Determinants of global CO_2 emissions growth

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Abstract: This paper analyzes global CO_2 emissions growth by fossil fuel type (coal, oil or gas), demand type (consumption or investment), country group (developed or developing country) and industry group. The results indicate that, among the three fossil fuels, CO_2 emissions from coal use grew the most rapidly in developing countries, by 3.76 Gt in the period 1995-2009. By contrast, CO_2 emissions from natural gas use grew the most rapidly in developed countries, by 470 Mt in the period 1995-2009. Further decompositions show that, despite improvements in energy efficiency, the upgrades in infrastructures and changes in electricity requirements in developing countries have led to significant CO_2 emissions growth from coal use. Among these countries, China accounts for a high contribution, causing a coal-use-related CO_2 emissions growth of up to 2.79 Gt in the period 1995-2009. By contrast, consumption by the public and social services as well as chemical products is the dominant force driving CO_2 emission growth from gas in developed countries; the US accounts for a very high contribution, causing a gas-use-related CO_2 emissions growth of up to 100 Mt.

Keywords: Global CO_2 emission growth, Structural decomposition analysis, Fossil fuel type, WIOD.

1. Introduction

Global CO_2 emissions from fossil-fuel burning and industrial processes have doubled over the past 40 years, increasing from 16.9 gigatonnes (Gt) in 1974 to 35.5 Gt in 2014, with an annual growth rate of 1.8% (BP, 2015). Against the backdrop of the extensive discussions on global climate change mitigation, in recent years the growth rate of CO_2 emissions have accelerated from 1.0% per year for the period 1990-1999 to 2.4% per year for the period 2000-2014 (see also Raupach et al., 2007, Peters et al., 2012). Both developed countries and developing countries have witnessed continuous growth in their production-based CO_2 emissions, with developing countries having an annual rate of 3.2% for the period 1990-2014, larger than that of developed countries, 0.4% (BP, 2015).

According to the Kaya identity, the growth in global CO_2 emissions is driven by four factors, that is, $Ca = \frac{Ca}{E} \cdot \frac{E}{GDP} \cdot \frac{GDP}{P} \cdot P$, where Ca is CO_2 emissions, P is population, $\frac{GDP}{P}$ is gross domestic product (GDP) per capita, $\frac{E}{GDP}$ is the energy intensity of GDP, and $\frac{Ca}{E}$ is the carbon intensity of energy (emissions/energy). Gerland et al. (2014) project that the world population will continue to rise within this century, with a 95% chance that it will grow from 6.1 billion in 2000 to 9.0-13.2 billion by the year 2100. On a century-long basis, Baksi and Green (2007) find that the long-term average annual decline in global energy intensity is unlikely to substantially exceed 1.1%. Given an increase in GDP per capita is very crucial for improving living standards in developing countries, one of the most important ways to curb the growth of CO_2 emissions in developing countries is to decrease the carbon intensity of energy, i.e., the de-carbonization of energy consumption (see also, Wise et al., 2014; Cai et al., 2015; Chowdhury et al., 2015; Hong et al., 2015; Thangavelu et al., 2015; Tokimatsu et al., 2016)[1].

However, the share of renewable energies in global primary energy consumption as a total does not show any signs of increasing, especially in developing countries. On the contrary, it has remained more or less stable at approximately 13% since 1990 (Figure 1a). This stability may also be why we observe the acceleration in global CO_2 emissions growth (see also Raupach et al., 2007, Peters et al., 2012). Although the share of solar, wind and bio-renewable energies rose from 0.35% in 1990 to 2.45% in 2014, that rise has been largely offset by a 1.1 percentage point decline in the

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[1] Note that an increase in GDP per capita does not necessarily bring an improvement of quality of life or subjective well-being in developing countries. Therefore, the intervention in unsustainable lifestyles has been highly encouraged to achieve global emission reductions (Malik, et al., 2016).

share contributed by nuclear energy - also a low-carbon energy source (see also Green, 2015). In terms of countries, the performance of developed countries with regard to renewable energy usage is slightly better than that of developing countries. The share of carbon-free renewable energy in total primary energy consumption in developing countries has remained steady at 9% during the period 1990-2010 and, in 2014, increased to 10% (Figure 1c), whereas that of developed countries slowly increased from 13.3% in 1990 to 15.6% in 2000 and 17.9% in 2014 (Figure 1b).

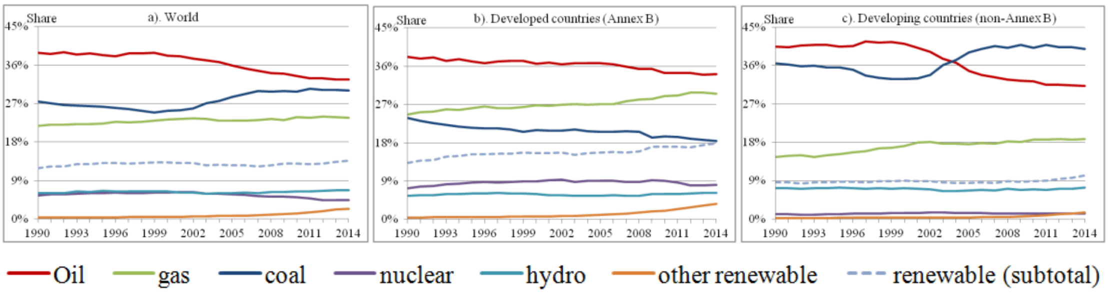

Figure 1. The share of primary energy consumption by energy type, a) world; b) developed countries (Annex B); and c) developing countries (non-Annex B), 1990-2014. The data are taken from BP statistics (2015).

The stable share of carbon-free renewable energies implies that the total share of fossil fuels in global energy consumption has remained relatively steady. Note that this stability does not necessarily mean fixed carbon energy intensity. Indeed, there is an internal structural change by fossil fuel (Fig. 1). Developed countries have witnessed an increase in the share of natural gas by 5.0 percentage points from 1990 to 2014 and drops in the shares of coal and oil by 5.5 and 4.1 percentage points, respectively (Fig. 1b). Meanwhile, developing countries have witnessed a drop in the share of oil by 9.2 percentage points and increases in the shares of coal and gas by 3.4 and 4.2 percentage points, respectively (Fig. 1c). On average, coal and oil have higher carbon contents than gas when generating the same amount of heat[2]. The change in the relative share of different fossil fuels may lead to changes in the total CO_2 emissions for an economy, even when its total primary energy consumption remains the same. As suggested by Figure 2, CO_2 emissions from gas use increased significantly over time in developed countries, whereas CO_2 emissions from coal use increased significantly in developing countries.

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[2] On average, coal has the highest carbon contents, with 3.96 tons of CO_2 per ton of oil equivalent (toe), followed by oil (2.35 tons of CO_2 per toe) and natural gas (3.07tons of CO_2 per toe) (BP, 2015).

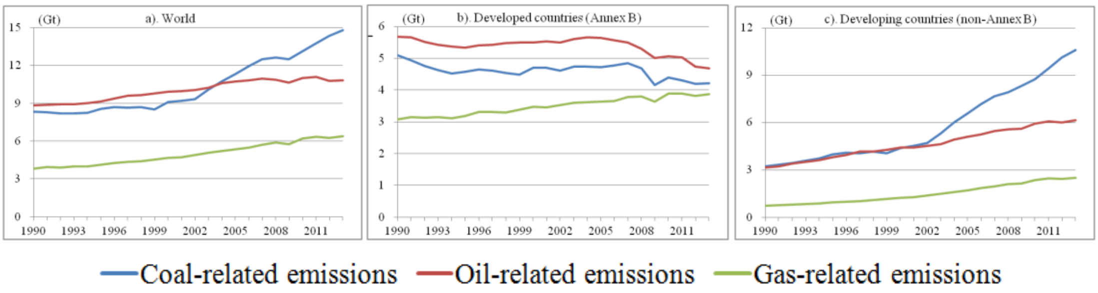

Figure 2. CO_2 emissions by fuel type, a) world; b) developed countries (Annex B); and c) developing countries (non-Annex B), 1990-2013. The data are taken from the International Energy Agency (www.iea.org).

Due to the separation of emissions caused by international trade, the increasing attention to global CO_2 emissions has shifted from a production-based perspective to a consumption-based perspective (see, e.g., Munksgaard and Pedersen, 2001; Gallego and Lenzen, 2005; Lenzen et al., 2007; Davis and Caldeira, 2010; Arto and Dietzenbacher, 2014). That is, concern has shifted from answering the question “Who emits?” to answering the question “For whom is it emitted?”. For example, Arto and Dietzenbacher (2014) used WIOD and found that the changes in the levels of consumption per capita and population growth have dominated global CO_2 emissions growth for the period 1995-2008. However, there are scarce studies that discuss the reasons behind the CO_2 emissions growths by fossil fuel type from the consumption-based perspective. One of the pioneer studies might be from Malik et al. (2016). Based on Eora, they decomposed the global CO_2 emission growth by fuel type for the period 1990-2010, and demonstrate that affluence (per-capita consumption) and population growth are outpacing any improvements in carbon efficiency in driving up emissions worldwide. In this paper, based on the WIOD, we further distinguish the final demand into consumption and investment, and employ a structural decomposition model (SDA) to explore the driving forces behind global CO_2 emissions growth by demand type (consumption or investment), country group (developed or developing country), fossil fuel type (coal, oil or gas) and industry group. By such a decomposition, we hope to understand the global CO_2 emissions growth at a more detailed level. For example, for whom gas-use-related CO_2 has been emitted in developed countries or for whom coal-use-related CO_2 has been emitted in developing countries? Is there a difference in the demand structures and consumption bundles between developed and developing countries that have led to different oil, coal, and gas requirements? It is hoped that doing so may illuminate the questions noted above.

2. Methodology and Data

In this paper, we employed a structural decomposition model (SDA) based on a global multi-regional input-output (GMRIO) framework to explore the reasons behind global CO_2 emissions growth by fossil fuel type and region. The GMRIO framework has been widely accepted to analyze the global energy consumption and CO_2 emissions growth (see, Wiedmann, 2009; Arto and Dietzenbacher, 2015; Mundaca et al., 2015; Zhang et al., 2015; Brizga et al., 2016; Lan et al., 2016). Table 1 presents the GMRIO framework employed in this paper. The diagonal matrices of intermediate use give the intra-regional intermediate deliveries. For example, the elements z_{ij}^{rr} of matrix $\mathbf{Z^{rr}}$ give the intermediate deliveries from industry *i* in region *r* to industry *j* in region *r*, with *i*, *j* =1,…,*m*, where *m* is the number of industries, and *r* =1,…,*n*, where *n* is the number of regions. The non-diagonal matrices indicate inter-regional intermediate deliveries. For example, the elements z_{ij}^{rs} of matrix $\mathbf{Z^{rs}}$ indicate the deliveries of products from industry *i* (=1,..,m) in country *r* (=1,..,n) for input use in industry *j* (=1,..,m) in country *s* (=1,..,n; ≠ *r*). The matrices of final demand have a similar structure; they are divided by consumption (including consumption by households, governments and non-government organizations), $\mathbf{F_c^{rs}}$(*r*, *s*=1,...,n), and investment (for fixed capital formation), $\mathbf{F_i^{rs}}$ (*r*, =1,...,n).

Table 1. The multi-regional input-output framework

			Intermediate Use			Final Use					Total Output
			Country 1	…	Country n	Country 1		…	Country n		
			Industry 1,.., m		Industry 1,…,m	Cons.	Inv.		Cons.	Inv.	
Intermediate Use	Country 1	industry	Z^{11}	…	Z^{1n}	F_c^{11}	F_i^{11}	…	F_c^{1n}	F_i^{1n}	X^1
	…	…	…	…	…			…		…	…
	Country n	industry	Z^{n1}	…	Z^{nn}	F_c^{n1}	F_i^{n1}	…	F_c^{nn}	F_i^{nn}	X^n
Value Added			V^1	…	V^n						
Total Inputs			X^1	…	X^n						

According to Table 1, we have row equilibrium in matrix notation as follows:

$$\begin{bmatrix} \mathbf{Z}^{\mathbf{11}} & \cdots & \mathbf{Z}^{\mathbf{1n}} \\ \vdots & \ddots & \vdots \\ \mathbf{Z}^{\mathbf{n1}} & \cdots & \mathbf{Z}^{\mathbf{nn}} \end{bmatrix} + \begin{bmatrix} \mathbf{F}_{\mathbf{c}}^{\mathbf{11}} + \cdots + \mathbf{F}_{\mathbf{c}}^{\mathbf{1n}} + \mathbf{F}_{\mathbf{i}}^{\mathbf{11}} + \cdots + \mathbf{F}_{\mathbf{i}}^{\mathbf{1n}} \\ \cdots \\ \mathbf{F}_{\mathbf{c}}^{\mathbf{n1}} + \cdots + \mathbf{F}_{\mathbf{c}}^{\mathbf{nn}} + \mathbf{F}_{\mathbf{i}}^{\mathbf{nn}} + \cdots + \mathbf{F}_{\mathbf{i}}^{\mathbf{nn}} \end{bmatrix} = \begin{bmatrix} \mathbf{X}^{\mathbf{1}} \\ \vdots \\ \mathbf{X}^{\mathbf{n}} \end{bmatrix} \qquad (1)$$

The direct input coefficients can then be obtained by normalizing the columns in the IO table; that is:

$$\mathbf{A}^{\mathbf{rs}} = \mathbf{Z}^{\mathbf{rs}}(\widehat{\mathbf{X}^{\mathbf{s}}})^{-\mathbf{1}} \qquad (2)$$

where *r*, *s*=1,...,n, and $(\widehat{\mathbf{X}^{\mathbf{s}}})^{-\mathbf{1}}$ denotes the inverse of a diagonal matrix of total outputs in region s.

Define the input coefficients matrix $\mathbf{A} = \begin{bmatrix} \mathbf{A}^{\mathbf{11}} & \cdots & \mathbf{A}^{\mathbf{1n}} \\ \vdots & \ddots & \vdots \\ \mathbf{A}^{\mathbf{n1}} & \cdots & \mathbf{A}^{\mathbf{nn}} \end{bmatrix}$ where $\mathbf{A}^{\mathbf{rs}}$ is the input coefficient from region *r* to region *s*. Then, the Leontief inverse can be calculated as $\mathbf{B} = (\mathbf{I} - \mathbf{A})^{-\mathbf{1}}$; that is, $\mathbf{B} = \begin{bmatrix} \boldsymbol{B}^{\mathbf{11}} & \cdots & \boldsymbol{B}^{\mathbf{1}\boldsymbol{n}} \\ \vdots & \ddots & \vdots \\ \boldsymbol{B}^{\boldsymbol{n}\mathbf{1}} & \cdots & \boldsymbol{B}^{\boldsymbol{nn}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{I} - \boldsymbol{A}^{\mathbf{11}} & \cdots & -\boldsymbol{A}^{\mathbf{1}\boldsymbol{n}} \\ \vdots & \ddots & \vdots \\ -\boldsymbol{A}^{\boldsymbol{n}\mathbf{1}} & \cdots & \boldsymbol{I} - \boldsymbol{A}^{\boldsymbol{nn}} \end{bmatrix}^{-1}$, where **I** is the identity matrix with diagonal elements as ones and non-diagonal elements as zeros. The Leontief inverse describes both the direct and indirect linkages across countries and sectors.

Using $\mathbf{E}_{\mathbf{o}}^{\mathbf{r}}$ to denote CO_2 emissions linked to fossil fuel type o (=coal, oil and gas) in region *r* and $\mathbf{CA}_{\mathbf{o}}^{\mathbf{r}} = \mathbf{E}_{\mathbf{o}}^{\mathbf{r}}(\widehat{\mathbf{X}^{\mathbf{r}}})^{-1}$ to denote the carbon emissions intensity per unit of output linked to fossil fuel type o (=coal, oil and gas) in region *r*, CO_2 emissions by fuel type generated along global production chains can be calculated as follows:

$$\begin{bmatrix} E_o^{1p} \\ \vdots \\ E_o^{np} \end{bmatrix} = \begin{bmatrix} \widehat{\mathbf{CA}_{\mathbf{o}}^{\mathbf{1}}} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \widehat{\mathbf{CA}_{\mathbf{o}}^{\mathbf{n}}} \end{bmatrix} \begin{bmatrix} \mathbf{B}^{\mathbf{11}} & \cdots & \mathbf{B}^{\mathbf{1n}} \\ \vdots & \ddots & \vdots \\ \mathbf{B}^{\mathbf{n1}} & \cdots & \mathbf{B}^{\mathbf{nn}} \end{bmatrix} \begin{bmatrix} \mathbf{F}_{\mathbf{c}}^{\mathbf{11}} + \cdots + \mathbf{F}_{\mathbf{c}}^{\mathbf{1n}} + \mathbf{F}_{\mathbf{i}}^{\mathbf{11}} + \cdots + \mathbf{F}_{\mathbf{i}}^{\mathbf{1n}} \\ \cdots \\ \mathbf{F}_{\mathbf{c}}^{\mathbf{n1}} + \cdots + \mathbf{F}_{\mathbf{c}}^{\mathbf{nn}} + \mathbf{F}_{\mathbf{i}}^{\mathbf{n1}} + \cdots + \mathbf{F}_{\mathbf{i}}^{\mathbf{nn}} \end{bmatrix} \qquad (3a)$$

$$\begin{bmatrix} E_o^{1c} \\ \vdots \\ E_o^{nc} \end{bmatrix} = \begin{bmatrix} \mathbf{CA}_{\mathbf{o}}^{\mathbf{1}} & \cdots & \mathbf{CA}_{\mathbf{o}}^{\mathbf{n}} \end{bmatrix} \begin{bmatrix} \mathbf{B}^{\mathbf{11}} & \cdots & \mathbf{B}^{\mathbf{1n}} \\ \vdots & \ddots & \vdots \\ \mathbf{B}^{\mathbf{n1}} & \cdots & \mathbf{B}^{\mathbf{nn}} \end{bmatrix} \begin{bmatrix} \mathbf{F}_{\mathbf{c}}^{\mathbf{11}} + \mathbf{F}_{\mathbf{i}}^{\mathbf{11}} & \cdots & \mathbf{F}_{\mathbf{c}}^{\mathbf{1n}} + \mathbf{F}_{\mathbf{i}}^{\mathbf{1n}} \\ \vdots & \ddots & \vdots \\ \mathbf{F}_{\mathbf{c}}^{\mathbf{n1}} + \mathbf{F}_{\mathbf{i}}^{\mathbf{n1}} & \cdots & \mathbf{F}_{\mathbf{c}}^{\mathbf{nn}} + \mathbf{F}_{\mathbf{i}}^{\mathbf{nn}} \end{bmatrix} \qquad (3b)$$

Eq. (3a) calculates the production-based CO_2 emissions by fuel type o (=coal, oil and gas) in region *r* (=1,...,n), whereas eq. (3b) calculates the consumption-based CO_2 emissions by fuel type o (=coal, oil and gas) because of the final demand in region *r* (=1,...,n). The WIOD divides sectors and regions into 35 sectors and 41 regions, as shown in Appendix Table A; therefore, we have n=41 and $\mathbf{CA}_{\mathbf{o}}^{\mathbf{r}}$ (*r*=1,...,41) as a 1*35 vector, $\mathbf{B}^{rs}$(*r*,*s*=1,..,41) as a 35*35 matrix, and $\mathbf{F}_{\mathbf{c}}^{\mathbf{rs}}$ and $\mathbf{F}_{\mathbf{i}}^{\mathbf{rs}}$ (*r*,*s*=1,..,41) as a 35*1 matrix.

Structural Decomposition Analysis (SDA) has been extensively applied to decompose the global energy use and emissions growth (see, e.g. Hoekstra et al., 2016; Malik and Lan, 2016; Malik et al., 2016 and Lenzen (2016) for a very recent review). The decomposition in consumption-based CO_2 emissions by fuel type can be conducted according to eq. (3). To simplify the analysis, we firstly conduct the decompositions on a full WIOD table, and then aggregate the results of decompositions from 41 regions as shown in the WIOD into two group, i.e., developed countries that fall into the Annex B countries list and developing countries that are not Annex B countries (non-Annex B countries) (see also Peters et al., 2012)[3]. In addition, given that China has a high dependency on coal and the world's largest CO_2 emissions, we separate China from the developing countries group to avoid distorting the picture of developing countries. That is, we explore the driving forces behind the consumption-based CO_2 emission by fuel type for three country groups: developed countries (Annex B), China, and developing countries excluding China (non-Annex B excluding China).

Arto and Dietzenbacher (2014) have found that final demand is the dominant force driving global CO_2 growth. Given that investment, especially infrastructure construction, is highly carbon-intensive (see also Perz, 2014), we further divide final demand into consumption and investment. We also separate the demand of developed countries and developing countries, and of these groups, the largest developed country, the US (r = 41 in the WIOD), and the largest developing country, China (r =7 in WIOD), are singled out. The idea is to trace the global CO_2 emission growth by fuel type into specific types of demand for specific countries groups. That is, we have consumption for four country groups as follows: $\mathbf{F}_{\boldsymbol{c}}^{\boldsymbol{Annex\,B}} = \begin{bmatrix} \sum_{r \in Annex\,B}^{r=1,\ldots,n} F_c^{r1} \\ \vdots \\ \sum_{r \in Annex\,B}^{r=1,\ldots,n} F_c^{rn} \end{bmatrix}$, $\mathbf{F}_{\boldsymbol{c}}^{\boldsymbol{US}} = \begin{bmatrix} F_c^{41,1} \\ \vdots \\ F_c^{41,n} \end{bmatrix}$, $\mathbf{F}_{\boldsymbol{c}}^{\boldsymbol{non-Annex\,B}} = \begin{bmatrix} \sum_{r \in non-Annex\,B}^{r=1,\ldots,n} F_c^{r1} \\ \vdots \\ \sum_{r \in non-Annex\,B}^{r=1,\ldots,n} F_c^{rn} \end{bmatrix}$ and $\mathbf{F}_{\boldsymbol{c}}^{\boldsymbol{CHN}} = \begin{bmatrix} F_c^{7,1} \\ \vdots \\ F_c^{7,1} \end{bmatrix}$. Similarly we can have the level of investment of the four country groups as follows: $\mathbf{F}_{\mathbf{i}}^{\mathbf{Annex\,B}}$, $\mathbf{F}_{\mathbf{i}}^{\mathbf{US}}$, $\mathbf{F}_{\mathbf{i}}^{\mathbf{non-Annex\,B}}$ and $\mathbf{F}_{\mathbf{i}}^{\mathbf{CHN}}$.

Then, we can decompose the CO_2 emissions growth from the demand perspective. For example, for the CO_2 emissions of China ($r = 7$) linked to fuel type o (=coal, oil and gas) for year t, we have:

$$\begin{aligned} & E_o^{7p}(t) \\ & = [0 \cdots 0 \quad \mathbf{CA}_{\mathbf{o}}^{\mathbf{7}}(\mathbf{t}) \quad 0 \cdots 0] \begin{bmatrix} \mathbf{B}^{\mathbf{11}}(\mathbf{t}) & \cdots & \mathbf{B}^{\mathbf{1n}}(\mathbf{t}) \\ \vdots & \ddots & \vdots \\ \mathbf{B}^{\mathbf{n1}}(\mathbf{t}) & \cdots & \mathbf{B}^{\mathbf{nn}}(\mathbf{t}) \end{bmatrix} \begin{bmatrix} F_c^{11}(t) + \cdots + F_c^{1n}(t) + F_i^{11}(t) + \cdots + F_i^{1n}(t) \\ \cdots \\ F_c^{n1}(t) + \cdots + F_c^{nn}(t) + F_i^{n1}(t) + \cdots + F_i^{nn}(t) \end{bmatrix} \\ & = \mathbf{CA}_{\mathbf{o}}^{\mathbf{7}}(\mathbf{t}) \cdot \mathbf{B}(\mathbf{t}) \cdot \mathbf{F}(\mathbf{t}) \qquad (5) \end{aligned}$$

Then, we have the decomposition from year t-1 to year t based on the average of the polar decompositions:

$$\Delta E_o^{7p} = E_o^{7p}(t) - E_o^{7p}(t-1)$$

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[3] Note that the WIOD covers the majority of Annex B countries but excludes Belarus, Croatia, Iceland, Liechtenstein, Monaco and Ukraine. Please refer to Appendix Table A for more details.

$$= \mathbf{CA_o^7(t)\cdot B(t)\cdot F(t) - CA_o^7(t-1)\cdot B(t-1)\cdot F(t-1)}$$

$$= \frac{1}{2}\mathbf{[CA_o^7(t) - CA_o^7(t-1)]\cdot[B(t)\cdot F(t) + B(t-1)\cdot F(t-1)]} \quad \text{(6a)}$$

$$+\frac{1}{2}\mathbf{CA_o^7(t)\cdot[B(t) - B(t-1)]\cdot F(t-1)} + \frac{1}{2}\mathbf{CA_o^7(t-1)\cdot[B(t) - B(t-1)]\cdot F(t)} \quad \text{(6b)}$$

$$+\frac{1}{2}\mathbf{[CA_o^7(t)\cdot B(t) + CA_o^7(t-1)\cdot B(t-1)]\cdot[F_c^{Annex\,B}(t) - F_c^{Annex\,B}(t-1)]} \quad \text{(6c)}$$

$$+\frac{1}{2}\mathbf{[CA_o^7(t)\cdot B(t) + CA_o^7(t-1)\cdot B(t-1)]\cdot[F_c^{US}(t) - F_c^{US}(t-1)]} \quad \text{(6d)}$$

$$+\frac{1}{2}\mathbf{[CA_o^7(t)\cdot B(t) + CA_o^7(t-1)\cdot B(t-1)]\cdot[F_c^{non-Annex\,B}(t) - F_c^{non-Annex\,B}(t-1)]} \quad \text{(6e)}$$

$$+\frac{1}{2}[\boldsymbol{CA_o^7(t)}\cdot \mathbf{B}(\boldsymbol{t}) + \boldsymbol{CA_o^7(t-1)}\cdot \mathbf{B}(\boldsymbol{t}-\mathbf{1})]\cdot\mathbf{[F_c^{CHN}(t) - F_c^{CHN}(t-1)]} \quad \text{(6f)}$$

$$+\frac{1}{2}\mathbf{[CA_o^7(t)\cdot B(t) + CA_o^7(t-1)\cdot B(t-1)]\cdot[F_i^{Annex\,B}(t) - F_i^{Annex\,B}(t-1)]} \quad \text{(6g)}$$

$$+\frac{1}{2}\mathbf{[CA_o^7(t)\cdot B(t) + CA_o^7(t-1)\cdot B(t-1)]\cdot[F_i^{US}(t) - F_i^{US}(t-1)]} \quad \text{(6h)}$$

$$+\frac{1}{2}\mathbf{[CA_o^7(t)\cdot B(t) + CA_o^7(t-1)\cdot B(t-1)]\cdot[F_i^{non-Annex\,B}(t) - F_i^{non-Annex\,B}(t-1)]} \quad \text{(6i)}$$

$$+\frac{1}{2}\mathbf{[CA_o^7(t)\cdot B(t) + CA_o^7(t-1)\cdot B(t-1)]\cdot[F_i^{CHN}(t) - F_i^{CHN}(t-1)]} \quad \text{(6j)}$$

where eq. (6a) gives the effect of changes in carbon intensity per unit of Chinese output on China's CO_2 emissions growth by fuel type o (=coal, oil and gas); eq. (6b) gives the effect of changes in the input structure and intermediate trade bundle (Leontief inverse B); eq. (6c) – (6f) give the effects of changes in the consumption of developed countries (Annex B) excluding the US, the US, developing countries (non-Annex B) excluding China, and China, respectively; and eq. (6g) – (6j) give the effects of changes in the investment of developed countries (Annex B) excluding the US, the US, developing countries (non-Annex B) excluding China, and China, respectively.

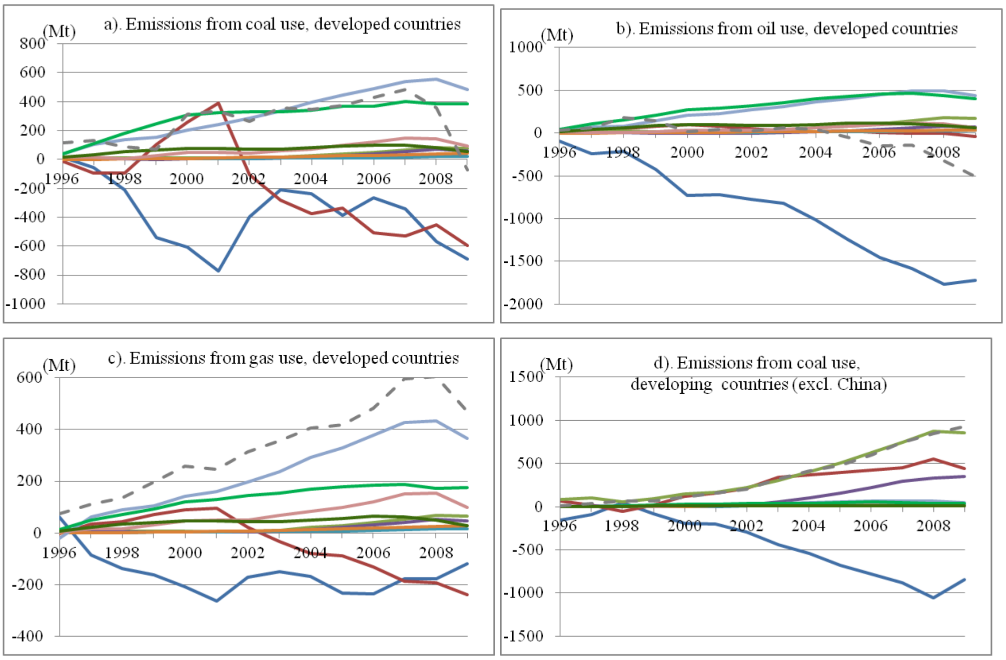
Let $\mathbf{CA_o^{Annex\,B}}$ indicate the carbon intensity vector for the developed (Annex B) country group where the sub-vector of Annex B countries are filled with exact numbers and that of developing (non-Annex B) countries are filled with zeros, and let $\mathbf{CA_o^{non-Annex\,B}}$ indicate the carbon intensity vector for the developing (non-Annex B) country group excluding China; the CO_2 emissions growth of developed countries (Annex B) and developing countries (non-Annex B excl. China) by fuel type o (=coal, oil and gas) can be decomposed similarly. The WIOD provides the GMRIO table of year t in constant prices of year t-1 for the period 1995-2009; thus, we can decompose the global emissions growth from any year t to year t+1 in constant prices.

3. Empirical Results

3.1. Decomposition results of CO_2 emissions growth by fuel type and country group

In Figure 3, we decompose the cumulative CO_2 emissions growth by fuel type and country group from a demand perspective, where “demand” is divided into eight groups. More specifically, we decompose the CO_2 emissions growth year by year in constant prices and summarize them as cumulative decomposition results for the period 1995-2009.

Comparing the magnitudes of CO_2 emissions growths indicates that Chinese CO_2 emissions from coal use have the highest growth within the period 1995-2009, with an increase of 2794 Mt, followed by the CO_2 emissions from coal and gas use of developing countries excluding China, with increases of 967 Mt and 814 Mt, respectively. At 471 Mt, the CO_2 emissions from gas of developed countries also have substantial increases. The CO_2 emissions from gas of China only increased by 132 Mt, whereas the CO_2 emissions from oil of developed countries decreased by 506 Mt. Note that the developing countries (incl. China) and developed countries show completely different trend during the period 2007-2009 when international financial crisis happened. The CO_2 emissions from coal, oil and gas use in China keep growing from 2007 to 2009, by 641 Mt, 48 Mt and 36 Mt, respectively. The developing countries (excl. China) also experienced growths in CO_2 emissions, mainly from coal and gas, increased by 155 Mt and 63 Mt respectively during 2007-2009. On contrary, developed countries experienced serious reduction of CO_2 emissions from coal, oil and gas use by respective 555 Mt, 362 Mt and 124 Mt for the same period.



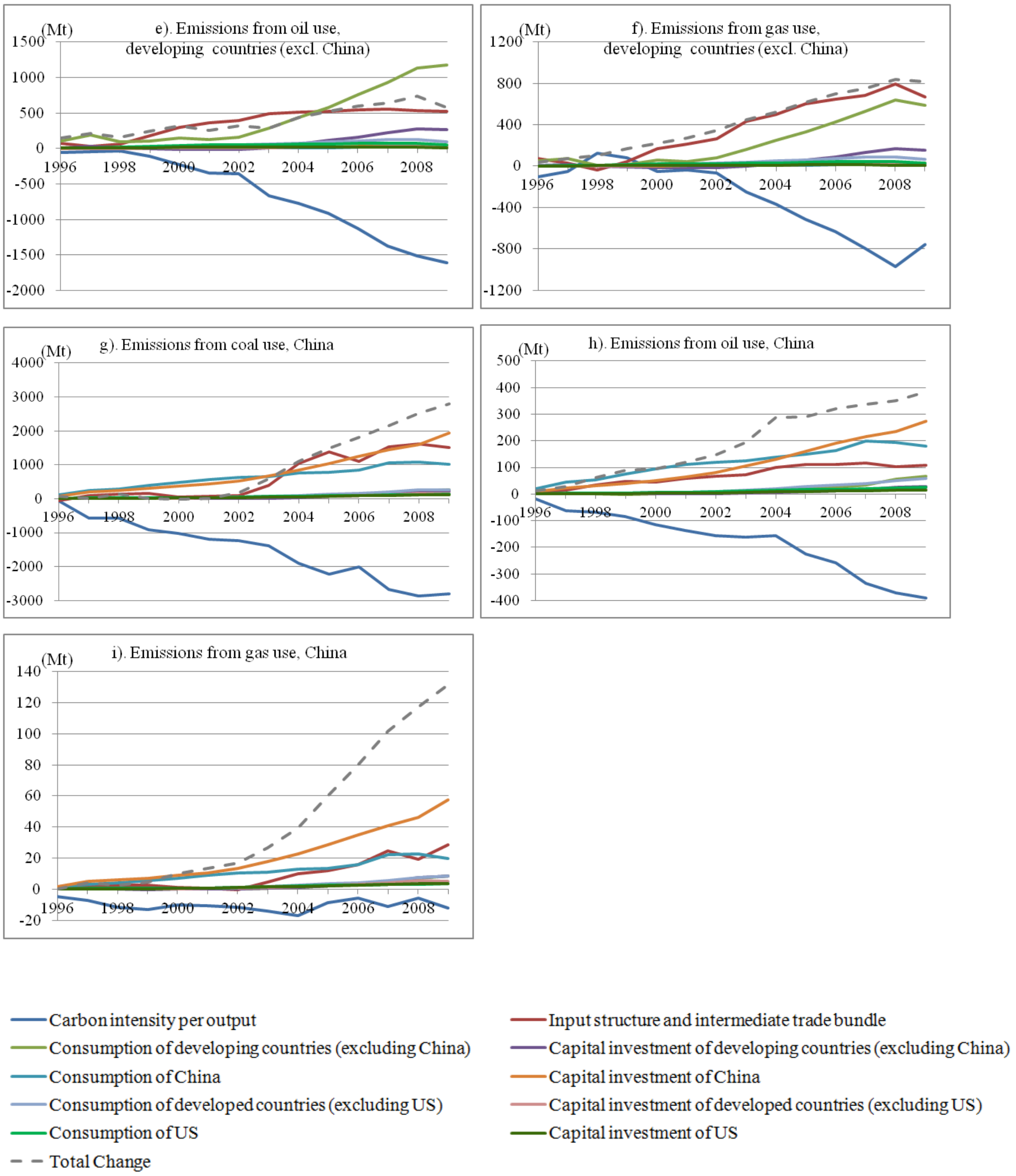


Figure 3. The decompositions of cumulative CO_2 emissions growth by fuel type and country group, 1995-2009, in million tons (Mt)

Considerable differences lie in the contributions behind the CO_2 emissions growth by fuel type in 1995-2008. Although the change in carbon intensity has been the dominant force driving the decrease in CO_2 emissions, the effects vary to a large extent. If only the coal-use-related carbon intensity (i.e. CO_2 emission from coal use per output) of China – which includes a shift to cleaner coal bundle and less coal consumption per output – decreased in the manner it actually did while everything else had remained constant, then China's CO_2 emissions in 2009 would have decreased by 2803 Mt compared to the 1995 level (Fig. 3g). The share of coal in the total primary energy consumption of China only decreased slightly, from 75.3% in 1995 to 72.6% in 2009. The implication is that China’s energy intensity per output actually decreased substantially for the same period. The change in the oil-use-related carbon intensity of developing countries (excl. China) and developed countries also led to substantial decreases in the CO_2 emissions in these countries of 1612 Mt and 1725 Mt, respectively. Further investigation shows that the share of oil in total primary energy consumption dropped by 7.5 and 1.7 percentage points in developing (excl. China) and developed countries during 1995-2009, respectively. Given the similar carbon contents in different types of petroleum, the implication is that developed countries generally have a larger reduction in energy intensity than developing countries (excl. China). The IEA statistics confirm that both developed countries (Annex B countries) and China have reduced their energy intensity per GDP by 23.9% and 31.1%, respectively, by using purchasing power parities (in constant prices) whereas developing countries (non-Annex B excluding China) only reduced their energy intensity by 8.6% during 1995-2009. Therefore, the reductions in CO_2 emissions from coal use in China and CO_2 emissions from oil use in developed countries derived from the change in carbon intensity are mainly attributable to an improvement in energy efficiency, whereas the reduction in CO_2 emissions from oil use in developing countries (excluding China) derived from the change in carbon intensity is mainly attributable to a shift from oil to other fossil fuels.

Note that the change in carbon intensity led to only a very small reduction in CO_2 emissions from gas use in general – that is, 12 Mt for China and 117 Mt for developed countries in 1995-2009. Further exploration shows that the share of gas in total primary energy expanded by 1.8 and 2.2 percentage points in China and developed countries, respectively. Given the considerable drops in energy intensity in China and developed countries for the same period, these countries may tend to use more gas when generating the same amount of output, e.g., a structural shift toward sectors that heavily rely on gas rather than coal or oil. We return to this point below in section 3.2.

The change in intermediate inputs – which includes the change in the input structure and trade pattern of intermediates – has led to different changes in the CO_2 emissions in developed countries and developing countries. If only the intermediate inputs changed as they did and the other factors remained constant, then the CO_2 emissions from coal and gas use in developed countries in 2009 would have decreased by 597 Mt and 239 Mt compared to the 1995 level, respectively. By contrast, the change in the intermediate inputs in developing countries including China would have led to an increase of their CO_2 emissions by all fuel types, for a total increase of 3290 Mt. Unlike developed countries, developing countries have a high level of dependency on manufacturing and have experienced a shift of production from labor-intensive to capital-intensive methods. As a result, in recent years, the ratios of intermediates over output in China, for example, have shown an increasing trend. Meanwhile developed countries are mainly concentrated on low-energy-intensive services. In addition, there is a sign that, in recent decades, the global manufacturing center has shifted from developed countries to China and some other emerging countries such as India, Brazil, and Mexico (see, e.g., Lehmann, 2012; Stratfor, 2013; AfDB, OECD and UNDP, 2014). This phenomenon may explain the controversial roles played by the change in intermediate inputs for CO_2 emissions changes in developed and developing countries.

With respect to the effects of final demands, domestic demands are the major force driving CO_2 emissions changes, regardless of country group and fuel type. That is, the change in final demands of China itself has dominated the growth in CO_2 emissions in China, and so on. If we further divide the final demands into consumption and investment, then the performances of developed countries and developing countries show substantial differences. The changes in consumption in the US and other developed countries together dominate their own CO_2 emissions change, whereas the growth in US consumption has led to a total CO_2 emissions growth of 958 Mt during 1995-2009; and the growth in consumption of all other developed countries (excl. US) has led to a total CO_2 emissions growth of 1285 Mt for the same period. At the end of 2012, the total population of the US was approximately 314 million, less than half the total of all other developed countries (Annex B countries excluding US), which was approximately 759 million (World Bank, 2014). This difference suggests that, for the period 1995-2009, the US consumption structure has moved toward a bundle that is much more carbon-intensive than other developed countries did for the period 1995-2009. In general, the European Union and Japan play much more active roles in global climate change mitigation than the US does.

The change in the consumption of developing countries (non-Annex B countries excl. China) is also the dominant force of their own CO_2 emissions growth, for a total effect of 2623 Mt during 1995-2009. Their CO_2 emissions from oil use are especially influenced by the change in consumption, increasing by 1173 Mt. Unlike developed countries, the change in investment demands also plays a significant role in CO_2 emissions growth, leading to a total growth of 763 Mt as the second major driving force. The reason is in developing countries a series of infrastructures, such as roads, railways and power plants, remain in short supply. Their construction requires a considerable amount of steel, cement, and primary energy and is therefore highly carbon-intensive given the high dependence on fossil fuels for baseload energy.

The change in capital investment demands in China even outperformed its change in consumption and became the major force driving China's CO_2 emissions growth. It brought growths of 1928 Mt of CO_2 emissions from coal use, 274 Mt of CO_2 emissions from oil use, and 58 Mt of CO_2 emissions from gas use in China, for a total increase of 2260 Mt during 1995-2009. In recent decades, China has experienced an unprecedented level of infrastructural growth. For example, China's total highway mileage increased from 1.15 million km to 3.86 million km, and the electricity generation capacity more than tripled for the period 1995-2009[4]. This type of growth has not only contributed to social and economic development in China but also entailed considerable CO_2 emissions.

The change in consumption in China has brought a total CO_2 emissions growth of 1209 Mt during 1995-2009. At the end of 2012, the total population of China was approximately 1350 million, almost equivalent to that of all developed countries and less than 1/3 of all other developing countries (excl. China). Recalling the fact that the changes in consumption in developed countries and developing countries (excl. China) have led to growths of 2243 Mt and 2623 Mt of CO_2 emissions for the same period, respectively, it implies that developed countries have moved the most significantly toward a carbon-intensive consumption bundle, followed by China and then the remaining developing countries.

It is therefore not surprising that developed and developing countries show completely different trend of changes during the period 2007-2009 when international financial crisis happened. Fuelled by the growth in investment, the CO_2 emissions from coal, oil and gas use in China have witnessed a total growth of 567 Mt from 2007 to 2009. Similarly, the growth in investment led to a total of 110 Mt growth of CO2 emissions from coal, oil and gas use during 2007-2009. On contrast, developed countries have experienced serious shrunk of consumption during the international financial crisis, as a result their CO_2 emissions has been reduced by 276 Mt during 2007-2009.

It should be noted that although both China and the developing countries group have experienced a growth in CO_2 emissions that is mainly led by capital investment, their dependency on fuel by fuel type is different. Over 90% of China's investment-driven CO_2 emissions are from coal, whereas these emissions in other developing countries (excl. China) are almost equally distributed among coal, oil and gas. China has a high level of dependency on coal as the primary energy input (above 70% in 2008), and its share of coal in total primary energy consumption is much higher than that in other developing countries (approximately 40% in 2008). Given that coal has higher carbon contents than the equivalent level of oil and gas, this phenomenon may also be one of the reasons behind China's considerable growth in CO_2 emissions.

3.2 The top 5 industries with the largest effects on CO_2 emission growth by fuel type and country group, prior to economic crisis

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[4] The data are taken from www.stats.gov.cn.

Figure 3 only sketches the overall patterns of CO_2 emissions by fuel type from the demand perspective. Given the dominant role played by the change in final demands, it is interesting to further explore the differences in the demand structures among the different country groups, e.g., whether they have different requirements for different fuel types. In this section, to provide a more explicit picture, we focus on the top 5 industries for which the changes in final demand bring the largest CO_2 emissions growth when all other factors remain constant. That is, we adapt the decomposition formula (6) as follows:

$$\begin{aligned} \Delta E_o^p &= E_o^p(t) - E_o^p(t-1) \\ &= \mathbf{CA_o}\,(\mathbf{t}) \cdot \mathbf{B}(\mathbf{t}) \cdot \mathbf{F^i}(\mathbf{t}) - \mathbf{CA_o}\,(\mathbf{t-1}) \cdot \mathbf{B}(\mathbf{t-1}) \cdot \mathbf{F^i}(\mathbf{t-1}) \qquad (7) \end{aligned}$$

where $\mathbf{CA_o} = [\mathbf{CA_o^1} \quad \cdots \quad \mathbf{CA_o^{41}}]$ indicates the global carbon intensity matrix, $\mathbf{B}$ indicates the Leontief inverse, and $\mathbf{F}^i$ indicates the matrix of consumption or investment for industry *i* (=1,...,35). Given that developed countries and most developing countries experienced serious decrease of consumptions especially in 2009, we only focus on the period 1995-2008. To simplify the study, we only focus on the changes in consumption or capital investment for which the derived global CO_2 growth exceeds 200 Mt.

Table 2 summarizes the top 5 industries for each fuel type, final demand and country group, their corresponding subtotal effect on global CO_2 emissions growth, and the concentration ratio (subtotal effect/total effect of all 35 industries). First, Table 2 shows that investment-led CO_2 emission growth is highly concentrated in a few industries. The top 5 industries explain 84%-96% of all 35 industries' investment-led CO_2 growth; that is, the concentration ratios of the top 5 industries range from 84% to 96% for investment. Meanwhile regarding consumption, the concentration ratio ranges from 40% to 67%. More specifically, the changes in capital investment in construction and few "high-end" manufacturing sectors, such as machinery (ind. 13), electrical and optical equipment (ind. 14) and transport equipment (ind. 15), dominate the CO_2 emissions growth in all developing countries. Construction that is largely attributable to upgrades in infrastructure alone has a concentration ratio of approximately 65% for the investment-led CO_2 emissions growth in developing countries including China. The remaining 35% of investment-led CO_2 emissions growth is mainly attributable to the upgrading of machinery for production in manufacturing industries, especially high-end manufacturing industries. Production in developing countries has shifted from labor-intensive methods to capital-intensive methods. As a result, considerable requirements for capital investment in infrastructure and these "high-end" manufacturing sectors have been stimulated, consequently leading to a considerable growth in CO_2 emissions in developing countries.

With respect to consumption, the pattern of the top 5 industries varies among the three fuel types and four country groups. The consumption of electricity (ind. 17) is clearly the largest source of coal-use-related, oil-use-related and gas-use-related CO_2 emissions growth in developing countries, whereas for developed countries, electricity is the only large source of coal-use-related but not oil-use-related or gas-use-related CO_2 emissions growth. Developing countries (including China) mainly rely on fossil fuels as electricity generation inputs. As a result, electricity (ind. 17) alone explains growths of 674 Mt of coal-use-related, 218 Mt of oil-use-related and 384 Mt of gas-use-related CO_2 emission in developing countries (incl. China), for a total of 1276 Mt during 1995-2008.

Table 2. The top 5 industries with the largest effects on CO_2 emissions growth by final demand, fuel type and country group, 1995-2008

Demand type	Fuel type	Country group	Top 5 industries					Subtotal* (in Mt)	Concentration ratio
Consumption-led CO_2 growth	Coal	Developing excl. China	17	4	3	14	23	776	58.4%
		China	17	3	33	32	31	750	66.9%
		Developed excl. US	17	14	4	29	33	359	49.3%
		US	17	31	33	29	21	283	52.0%
	Oil	Developing excl. China	17	24	25	3	23	698	46.8%
		Developed excl. US	25	8	33	31	17	218	39.5%
		US	31	33	21	8	22	275	51.9%
	Gas	Developing excl. China	17	31	3	20	33	605	63.1%
		Developed excl. US	17	8	9	33	31	146	50.6%
		US	31	33	8	9	17	135	62.4%
Investment-led CO_2 growth	Coal	Developing excl. China	18	14	13	15	12	617	91.3%
		China	18	13	15	14	12	1611	96.3%
		Developed excl. US	14	13	15	17	30	229	91.5%
	Oil	Developing excl. China	18	14	15	13	2	368	83.9%
		China	18	13	14	15	20	287	94.8%
	Gas	Developing excl. China	18	14	13	2	15	304	90.4%

* The subtotal indicates the subtotal of global CO_2 emissions growth in the period 1995-2008 led by the top 5 industries of consumption or investment by each fuel type and country group. The concentration ratio gives the share of the subtotal in a total 35 industries.

Industry code: 2=Mining and Quarrying; 3=Food, Beverages and Tobacco; 4=Textiles and Textile Products; 8=Coke, Refined Petroleum and Nuclear Fuel; 9=Chemicals and Chemical Products; 12=Basic Metals and Fabricated Metal; 13=Machinery, Nec; 14=Electrical and Optical Equipment; 15=Transport Equipment; 17=Electricity, Gas and Water Supply; 18=Construction;

20=Wholesale Trade and Commission Trade, Except Motor Vehicles and Motorcycles; 21=Retail Trade, Except Motor Vehicles and Motorcycles; Repair of Household Goods; 22=Hotels and Restaurants; 23=Inland Transport; 24=Water Transport; 25=Air Transport; 27=Post and Telecommunications; 29=Real Estate Activities; 31= Public Administration and Defense, Compulsory Social Security; 32=Education; 33=Health and Social Work; 33=Health and Social Work.

By contrast, developed countries rely on a variety of renewable energies, such as wind, solar and nuclear energies, to generate electricity. As a result, we find that the growths in CO_2 emissions from oil and gas use in developed countries are mainly led by few manufacturing and services industries such as wholesale and retail (ind. 20 and 21). In addition, the change in consumption in public administration and defense (ind. 31) and health and social work (ind. 33) also led to a considerable CO_2 emissions growth. For the US, the change in consumption in these two industries (31 and 32) jointly led to growths of 103 Mt of coal-use-related, 156 Mt of oil-use-related, and 86 Mt of gas-use-related CO_2 emissions, for a total of 345 Mt, which is much higher than the CO_2 emissions growth brought by electricity consumption (145Mt) in the US during 1995-2008.

There are also differences in the top 5 industries for each fuel type, even within the same country group. For developing countries (excl. China), the changes in consumption in food products (ind. 3), textiles (ind. 4) and electric and optical equipment (ind. 14) are the major source of coal use, leading to a total CO_2 emissions growth of 246 Mt during 1995-2008; the changes in consumption in the various transportation sectors (ind. 23-25) are the major source of oil use, leading to a total CO_2 emissions growth of 361 Mt for the same period. For developed countries (excl. US), textiles (ind. 4) and real estate activities (ind. 29) are the major source of coal use, whereas coke and petroleum (ind. 8) and chemicals (ind. 9) are the major source of gas use.

4. Discussion

4.1 Robustness of the results

Recent years have seen a proliferation of global MRIO tables that are available to analyze the global energy use and emissions issues, such as Eora, EXIOBASE, OECD-ICIO, GTAP-MRIO (see Tukker and Dietzenbacher (2013) for a review). In addition to each databases adhering to different sector and regional compositions, the MRIO tables also source their data from different places and have different recipes to construct the data. It is therefore not surprising that each MRIO may generate different outcomes (see, e.g. Steen-Olsen et al. (2016), Inomata and Owen (2014) for a review). Even though, the insights from different MRIO tables are similar. Moran and Wood (2014), for example, compared the results of consumption-based carbon accounts based on four global MRIOs: Eora, WIOD, EXIOBASE, and the GTAP-based OpenEU databases. They found that carbon footprint results for most major economies disagree by <10% between MRIOs, and the results for the temporal change across models appear to agree.

To validate our results, we also compare our results with Malik et al. (2006), that used Eora to decompose the global CO_2 emissions growth by fuel type in 1990-2010. It is found that in spite of different region disaggregation and decomposition formula, the basic conclusions are very similar. For example, Malik et al.'s assessment of trends in fuel-use reveals affluence (per-capita consumption) and population growth are outpacing any improvements in carbon efficiency in driving up emissions worldwide. Our decompositions also demonstrated that the growth in demand (incl. consumption and investment) is the dominant driving force behind the CO_2 emissions growth worldwide. By fuel type, Malik et al. (2016) suggest that a number of developed countries (e.g. Canada, Germany and the United Kingdom) experienced a shift from coal to natural gas, and in spite of the improvement in the emission intensity of coal, the coal demand used for the production of electricity and/or heat still drives the growth of coal use and the related CO_2 emissions, especially in developing countries. All of these are in line with our findings.

4.2 Conclusion

Our decompositions indicate that, despite the improvements in energy efficiency, the growth in final demands has led to considerable CO_2 growth worldwide, where developed countries (Annex B) and developing countries (non-Annex B) have very different performances in terms of changes by fuel type and demand type. In recent years, the demands for infrastructure and electricity in developing countries account for the largest contribution, leading to 3.02 Gt and 1.10 Gt of global CO_2 emissions growth, respectively, in the period 1995-2009. Among others, China accounts for a significant share. The improvement in infrastructure and the high dependency on coal for electricity generation in China alone has contributed over 2.46 Gt of global CO_2 emissions growth. By contrast, the change in infrastructure and electricity demand in developed countries only lead to a total CO_2 emission growth of less than 1.0 Gt. For this growth the reason is not only that developed countries already have well-functioning infrastructure but also that they have a much higher share of renewable energy use. From the perspective of sustainable development, the ratios of renewable energies, such as solar and wind energies, in developing countries still need to be significantly increased.

The growth of CO_2 emissions in developed countries is mainly driven by consumption in services, especially prior the international crisis in 2007. Among others, the change in consumption in the US has led to a growth of 1.01 Gt of global CO_2 emissions during 1995-2008, whereas the consumption growth of all of the remaining developed countries (excl. US) together has led to a total CO_2 emissions growth of 1.46 Gt. Given that the population of the US is only half that of the remaining developed countries, it seems that the developed countries especially US need to pay more attention on a more environment-friendly method of consumption.

When we decompose CO_2 growth by fuel type and industry group, it is also found that developed and developing countries have different patterns in terms of fossil fuel use. For example, the change in electricity requirements dominates the coal, oil and gas use of developing countries (including China), whereas the consumption changes in coke, petroleum and chemical manufacturing play significant roles in the gas use of developed countries. CO_2 emissions from gas use in developed countries have been found to have a considerable level of growth. In this context, the energy efficiency of the coke, petroleum and chemical industries in developed countries may need some further improvement for global sustainable development.

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Reference

[1]. AfDB, OECD and UNDP, Global Value Chains and Africa’s Industrialisation: African Economic Outlook, 2014, available at http://www.africaneconomicoutlook.org/.

[2]. Arto, I. and Dietzenbacher, E., Drivers of the growth in global greenhouse gas emissions, Environmental Science & Technology, 2014, 48: 5388-5394.

[3]. Baksi, S. and Green, C., Calculating economy-wide energy intensity decline rate: the role of sectoral output and energy shares, Energy Policy, 2007, 35: 6457–66.

[4]. Brizga, J., Feng, K., Hubacek, K., Household carbon footprints in the Baltic States: A global multi-regional input–output analysis from 1995 to 2011, Applied Energy, 2016, forthcoming, http://doi:10.1016/j.apenergy.2016.01.102.

[5]. Cai, Y., Newth, D., Finnigan, J., Gunasekera, D., A hybrid energy-economy model for global integrated assessment of climate change, carbon mitigation and energy transformation, Applied Energy, 2015, 148(12): 381–395.

[6]. Chowdhury, R., Freire, F., Bioenergy production from algae using dairy manure as a nutrient source: Life cycle energy and greenhouse gas emission analysis, Applied Energy, 2015, 154(18): 1112–1121.

[7]. Davis, S. J. and Caldeira, K., Consumption-based accounting of CO_2 emissions, PNAS, 2010, 107(12): 5687-5692.

[8]. Gallego, B. and M. Lenzen, A Consistent Input-Output Formulation of Shared Producer and

Consumer Responsibility. Economic Systems Research, 2005, 17(4): 365-391.

[9]. Gerland, P., Raftery, A. E., Ševčíková, H., Li, N., Gu, D., et al., World population stabilization unlikely this century, Science, 2014, 346 (6206), 234-237.

[10]. Hoekstra, R., Michel, B. and S. Suh, The emission cost of international sourcing: Using Structural Decomposition Analysis to calculate the contribution of international sourcing to CO2-emission growth. Economic Systems Research, 2016, 28(2): 151-167.

[11]. Hong, S., Bradshaw, C. J. A., Brook, B. W., Global zero-carbon energy pathways using viable mixes of nuclear and renewables, Applied Energy, 2015, 143(7): 451–459.

[12]. Inomata, S. and Owen, A., Comparative evaluation of MRIO databases, Economic Systems Research, 2014, 26(3): 239-244,

[13]. Lan, J., Malik, A., Lenzen, M., McBain, D., Kanemoto, K., A structural decomposition analysis of global energy footprints, Applied Energy, 2016, 163(3): 436–451.

[14]. Lehmann, J. P., China and the Global Supply Chain in Historical Perspective, in World Economic Forum: The Shifting Geography of Global Value Chains: Implications for Developing Countries and Trade Policy, p. 10-16, 2012, Geneva, Switzerland. available at www.weforum.org.

[15]. Lenzen, M., Structural analyses of energy use and carbon emissions – an overview, Economic Systems Research, 2016, 28(2): 119-132

[16]. Lenzen, M., J. Murray, Sack, F. and Wiedmann, T., Shared Producer and Consumer Responsibility: Theory and Practice. Ecological Economics, 2007, 61(1): 27-42.

[17]. Malik, A. and J. Lan, The role of outsourcing in driving global carbon emissions. Economic Systems Research, 2016, 28(2): 168-182.

[18]. Malik, A., Lan, J., and Lenzen, M., Trends in Global Greenhouse Gas Emissions from 1990 to 2010, Environmental Science and Technology, 2016, 50(9): 4722–4730.

[19]. Moran D. and Wood, R. (2014),-based carbon accounts, Economic Systems Research, 2014, 26(3): 245-261,

[20]. Mundaca, L., Román, R., Cansino, J. M., Towards a Green Energy Economy? A macroeconomic-climate evaluation of Sweden's CO_2 emissions, Applied Energy, 2015, 148(11): Pages 196–209.

[21]. Munksgaard, J. and Pedersen, K.A., CO_2 Accounts for Open Economies: Producer or Consumer Responsibility? Energy Policy, 2001, 29: 327-334.

[22]. Perz, S. G., Sustainable development: The promise and perils of roads, Nature, 2014, 513: 178–179.

[23]. Peters, G. P., Marland, G., Le Quéré, C., Boden, T., Canadell, J. G. and Raupach, M. R., Rapid growth in CO2 emissions after the 2008–2009 global financial crisis, Nature Climate Change,

2012, 2 (1): 2-4.

[24]. Raupach, M. R., Marland, G., Ciais, P., Le Quere, C., Canadell, J. G., Klepper, G. and Field, C. B., Global and regional drivers of accelerating CO2 emissions, PNAS, 2007, 104(24): 10288-10293.

[25]. Stratfor, The PC16: Identifying China's Successors, 2013, Stratfor publication, United States.

[26]. Thangavelu, S. R., Khambadkone, A. M., Karimi, I. A., Long-term optimal energy mix planning towards high energy security and low GHG emission, Applied Energy, 2015, 154(18): 959–969.

[27]. Tokimatsu, K., Yasuoka, R., Nishio, M., Global zero emissions scenarios: The role of biomass energy with carbon capture and storage by forested land use, Applied Energy, 2016, forthcoming, http://doi:10.1016/j.apenergy.2015.11.077.

[28]. Tukker A. and Dietzenbacher, E., Global multiregional input-output frameworks: An introduction and outlook, Economic Systems Research, 2013, 15(1): 1-19.

[29]. Wiedmann, T., A review of recent multi-region input–output models used for consumption-based emission and resource accounting, Ecological Economics, 2009, 69(2): 211–222.

[30]. Wise, M., Dooley, J., Luckowa, P., Calvina, K., Kylea, P., Agriculture, land use, energy and carbon emission impacts of global biofuel mandates to mid-century, Applied Energy, 2014, 114(3): 763–773.

[31]. World Bank, Population Estimates and Projections, 2014, World Bank Publication, Geneva, Switzerland, available at datatopics.worldbank.org/hnp/popestimates.

[32]. Zhang, W., Peng, S., Sun, C., CO_2 emissions in the global supply chains of services: An analysis based on a multi-regional input–output model, Energy Policy, 2015, 86: 93–103.

Appendix table A. Region and Sector list

No.	Region	Country group	No.	Sector
1	Australia	Annex B	1	Agriculture, Hunting, Forestry and Fishing
2	Austria	Annex B	2	Mining and Quarrying
3	Belgium	Annex B	3	Food, Beverages and Tobacco
4	Bulgaria	Annex B	4	Textiles and Textile Products
5	Brazil	non-Annex B	5	Leather, Leather and Footwear
6	Canada	Annex B	6	Wood and Products of Wood and Cork
7	China	non-Annex B	7	Pulp, Paper, Paper , Printing and Publishing
8	Cyprus	Annex B	8	Coke, Refined Petroleum and Nuclear Fuel
9	Czech Rep.	Annex B	9	Chemicals and Chemical Products
10	Germany	Annex B	10	Rubber and Plastics
11	Denmark	Annex B	11	Other Non-Metallic Mineral
12	Spain	Annex B	12	Basic Metals and Fabricated Metal
13	Estonia	Annex B	13	Machinery, Nec
14	Finland	Annex B	14	Electrical and Optical Equipment
15	France	Annex B	15	Transport Equipment
16	United Kingdom	Annex B	16	Manufacturing, Nec; Recycling
17	Greece	Annex B	17	Electricity, Gas and Water Supply
18	Hungary	Annex B	18	Construction
19	Indonesia	non-Annex B	19	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel
20	India	non-Annex B	20	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles
21	Ireland	Annex B	21	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods
22	Italy	Annex B	22	Hotels and Restaurants
23	Japan	Annex B	23	Inland Transport
24	South Korea	Annex B	24	Water Transport
25	Lithuania	Annex B	25	Air Transport
26	Luxembourg	Annex B	26	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies
27	Latvia	Annex B	27	Post and Telecommunications
28	Mexico	non-Annex B	28	Financial Intermediation
29	Malta	Annex B	29	Real Estate Activities
30	Netherlands	Annex B	30	Renting of M&Eq and Other Business Activities
31	Poland	Annex B	31	Public Admin and Defence; Compulsory Social Security
32	Portugal	Annex B	32	Education

33	Romania	Annex B	33	Health and Social Work
34	Russia	Annex B	34	Other Community, Social and Personal Services
35	Slovakia	Annex B	35	Private Households with Employed Persons
36	Slovenia	Annex B		
37	Sweden	Annex B		
38	Turkey	Annex B		
39	Taiwan	non-Annex B		
40	United States	Annex B		
41	Rest of World	non-Annex B		