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Electricity footprint of China's industrial sectors and its socioeconomic drivers

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ABSTRACT

China has become the largest electricity consumer in the world. Existing studies focus on the direct electricity use of industrial sectors and investigate the factors that influence direct electricity consumption. However, the critical sectors that play important roles as final consumers or primary suppliers and indirectly drive up the electricity use of upstream or downstream sectors are not identified. This study comprehensively quantifies the electricity footprint of the industrial sectors using consumption-based and income-based accounting methods The key drivers of changes in the consumption-based and income-based electricity footprints are also investigated using structural decomposition analysis (SDA). The results show that the accounting of the electricity footprint using consumption-based and income-based methods is quite different from that of the production-based method (i.e., direct electricity use). Moreover, the change in the energy structure (i.e., the percentage share of electricity in total energy consumption, also known as electrification level) of industrial sectors is a major driver of the increment in electricity use in addition to the final demand level and primary input level change. Improvement in the energy efficiency of sectors is the dominant factor that reduces electricity use. However, changes in the production input/output structure, final demand structure, and primary input structure are not found to have significant effects on reducing electricity use. This indicates that the role of structure change should be explored further. China can implement policies that further stimulate structural transformation, such as encouraging the consumption of less energy-intensive products and promoting primary inputs and production allocation to less energy-intensive sectors.

1. Introduction

Electricity has become an important energy source in all sectors in China. The constant increase in electricity production has led to the excessive consumption of fossil fuels. For instance, the electric power and heat power supply sector used more than 42% of the total coal resources in 2014 (NBS, 2016). Moreover, it is the largest contributor to CO_2 emissions in China (Xu et al., 2014b; Yuan et al., 2012; Zhang et al., 2014b), accounting for 53% of China's CO_2 emissions from fuel combustion in 2013 (WorldBank, 2017). Existing studies have investigated measures to improve energy efficiency and reduce the use of fossil fuels in electricity production, such as through technological innovation in power generation (Zhang et al., 2014a; Zhou et al., 2014), size control of power plants (Zhang et al., 2014b; Zhou et al., 2014), optimization of the power generation form (Xie et al., 2012), development of a super smart grid and integrated resource strategic planning to facilitate renewable electric power distribution and power structure improvement (Hu et al., 2010, 2011; Yuan et al., 2014; Zheng et al., 2014).

Given the technology of electricity generation and distribution, it is important to reduce the total electricity consumption from the demand side. With the rapid electrification of industry, the electricity consumption in China is growing fast (Yuan et al., 2011). Total electricity consumption increased by 463%, from 1002 TWh in 1995 to 5638 TWh in 2014 (NBS, 2016), and China surpassed the United States to become the largest electricity consumer in the world in 2011, accounting for approximately 23% of the total world electricity consumption in 2013 (WorldBank, 2017). Existing studies have investigated the relationship between electricity consumption and economic growth in China (Lin and Liu, 2016; Steenhof, 2006; Zhao et al., 2016) and have forecasted the electricity demand in China using factors such as the economic development level, population growth, and energy intensity from the macroscopic view or medium view by dividing the economy into several sectors (Liang et al., 2016c; Yuan et al., 2016; Zhao et al., 2016). These studies focus on direct electricity users. However, the economy can be regarded as both demand driven (Liang et al., 2014b,

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2015) and supply driven (Gereffi, 2001; Gibbon, 2001; Hull, 2005; Liang et al., 2016b, 2017). Therefore, the importance of sectors as final consumers of electricity (a.k.a. consumption-based electricity use) and as primary suppliers that enable the electricity use of downstream sectors through supply chains (a.k.a. income-based electricity use) should not be overlooked.

In addition, investigating the socioeconomic factors that drive up or reduce electricity use during a specific period from both the consumption side and supply side can help policymakers take effective measures when intervening in electricity consumption. However, the socioeconomic factors that contribute to the changes in the electricity use of China's industrial sectors from the consumption and supply sides are not revealed. This study will fill this gap by comprehensively quantifying the electricity footprint of industrial sectors based on an environmentally extended input-output model. The results will help identify critical sectors that contribute the most to electricity consumption from three different perspectives: production-based, consumption-based, and income-based electricity use. Moreover, the relative contribution of six socioeconomic factors to the evolution of electricity use during the period 1995–2009 will be investigated using input-output based structural decomposition analysis from both the consumption side (including final demand level, final demand structure, production input structure, energy structure, energy intensity, and population) and supply side (including primary input level, primary input structure, production output structure, energy structure, energy intensity, and population). These results will help policymakers take effective measures to influence electricity consumption.

2. Methods and data

2.1. Consumption-based and income-based electricity footprint

The environmentally extended input-output (EEIO) model is used to evaluate the consumption-based and income-based electricity use of sectors. The direct electricity use t (i.e., production-based electricity use, $1 \times n$ row vector) of sectors is treated as the satellite account of the input-output model. The data of production-based electricity use can be gathered from bureau of statistics or existing database (e.g., World Input-Output Database (WIOD)). Then, the electricity intensity vector f (i.e., electricity use of each sector per unit output) can be calculated using Eq. (1).

$$f = t(\hat{x})^{-1} \tag{1}$$

x is a $n \times 1$ column vector that represents each sector's total output. The hat ˆ means diagonalization.

The consumption-based and income-based electricity footprints of sectors can be calculated by Eqs. (2) and (3), respectively, based on the input-output model (Miller and Blair, 2009).

$$c = f\hat{x} = f(I - A)^{-1}\hat{y} = f\mathrm{L}\hat{y} \tag{2}$$

$$i = \hat{x}f' = \hat{v}(I - B)^{-1}f' = \hat{v}\mathrm{G}f' \tag{3}$$

c is a $1 \times n$ row vector and i is a $n \times 1$ column vector. y is a $n \times 1$ column vector, representing final demand; v is a $1 \times n$ row vector, indicating each sector's primary input or industrial activity; and I is an identity matrix. Matrices A and B are the direct input coefficient matrix and direct output coefficient matrix, respectively. Matrix $\mathrm{L} = (\mathrm{I} - \mathrm{A})^{-1}$ is the *Leontief Inverse* matrix, representing the production input structure; matrix $\mathrm{G} = (\mathrm{I} - \mathrm{B})^{-1}$ is the *Ghosh Inverse* matrix, indicating the production output structure; and the notation ' refers to the transposition.

2.2. Structural decomposition analysis

The electricity intensity vector f can be decomposed into the energy intensity e (i.e., total energy use by each sector for unitary output, $1 \times n$ row vector) and energy structure of a sector e_s (i.e., the percentage share of electricity in total energy used by each sector, $1 \times n$ row vector), as expressed by Eq. (4).

$$f = e_s\hat{e} \tag{4}$$

The final demand vector y and primary input vector v in Eqs. (2) and (3) can both be decomposed into three factors, as expressed by Eqs. (5) and (6).

$$y = \mathrm{Y_s}y_l p \tag{5}$$

$$v = pv_l\mathrm{V_s} \tag{6}$$

Matrices $\mathrm{Y_s}$ and $\mathrm{V_s}$ represent the final demand structure and primary input structure, respectively; vectors y_l and v_l stand for the per capita final demand volume and input volume (i.e., final demand level and primary input level), respectively; and p represents the population.

The total electricity use of the economy (j) from the consumption side and supply side can be expressed by Eqs. (7) and (8), respectively.

$$\mathrm{j} = e_s\hat{e}\mathrm{L}\mathrm{Y_s}y_l p \tag{7}$$

$$\mathrm{j} = pv_l\mathrm{V_s}\mathrm{G}\hat{e}e_s{}' \tag{8}$$

Decomposition forms of Eqs. (7) and (8) can be written as Eqs. (9) and (10).

$$\Delta\,\mathrm{j} = \Delta e_s\hat{e}\mathrm{L}\mathrm{Y_s}y_l p + e_s\Delta\hat{e}\mathrm{L}\mathrm{Y_s}y_l p + e_s\hat{e}\Delta\mathrm{L}\mathrm{Y_s}y_l p + e_s\hat{e}\mathrm{L}\Delta\mathrm{Y_s}y_l p + e_s\hat{e}\mathrm{L}\mathrm{Y_s}\Delta y_l p + e_s\hat{e}\mathrm{L}\mathrm{Y_s}y_l\Delta p \tag{9}$$

$$\Delta\,\mathrm{j} = \Delta pv_l\mathrm{V_s}\mathrm{G}\hat{e}e_s{}' + p\Delta v_l\mathrm{V_s}\mathrm{G}\hat{e}e_s{}' + pv_l\Delta\mathrm{V_s}\mathrm{G}\hat{e}e_s{}' + pv_l\mathrm{V_s}\Delta\mathrm{G}\hat{e}e_s{}' + pv_l\mathrm{V_s}\mathrm{G}\Delta\hat{e}e_s{}' + pv_l\mathrm{V_s}\mathrm{G}\hat{e}\Delta e_s{}' \tag{10}$$

The relative contribution of socioeconomic factors from the consumption side and supply side can be calculated using these two equations, respectively. Eq. (9) indicates the relative contributions of each factor to the total change in electricity use Δj from the consumption side, including the change in energy structure Δe_s, the change in energy intensity Δe, the change in production input structure $\Delta\mathrm{L}$, the change in final demand structure $\Delta\mathrm{Y_s}$, the change in final demand level Δy_l, and the change in population Δp. Eq. (10) represents relative contributions of the change in population Δp, the change in primary input level Δv_l, the change in primary input structure $\Delta\mathrm{V_s}$, the change in production output structure $\Delta\mathrm{G}$, the change in energy intensity Δe, and the change in energy structure Δe_s to the change in total electricity use Δj.

To solve the non-uniqueness problem of SDA (Rørmose and Olsen, 2005), the average of all of the possible first-order decomposition results is used in this study. This method is widely used in existing studies (Feng et al., 2015; Guan et al., 2008, 2009; Haan, 2001; Hoekstra and Bergh, 2002; Liang et al., 2011, 2013, 2014a, 2016b ; Liang and Zhang, 2011; Minx et al., 2011; Peters et al., 2007; Rørmose and Olsen, 2005; Wang et al., 2013; Xu et al., 2011; Yamakawa and Peters, 2011; Zeng et al., 2014).

2.3. Data sources

Monetary input-output tables (MIOTs) and environmental accounts are collected from the World Input-Output Database (WIOD), including National Input-Output Tables (released November 2013), World Input-Output Tables in previous-year price (PYP) (released December 2014), and emission-relevant energy use by sector and energy commodity for China in WIOD's environmental accounts (released March 2012) (Dietzenbacher et al., 2013; Timmer et al., 2015). Emission-relevant energy use (in TJ) excludes the non-energy use of energy commodities (e.g., naphtha for plastics production, asphalt for road building) and energy commodities that are transformed to other types of energy (e.g., the coal that is transformed into coke and coke oven gas) (Genty et al., 2012). These data cover 35 sectors with the same classification and the