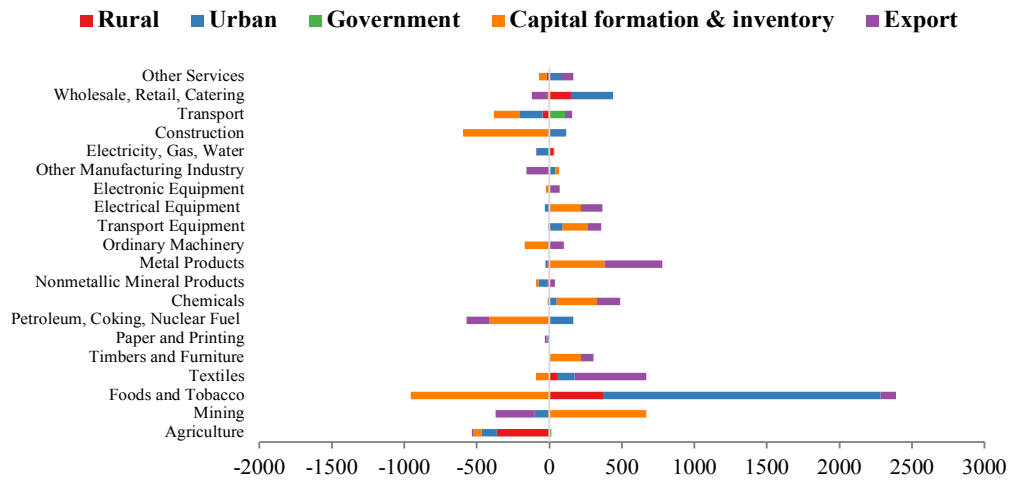
Figure 4: Fluctuations of the contributions of different factors to embodied CH<sub>4</sub> emissions

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4 Although the changes in those determinants varied greatly over time, the CH<sub>4</sub> emissions of  
5 China kept a stable growth rate. Figure 4 displays how the changes in the five components  
6 led to the observed CH<sub>4</sub> emissions. Efficiency change was the major driver of offsetting  
7 CH<sub>4</sub> emissions, but the advantage of efficiency improvement decreased suddenly after 2010,  
8 reflecting the slowdown of productivity growth. Consistent with the economic stimulus plan  
9 of expanding domestic demand, the growth rate of CH<sub>4</sub> emissions induced by per capita  
10 consumption reach its peak in 2010 and then decreased marginally. A startling change was  
11 the contribution of production input structure after 2010. It remained increasing until that  
12 time but suddenly jumped to negative. As aforementioned, this was the result of economic  
13 restructuring. The growth rates of the contribution from consumption patterns experienced  
14 ups and downs as well but at a more moderate rate.

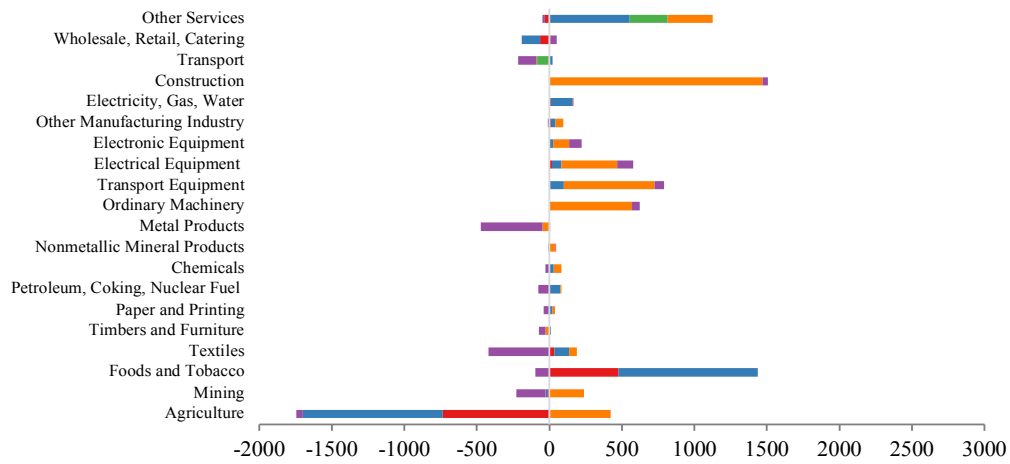
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27 Employing structural decomposition, we next examine CH<sub>4</sub> emission changes by sectors in  
28 the perspective of consumption. As presented in Figure 5, the Agriculture sector experienced  
29 notable changes: its consumption-based emissions witnessed a steady decline during 2005-  
30 2010 which decreased from 9950 Gg in 2005 to 8110 Gg in 2010, followed by a sharp increase  
31 to 10180 Gg in 2012. The sharp decrease during 2007-2010 was mainly driven by the declines  
32 of urban and rural consumption, due to the global financial crisis and economic downturn,  
33 while the considerable increase during 2010-2012 could be attributed to the reform of income  
34 distribution which promoted urban and rural consumption. For most manufacturing sectors,  
35 capital formation was the major driver of embodied emission changes before 2010. Capital  
36 formation actually significantly drove up almost all sectors' emissions from 2007 to 2010.  
37 This coincides with the economic stimulus plan that focused on fixed-asset investments and  
38 infrastructure. However, after 2010, the contribution from capital formation became much  
39 smaller, except for the Construction sector whose products are counted as fixed assets. This  
40 decrease again reflects the economic structure shifting from investment-driven economy to  
41 consumption-driven economy. Contrary to the trend of Agriculture, the embodied emissions  
42 from the Foods and tobacco sector increased significantly from 2005 to 2010, and decreased  
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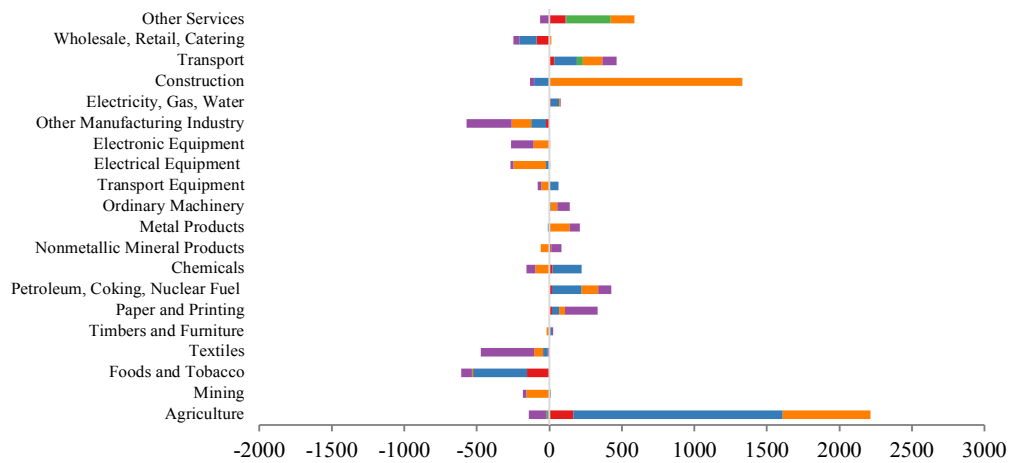
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(a) Changes from 2005 to 2007 (Gg)



(b) Changes from 2007 to 2010 (Gg)



(c) Changes from 2010 to 2012 (Gg)

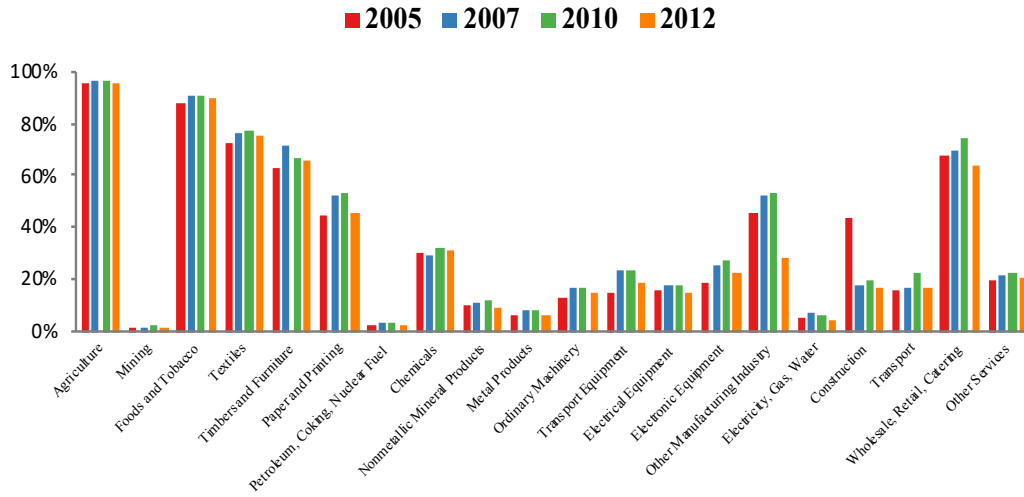
Figure 5: Contributions of different sectors to embodied CH<sub>4</sub> emissions

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4 about 8% after 2010, which were mainly led by urban and rural consumption changes.  
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6 The role of export is also significant. Before the financial crisis, it increased embodied  
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8 emissions of China's major export sectors, e.g. Textiles, Chemicals, Metal Products and  
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10 Electrical Equipment. But between 2007 and 2010, the contributions from export diminished  
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12 to negative or negligible due to the sharp decline in foreign demand, and then it recovered  
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14 gradually after 2010. Government consumption contributed negligible shares to all sectors  
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16 except Transport and Other Services.  
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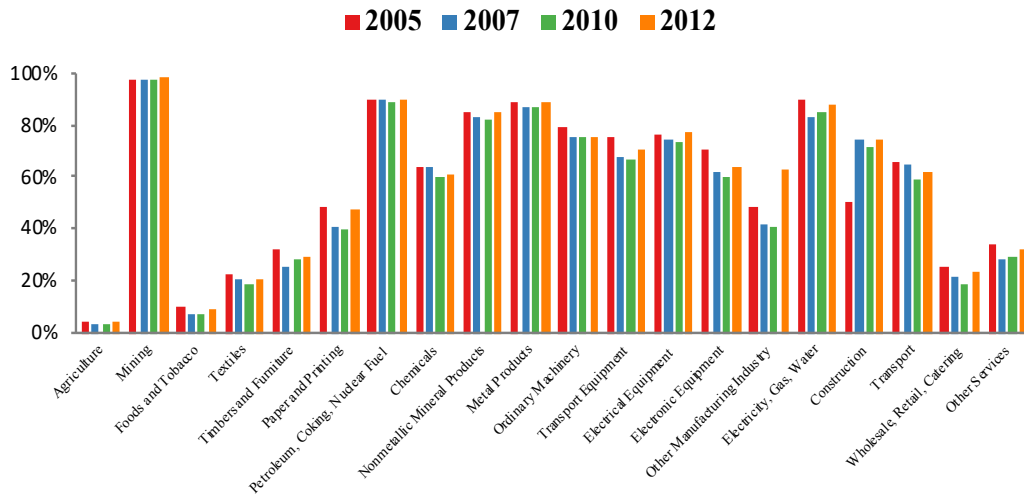
19 To better understand the role of Agriculture in the embodied CH<sub>4</sub> emissions, we conduct  
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21 a counter-factual analysis by assigning the emission intensity of other sectors to be zero  
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23 and leaving the emission intensity of Agriculture unchanged, then calculating the embodied  
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25 emissions for each sector. Figure 6 presents the percentages of the fabricated emissions to  
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27 actual induced emissions. More than 95% of Agriculture's CH<sub>4</sub> emissions came from itself,  
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29 and about 90% of Foods and tobacco's emissions also came from Agriculture. CH<sub>4</sub> emissions  
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31 induced from the final demand towards Textiles, Timbers and Furniture, and Paper and  
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33 Printing were mainly attributed to Agriculture as well, while it contributed little to the  
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35 Mining sector's CH<sub>4</sub> emissions.  
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38 In contrast to the previous results of Agriculture sector, the embodied emissions induced  
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40 by the Mining sector almost completely came from itself, while it contributed little to the  
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42 emissions of the Agriculture sector. About 90% of the embodied emissions from Petroleum,  
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44 coking, nuclear fuel, which required primary energy as intermediate inputs, could be at-  
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46 tributed to the Mining sector. Moreover, Mining's contribution was concentrated on the  
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48 heavy industries such as Metal Products, Nonmetallic Mineral Products, Ordinary Machin-  
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50 ery, Transport Equipment, Electrical Equipment, and Electronic Equipment. Most of the  
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52 embodied emissions from Construction and Transport also came from Mining. These sectors  
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54 consumed large amounts of energy and industrial raw materials which could be ultimately at-  
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56 tributed to the resource extraction of the Mining sector and were consequently energy-related  
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58 CH<sub>4</sub>-intensive inputs.  
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(a) Agriculture



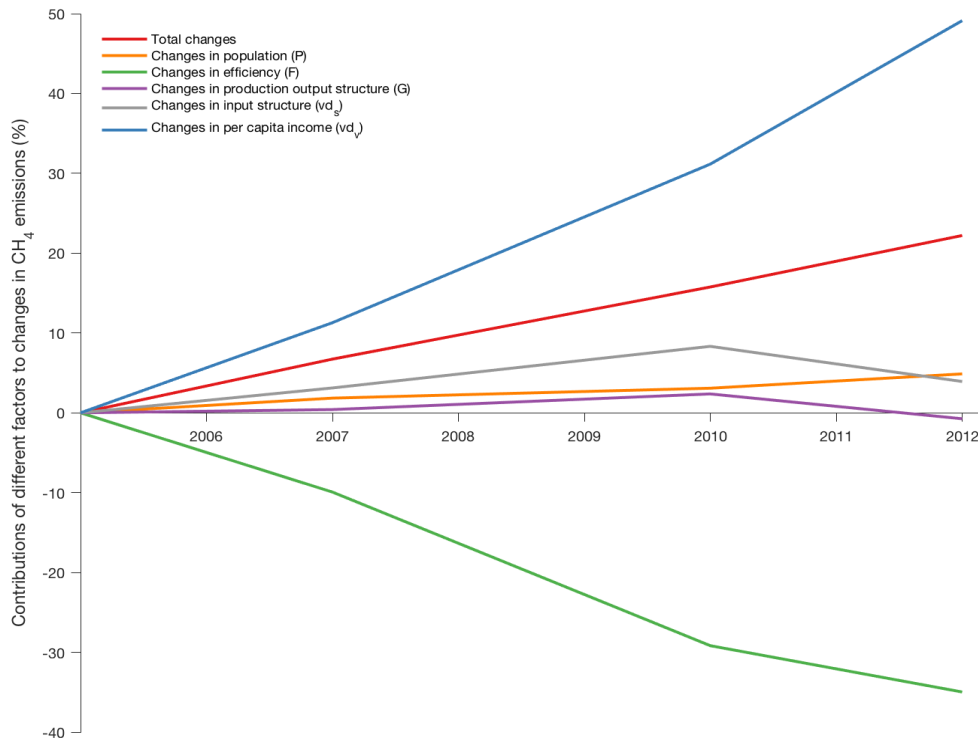
(b) Mining

Figure 6: Counterfactual analysis on the contribution of Agriculture and Mining to embodied CH<sub>4</sub> emissions of 17 sectors

### 3.3 Structural changes in income-based CH<sub>4</sub> emissions

From the income-based perspective, Figure 7 shows how the five determinants evolved from 2005 to 2012. Per capita income was the greatest driver of emission changes and shared the same trend as per capita consumption in Figure 2 due to the positive correlation between income levels and consumption. The changes in efficiency also remained the largest counter-part of CH<sub>4</sub> emissions. The contribution from production output structure fluctuated in a

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4 similar trend but at a more moderate rate compared with the production input structure in  
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6 Figure 2, implying production input structure changed at a greater extent than production  
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8 output structure. The change in input structure was another non-negligible contributor,  
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10 which kept increasing up to 10% in 2010 then decreased to 5% in 2012. This reflects the  
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12 transformation on economic structure towards more balanced and sustainable developing  
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14 mode. Moreover, the contribution of input structure was significantly larger than produc-  
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16 tion output structure, implying how inputs are organized plays a more fundamental role in  
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18 reducing enabled CH<sub>4</sub> emissions.  
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49 Figure 7: Contributions of different factors to changes in enabled CH<sub>4</sub> emissions

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52 Later on, we decompose the enabled CH<sub>4</sub> emissions into four different income-components,  
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54 as shown in Figure 8. Employee compensation was the major contributor of enabled CH<sub>4</sub>  
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56 emissions all the time, and its contribution was increasing steadily from 53% to 62%. The  
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58 contribution of net operating surplus continued decreasing from 25% to 17%. This phe-  
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60 nomenon actually coincided with the national reform on income distribution system, which  
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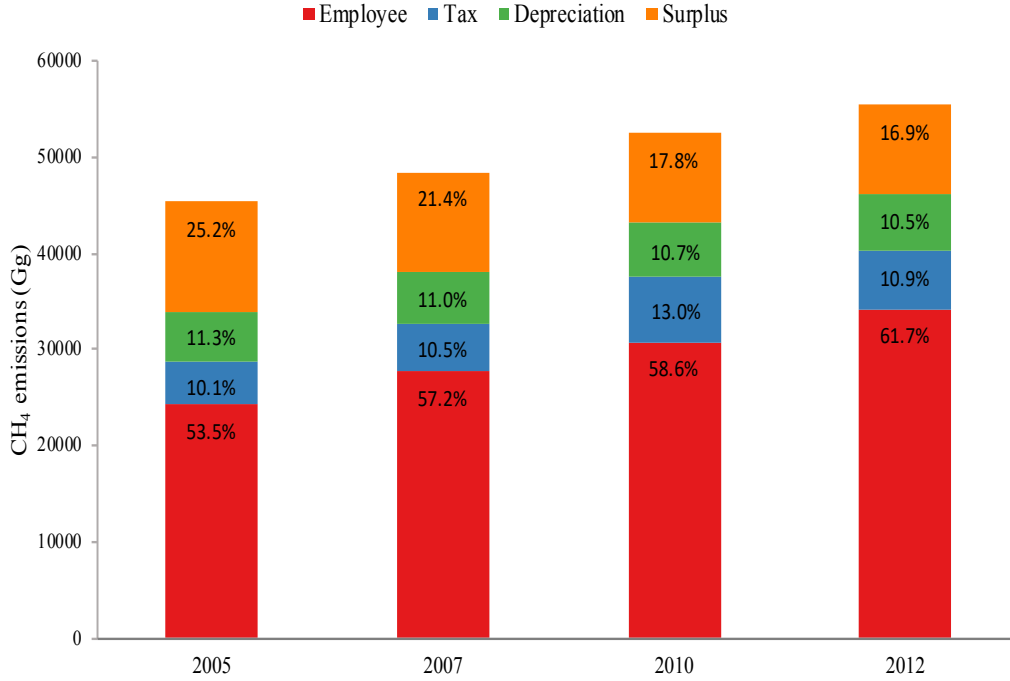


Figure 8: Enabled CH<sub>4</sub> emissions induced by primary inputs

increased the share of individual income in the distribution of national income and the share of work remuneration in primary distribution<sup>1</sup>. Therefore, the compensation to employees witnessed a notable surge and incurred higher CH<sub>4</sub> emissions, while the surplus of enterprises experienced a significant decrease and contributed less to the aggregate CH<sub>4</sub> emissions. As for the other two components, the contributions of net taxes on production and depreciation of fixed assets remained quite stable (around 11%) for all years.

Figure 9 describes how the determinants from structural decomposition led to the fluctuations of enabled CH<sub>4</sub> emissions from 2005 to 2012. The changes in per capita income, efficiency and population shared the same trend as Figure 5. Input structure became a major driver next to per capita income and efficiency, with the role of production output structure being more trivial. This was inherently consistent with the concept of income-based accounting because income-based emissions reflected the enabled emissions in primary

<sup>1</sup>According to the official report from National Bureau of Statistics of China, the share of household income to national income increased 3% from 2009 to 2012, while the share of enterprise surplus decreased 3.9%: [http://www.stats.gov.cn/tjsz/tjsj/tjcb/dysj/201511/t20151112\\_1273538.html](http://www.stats.gov.cn/tjsz/tjsj/tjcb/dysj/201511/t20151112_1273538.html).

inputs.

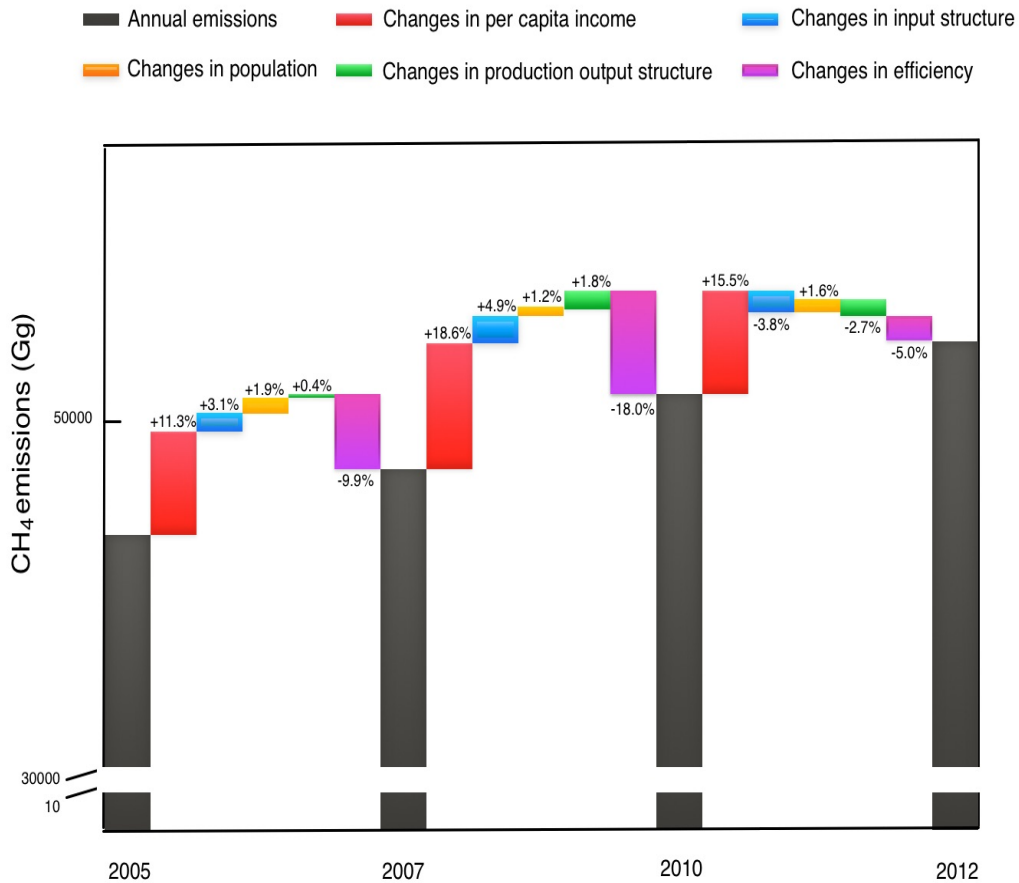


Figure 9: Fluctuations of the contributions of different factors to enabled CH<sub>4</sub> emissions

For the enabled emissions at sector level, Figure 10 shows Mining and Agriculture were the two sectors that experienced the largest increase in enabled CH<sub>4</sub> emissions from 2005 to 2012. In the Agriculture sector, the increase was driven by employee compensation all the time. But for the Mining sector, although employee compensation remained the greatest driver during the periods from 2005 to 2007 and from 2010 to 2012, net taxes on production surpassed wage compensation from 2007 to 2010. Furthermore, production taxes generally played a minor role except for years from 2007 to 2010, during which tax incentives were used to help enterprises live through economic downturn. Those tax incentives consequently led to production expansion and more enabled emissions. Another interesting fact on produc-

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4 tion tax is for the Agriculture sector, whose production taxes almost completely offset the  
5 emission increase incurred by employee compensation from 2010 to 2012. While employee  
6 compensation was the major driver of enabled CH<sub>4</sub> emissions, net operating surplus offset a  
7 large proportion of the enabled emissions from 2007 to 2010, but this offsetting effect almost  
8 disappeared during the period of 2010-2012. Depreciation of fixed assets accounted little for  
9 the enabled emissions in all sectors except Chemicals, Metal products, Utilities and Mining,  
10 which demand a large quantity of fixed assets to initiate production.  
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19 Similar to the analysis on consumption-based emissions, we conduct counter-factual de-  
20 compositions for Agriculture and Mining and present the results in Figure 11. Again, more  
21 than 90% of Agriculture, Foods and Tobacco's enabled emissions came from the Agriculture  
22 sector itself, but it contributed much less to the emissions from Textiles, and Timbers and  
23 Furniture compared with Figure 6. This suggests that the two sectors used CH<sub>4</sub>-intensive  
24 goods as intermediate inputs from Agriculture not to manufacture intermediate commodities  
25 for other sectors, but to produce final products for consumers. Moreover, in the sector of  
26 Chemicals, Agriculture explained much more enabled emissions than embodied emissions,  
27 indicating the intermediate goods supplied by Chemicals were made by the CH<sub>4</sub>-intensive  
28 inputs from Agriculture. As for the role of Mining, besides itself, it also contributed a signif-  
29 icant magnitude to most manufacturing sectors, suggesting its importance as intermediate  
30 input for those sectors.  
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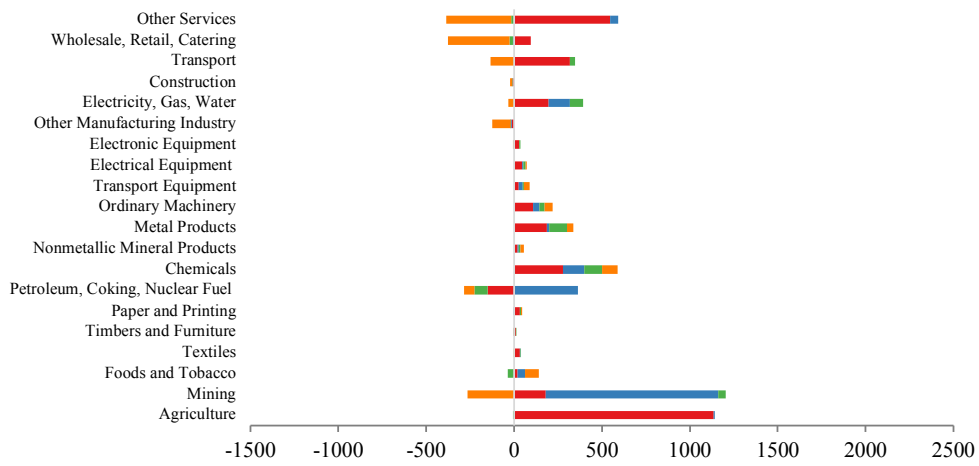
## 47 **4 Discussions**

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50 China's CH<sub>4</sub> emission has been maintaining a steady growth rate over the last decade, its  
51 determinants, however, were profoundly affected by the global financial crisis and national  
52 economic policies. The changes in per capita consumption/income and the changes in effi-  
53 ciency together shaped the trend of CH<sub>4</sub> emissions. Due to the rapid economic development  
54 and the reform on income allocation, household income as well as consumption witnessed  
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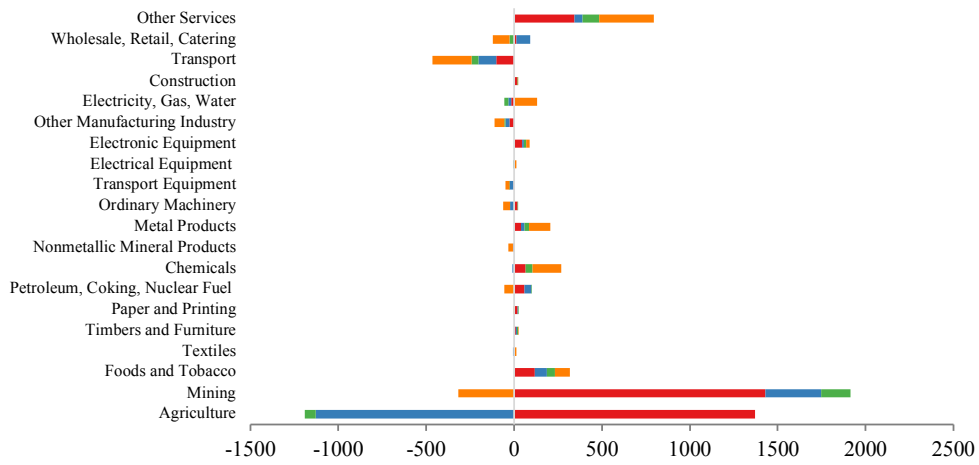
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(a) Changes from 2005 to 2007 (Gg)



(b) Changes from 2007 to 2010 (Gg)

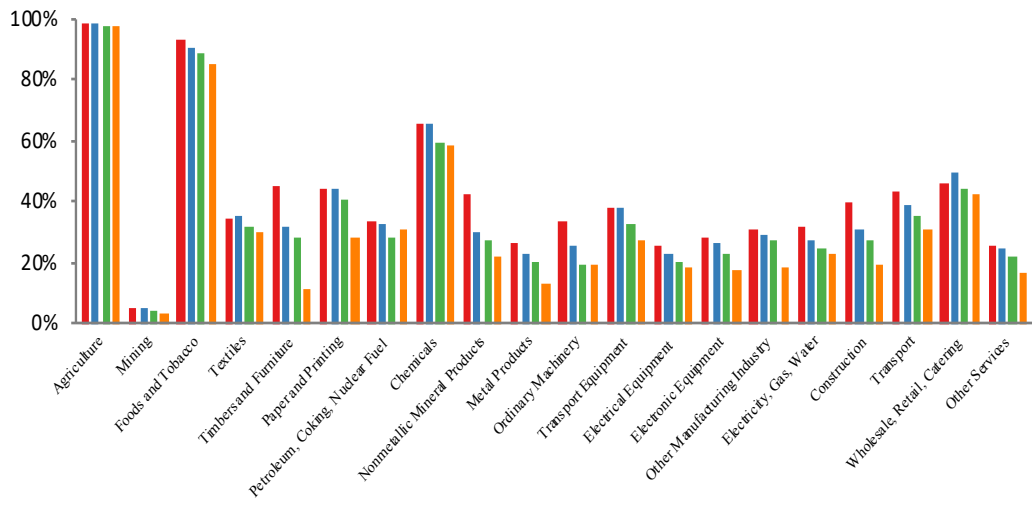


(c) Changes from 2010 to 2012 (Gg)

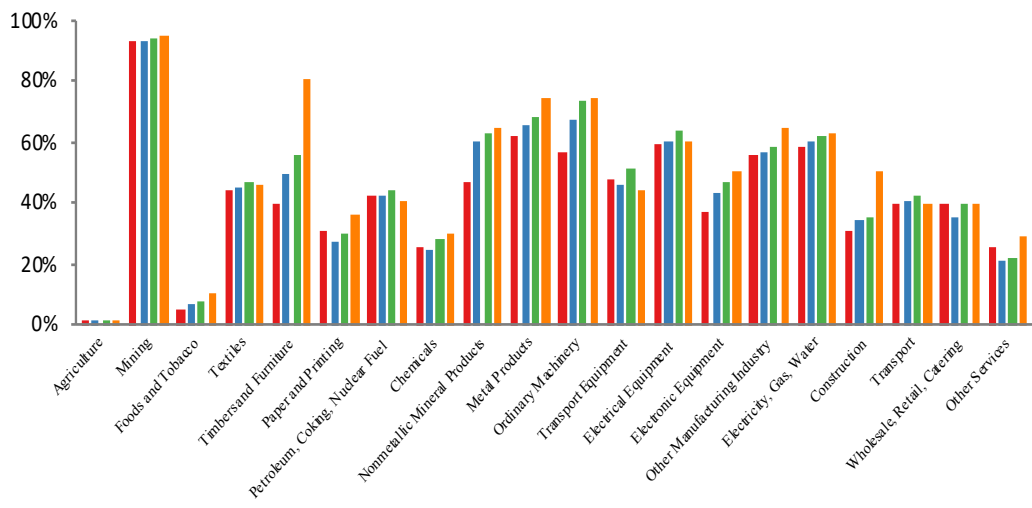
Figure 10: Contributions of different sectors to enabled CH<sub>4</sub> emissions



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(a) Agriculture



(b) Mining

Figure 11: Counterfactual analysis on the contribution of Agriculture and Mining to enabled CH<sub>4</sub> emissions of 17 sectors

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4 sharp increases, pushing up CH<sub>4</sub> emissions, which was also reflected in the contributions of  
5 employee compensation and enterprise surplus to aggregate CH<sub>4</sub> emissions. This surge in  
6 income and consumption could impose practical limits on the reduction of emissions as long  
7 as the growing trend continues. Furthermore, with Agriculture being the largest contrib-  
8 utor to CH<sub>4</sub> emissions, income growth generally shifts the structure of food consumption  
9 towards more CH<sub>4</sub>-intensive agricultural products (e.g., meat and dairy). This inevitably  
10 imposed further threats on CH<sub>4</sub> emission reduction. Meanwhile, efficiency change overall off-  
11 set 60% of the emission increases induced by per capita consumption/income, implying the  
12 improvement in technology and productivity significantly reduced CH<sub>4</sub> intensity. However,  
13 the contribution of efficiency declined a large magnitude after 2010. This poses another po-  
14 tential threat on emission reduction because the advantages of efficiency improvement might  
15 have been well exploited and little room was left for further improvement on the basis of  
16 current technology.

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32 Besides consumption and income, the contribution of export and capital formation also  
33 witnessed dramatic changes. Affected by external shocks of the global financial crisis, CH<sub>4</sub>  
34 emissions induced by export decreased after 2007, due to both the decline in external demand  
35 and the adjustment of export structure that lowered the export shares of farm products and  
36 minerals. Contrary to the trend of export, the CH<sub>4</sub> emissions induced by capital formation  
37 experienced a dramatical surge after 2007, coinciding with the four-trillion economic stimulus  
38 plan during the financial crisis. Those structural changes imply that the focus of controlling  
39 CH<sub>4</sub> emissions should be laid on the investment in construction and infrastructure instead  
40 of export.

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51 Next we compare the determinants in our decomposition with related literature. Table 1  
52 summarizes some literature that applies structural decomposition analysis to energy use and  
53 environmental emissions of China. In line with most existing studies, our findings emphasize  
54 the importance of consumption on CH<sub>4</sub> emissions. Meanwhile, efficiency change is found to  
55 be the major inhibitory factor in nearly all related literature, even in the studies of other

countries and regions like the United States (De Nooij et al., 2003), Japan (Kagawa and Inamura, 2004) and Taiwan (Lee and Lin, 2001). Similar to the research on CO<sub>2</sub> emissions (e.g. Feng et al., 2012; Mi et al., 2017a,b; Wang and Feng, 2017), our decomposition results imply that population had a minor effect on CH<sub>4</sub> emissions. Capital formation and exports, as the dominant driver of China’s CO<sub>2</sub> emissions (Feng et al., 2017) and energy demand (Xu et al., 2014; Wu and Zhang, 2016), also contributed significant shares to China’s CH<sub>4</sub> emissions.

Table 1: SDA studies on China’s environmental emissions and energy use

Publication	Indicator	Sample period	Method
Guan et al., 2008	CO <sub>2</sub> emissions	1980-2030	Consumption-based SDA
Guan et al., 2009	CO <sub>2</sub> emissions	2002-2005	Consumption-based SDA
Zhang, 2009	CO <sub>2</sub> emissions	1992-2006	Consumption-based SDA
Xu et al., 2011	CO <sub>2</sub> emissions	2002-2008	Consumption-based SDA
Guan et al., 2014	PM <sub>2.5</sub>	1997-2010	Consumption-based SDA
Xie, 2014	Energy use	1992-2010	Consumption-based SDA
Wu and Zhang, 2016	Energy use	1997-2012	Consumption-based SDA
Yuan and Zhao, 2016	CO <sub>2</sub> emissions	2005 and 2010	Consumption- and income-based SDA
Feng et al., 2017	CO <sub>2</sub> emissions	1995-2009	Consumption- and income-based SDA
Liu and Liang, 2017	Pollutants	2007-2012	Consumption-based SDA
Mi et al., 2017a	CO <sub>2</sub> emissions	2005-2012	Consumption-based SDA
Su and Ang, 2017	CO <sub>2</sub> emissions	2007-2012	Consumption-based SDA
Wang and Feng, 2017	CO <sub>2</sub> emissions	2000-2014	Income-based SDA
Zhao et al., 2017	CO <sub>2</sub> emissions	1992-2012	Income-based SDA
Zhang et al., 2018b	Mercury	1997-2012	Consumption- and income-based SDA

The shocks of the global financial crisis on GHG emissions are also detected by other researchers. Feng et al. (2015) found that the co-movements between CO<sub>2</sub> emissions and economic growth in the US, i.e. emissions before 2007 were risen by economic growth, and were decreased by the economic recession after 2007. Consistent with our findings on the contribution changes of export and capital formation to total emissions, Mi et al. (2017a) reported that CO<sub>2</sub> emissions induced by export declined while the emissions induced by capital formation surged upwards. Moreover, as we demonstrate that changes in production and input structure after 2010 decreased CH<sub>4</sub> emissions, they also found structural upgrading significantly offset CO<sub>2</sub> emissions. But contrary to the shift towards consumption-driven economy, at the aggregate level, the contribution of capital formation to CH<sub>4</sub> emissions has

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4 been increasing and it has become the greatest contributor since 2010. The importance of  
5 capital formation has also been noticed by the studies on energy consumption and pollutants  
6 emissions. Guan et al. (2014) and Deng et al. (2016) found that capital formation was the  
7 largest final demand category for increasing air pollutants, most of which were embodied  
8 in the construction sector. Energy-related CH<sub>4</sub> emissions account for a significant share of  
9 China's CH<sub>4</sub> emissions, while CO<sub>2</sub> emissions are mainly attributed to the energy consump-  
10 tion. Joint efforts and coordinated control should be taken on CH<sub>4</sub> and other environmental  
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## 23 **5 Concluding remarks**

27 Reducing global emissions of CO<sub>2</sub>, CH<sub>4</sub> and other greenhouse gases is a major challenge.  
28 The significant amount and sustained growth of anthropogenic CH<sub>4</sub> emissions in China has  
29 greatly affected the country's own efforts to mitigate GHG emissions. In combination with  
30 EEIOA and SDA methods, this paper employs both consumption- and income-based ac-  
31 counting technologies to clarify the socioeconomic determinants of China's CH<sub>4</sub> emissions  
32 from a systemic perspective. In contrast to production- and income-based emissions mainly  
33 from the Agriculture and Mining sectors, the Manufacturing, Construction and Service sec-  
34 tors accounted for a large magnitude of consumption-based emissions. Changes in per capita  
35 consumption/income and efficiency improvement collectively shaped the trend of CH<sub>4</sub> emis-  
36 sions, with per capita consumption and income proving to be the greatest driving forces.  
37 While changes in efficiency offset a significant amount of emission increases, its contribu-  
38 tion plunged after 2010. Capital formation- and exports-driven CH<sub>4</sub> emissions surged and  
39 declined separately after 2007. The relevant components of final demand and primary in-  
40 puts fluctuated dramatically, but capital formation and employee compensation remained  
41 as major determinants of embodied and enabled emissions respectively. China's growing  
42 CH<sub>4</sub> emissions were found to be profoundly affected by the global financial crisis of 2007,  
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4 as well as its economic stimulus plan and the income distribution reform implemented there  
5 after. These findings provide additional insights for policy makers on the mitigation of CH<sub>4</sub>  
6 and other emissions. Declining contribution from technology reinforces the unheeded warn-  
7 ing that the efficiency changes might have limited mitigation potential, and that relying on  
8 technology improvement alone is insufficient to achieve mitigation goals. Moreover, growing  
9 household income and consumption further doubts on the country’s ability to reducing CH<sub>4</sub>  
10 emissions. With the Chinese economy entering into a “new normal”, adjusting the consump-  
11 tion and supply structures could be more effective in mitigating CH<sub>4</sub>. Since China still lacks  
12 a comprehensive plan for CH<sub>4</sub> emissions reduction, examining both consumption-based and  
13 income-based emissions will be useful for understanding the drivers of China’s anthropogenic  
14 CH<sub>4</sub> emissions and thus for crafting appropriate mitigation policies and actions covering the  
15 entire supply chains.  
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