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Decomposition analysis of energy-related CO_2 emissions in South Africa

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Abstract
South Africa has become one of the most developing countries in the world, and its economic growth has occurred along with rising energy-related CO_2 emission levels. A deeper understanding of the driving forces governing energy-related CO_2 emissions is very important in formulating future policies. The LMDI (Log Mean Divisia Index) method is used to analyse the contribution of the factors which influence energy-related CO_2 emissions in South Africa over the period 1993-2011. The main conclusions drawn from the present study may be summarized as follows: the energy intensity effect plays the dominant role in decreasing of CO_2 emission, followed by fossil energy structure effect and renewable energy structure effect; the economic activity is a critical factor in the growth of energy-related CO_2 emission in South Africa.

Keywords: CO_2 emission; LMDI method; South Africa

1. Introduction

Currently, global warming is considered among the most important environmental problems. Accelerating use of fossil fuels cause a significant increase in the anthropogenic greenhouse gases (GHG), which lead to global warming? Among six kinds of GHG, the largest contribution to the greenhouse effect is carbon dioxide (CO_2), and its share of the greenhouse effect is about 56% (IPCC, 2014). Thus, the acceleration of CO_2 emission with regard to ever-increasing energy consumption has raised the concern of energy analysts and policy makers.

South Africa has become one of the most developing countries in the world, and its economic growth has occurred along with rising energy-related CO_2 emission levels. It took the bold step at the end of 2009 to commit itself to the Secretariat of the United Nations Framework Convention on Climate Change (UNFCCC) in taking all the necessary actions to decrease the country's greenhouse gas emissions by 34% to below the 'business-as-usual' scenario by 2020 (Winkler *et al.*, 2010). A deeper understanding of the driving forces governing energy-related CO_2 emission is very important in formulating future policies. To accomplish this purpose, a robust approach is to decompose the evolution of energy-related CO_2 emission into possible affecting factors.

Nowadays, the Index Decomposition Analysis (IDA) technique has been used successfully to quantify the impact of different factors on the change of energy consumption and CO_2 emission. In the literature, two well-known IDA decomposition techniques, namely the Laspeyres index decomposition analysis and the Divisia index decomposition analysis, have been widely applied (Wang *et al.* 2011). So far many researchers have utilized the IDA method to identify the driving factors influencing the variation of energy consumption or related CO_2 emission. Based on the Laspeyres index decomposition analysis, an analysis had been made of energy consumption, efficiency and savings in China in the period 1980–94 by Sun (1998). The Laspeyres index decomposition analysis is also utilized by Reddy and Ray (2010) to study energy consumption and energy intensity in Indian manufacturing industries. Wang *et al*. (2005) applied the logarithmic mean Divisia index approach to study the influencing factor of the energy-related CO_2 emission. The LMDI technique was also utilized by Tan *et al*. (2011) to examine the driving forces for reducing China's CO_2 emission intensity between 1998 and 2008.

The IDA method has been generalized to a different method, but there is no consensus among all IDA methods as to which is the `best' decomposition method. Ang (2004) compared various methods and their advantages and disadvantages and concluded that the LMDI method was the preferred method, due to its theoretical foundation, adaptability, ease of use and result interpretation, along with some other desirable properties in the context of decomposition analysis.

Currently, several studies have focused on energy consumption in South Africa. For example, Inglesi-Lotz and Blignaut (2011) conducted a sectoral decomposition analysis of the electricity consumption for the period 1993–2006 to determine the main drivers responsible for its increase. Inglesi-Lotz and Pouris (2012) examined the factors affecting the trends in energy efficiency in South Africa from 1993 to 2006 and particularly the impact of structural changes and utilization efficiency of the country's energy intensity. So far no study has been devoted to decomposing the energy-related CO_2 emission in South Africa. To deeper understand the driving forces governing energy-related CO_2 emission, this paper serves as a preliminary attempt to apply the LMDI method to analyse the contribution of the factors which influence energy-related CO_2 emission in South Africa over the period 1993-2011.

The remainder of this paper is organized as follows. The next section presents the methodologies of the study and related data. The decomposition results of CO_2 emission is presented in section 3. Finally, we conclude this study.

2. Methodology and data

In the first place, the method of estimation of CO_2 emission is presented in this section. Then we give the definition of effect factor and LMDI model formulation. In this paper, economic activity is measured by GDP (Gross Domestic Product), which is collected from SJGDP (2013).

The symbol definitions are as follows.

C^t: total CO_2 emission in year t (in Million tons (Mt));

C_i^t: total CO_2 emission based on fuel type i in year t;

E_i^t: total energy consumption of the fossil fuel type i in year t;

E_f^t: total fossil energy consumption in year t;

E^t: total energy consumption in year t;

$EF_i^t = C_i^t / E_i^t$: carbon emissions factor of the *ith* fuel in year t;

O_i: the fraction of carbon oxidized based on fuel type i;

M: the molecular weight ratio of carbon dioxide to carbon (44/12);

GDP^t : the value added in year t;

$EI^t = E^t / GDP^t$: the energy intensity in year t;

$ES_i^t = E_i^t / E_f^t$: the share of *i*th energy form to total energy consumption in year t;

$FS^t = E_f^t / E^t$: the share of fossil energy share to total energy consumption in year t.

2.1 Estimation of CO_2 emission

Following the method given by the IPCC (2014), total CO_2 emission from fuel combustion is estimated based on energy consumption, carbon emission factors by fuel as follows.

$$C^t = \sum_i C_i^t = \sum_i E_i^t \times EF_i^t \times O_i \times M \quad (1)$$

The carbon emission factors for different fuel type are calculated based on the data given by IPCC, as listed in Table 1. These carbon emission factors have changed over time because of a change in grade of fuel. Because the study period 1993-2011 analysed in this paper is relatively short term, this paper assumes that the carbon emission factors of all energy forms are constant. Only three fuel types are considered in this paper, namely Oil, Coal, and Natural gas. The unit for energy is million ton oil equivalents (Mtoe). All energy data is collected from Statistical Review of World Energy (2012).

Table 1: Carbon emission factors and fractions of carbon oxidized
Source: IPPC (2014)

Fuel type	*Oil*	*Coal*	*Natural gas*
Carbon emission factor (Unit: Mt Carbon/Mtoe)	0.832	1.068	0.633
Fraction of carbon oxidized (Unit: %)	0.98	0.9	0.99

2.2 LMDI model formulation

The energy-related CO_2 emission in year () can be expressed as Eq. (2)

$$C^t = \sum_i C_i^t = \sum_i \frac{C_i^t}{E_i^t} \times \frac{E_i^t}{E_f^t} \times \frac{E_f^t}{E^t} \times \frac{E^t}{GDP^t} \times GDP^t = \sum_i EF_i^t \times ES_i^t \times FS^t \times EI^t \times GDP^t \quad (2)$$

According to the LMDI method given by Ang

(2004), the change of CO_2 emission between a base year 0 and a target year t, denoted by ΔC^t_{tot}, can be decomposed into the following determinant factors:

(i) The economic activity effect (denoted by ΔC^t_{gdp}), which is defined as the total produced value added (GDP) from South Africa (measured in ZAR), reflecting changes in the development of economy (namely the theoretical CO_2 emission caused by economic activities).

(ii) The energy intensity effect (denoted by ΔC^t_{ei}), which is defined as the ratio of energy consumption to produced value added, reflecting changes in some variables like energy prices, energy conservation and energy-saving investments.

(iii) The fossil energy structure effect (denoted by ΔC^t_{es}), which is defined as the ratio of fossil energy forms to total fossil energy consumption, reflecting changes in the relative shares of different fossil energy type;

(iv) The renewable energy structure effect (denoted by ΔC^t_{fs}), which is defined as the ratio of total fossil energy consumption to total energy use, reflecting changes in the relative shares of renewable energy use;

(v) The emission-factor effect (denoted by ΔC^t_{ef}), which is defined by the ratio of CO_2 emission and energy consumption, reflecting changes in the fuel substitution, fuel quality and the installation of abatement technologies.

Thus, based on the LMDI method developed by Ang (2004), the difference ΔC^t_{tot} is decomposed into its components in additive form, as illustrated in Eq. (3):

$$\Delta C^t_{tot} = \Delta C^t_{gdp} + \Delta C^t_{ei} + \Delta C^t_{es} + \Delta C^t_{fs} + \Delta C^t_{ef} \quad (3)$$

Each effect in the right hand side of Eq. (5) can be computed as follows:

$$\Delta C^t_{gdp} = \sum_i L(C^t_i, C^0_i)\ln(\frac{GDP^t}{GDP^0}) \quad (3a)$$

$$\Delta C^t_{ei} = \sum_i L(C^t_i, C^0_i)\ln(\frac{EI^t}{EI^0}) \quad (3b)$$

$$\Delta C^t_{es} = \sum_i L(C^t_i, C^0_i)\ln(\frac{ES^t_i}{ES^0_i}) \quad (3c)$$

$$\Delta C^t_{fs} = \sum_i L(C^t_i, C^0_i)\ln(\frac{FS^t}{FS^0}) \quad (3d)$$

Because this paper assumes that the carbon emission factors (*EF*) of all energy forms are constant during the study period. The value of following formula (3e) is 0.

$$\Delta C^t_{ef} = \sum_i L(C^t_i, C^0_i)\ln(\frac{EF^t_j}{EF^0_j}) \quad (3e)$$

Here, $L(C^t_{ij}, C^0_{ij}) = \dfrac{C^t_{ij} - C^0_{ij}}{\ln C^t_{ij} - \ln C^0_{ij}}$.

In the index number, we form

$$(\frac{\Delta C^t_{gdp}}{\Delta C^t_{tot}} + \frac{\Delta C^t_{ei}}{\Delta C^t_{tot}} + \frac{\Delta C^t_{es}}{\Delta C^t_{tot}} + \frac{\Delta C^t_{fs}}{\Delta C^t_{tot}} + \frac{\Delta C^t_{ef}}{\Delta C^t_{tot}}) \times 100\% = 100\% \quad (4)$$

3. Results and discussion

Findings obtained from the decomposition analysis are shown in Table 2 and Figure 1. The components of the decomposition analysis, i.e. ΔC^t_{gdp} (economic activity effect), ΔC^t_{es} (fossil energy structure effect), ΔC^t_{ei} (energy intensity effect), ΔC^t_{fs} (renewable energy structure effect) and ΔC^t_{ef} (emission-factor effect) are calculated as given in Eqs. (3a-e), respectively. Our results show that energy intensity effect, fossil energy structure effect and renewable energy structure effect are the factors in decreasing energy-related CO_2 emission in South Africa. However, the economic activity effect plays a positive impact on the growth of energy-related CO_2 emission.

During the study period, the energy intensity effect played the dominant role in decreasing of CO_2 emission, followed by energy structure effect and fossil energy structure effect. The accumulated (period-wise) effect is a decrease of 66.28Mt, which accounts for 49.16% of the total change in absolute value. The change of South Africa's energy intensity for the study period is presented in Figure 2, illustrating a general decrease in energy intensities. The trend of energy intensity has three stages. The first stage is 1993-2002; in this stage the trend of energy intensity shows an inverted U-shape, and the energy intensity reached the highest in 1997. The next stage is 2002-2005, that trend also shows a small inverted U-shape. The third stage is 2005-2011, the energy intensity decreased continuously in this stage. The decreasing trend of energy intensity can be due to the use of new process, new technologies and new equipment, especially the extensive application of energy-saving technologies and the advancement of management level (Inglesi-Lotz and Pouris; 2012). The above reason can explain

Table 2: Complete decomposition of energy-related CO_2 emission change (1993-2011) (Unit: Mt)

	ΔC^t_{es}	ΔC^t_{fs}	ΔC^t_{ei}	ΔC^t_{gdp}	ΔC^t_{tot}
1993-1994	-2.09	-2.24	8.88	9.01	13.56
1994-1995	-0.42	-0.39	6.77	9.21	15.17
1995-1996	-0.26	-0.51	3.40	13.37	16.01
1996-1997	-0.74	-1.01	2.48	8.50	9.24
1997-1998	-0.80	-0.46	-1.76	1.67	-1.34
1998-1999	0.69	1.14	-12.83	7.90	-3.10
1999-2000	-0.77	-0.67	-12.74	13.62	-0.56
2000-2001	0.82	1.21	-12.33	8.79	-1.51
2001-2002	-0.66	-0.93	-1.26	12.12	9.26
2002-2003	1.75	1.34	9.97	10.16	23.23
2003-2004	-1.49	-0.62	3.80	16.47	18.16
2004-2005	0.15	1.44	-26.43	19.33	-5.51
2005-2006	0.16	0.58	-14.42	20.47	6.80
2006-2007	-0.41	-0.80	0.39	21.00	20.19
2007-2008	3.11	2.10	1.51	14.55	21.28
2008-2009	-2.22	-2.11	-12.62	-6.28	-23.24
2009-2010	-0.58	0.33	-1.18	12.25	10.81
2010-2011	0.10	0.21	-7.89	13.98	6.40
1993-2011	-3.66	-1.37	-66.28	206.13	134.82

why the energy intensity effect decreased CO_2 emission over 1993-2011.

As shown in Table 2, the fossil energy structure effect was another factor decreasing CO_2 emission over the study period. The accumulated effect is a decrease of about 3.66Mt CO_2 emissions, which only accounted for 2.72% of the total CO_2 emission change in absolute value. The tendency of fossil energy consumption structure over time is shown in Figure 3. There is a substitution between the increasing share of natural gas (from 1.13% in 1993 to 3.12% in 2011) and a decreasing share of coal (from 76.90% in 1993 to 75.58% in 2011) (authors' calculation based on Statistical Review of World Energy, 2012). The use of natural gas increased from 0.92Mtoe in 1993 to 3.84Mtoe in 2011, following an annual growth rate of 8.21%. However, the share of natural gas to total fossil energy consumption accounted for less than 3.2% over the period 1993-2011. During the study period, more than 75.0% fossil energy was coal in South Africa, which can explain why the energy structure effect on CO_2 emissions was relative small.

Table 2 also indicates that the renewable energy structure effect played a very minor role in decreasing CO_2 emissions in 11 out of 19 years. The accumulated effect is a decrease of about 1.37Mt CO_2 emission, which only accounted for 1.02% of the

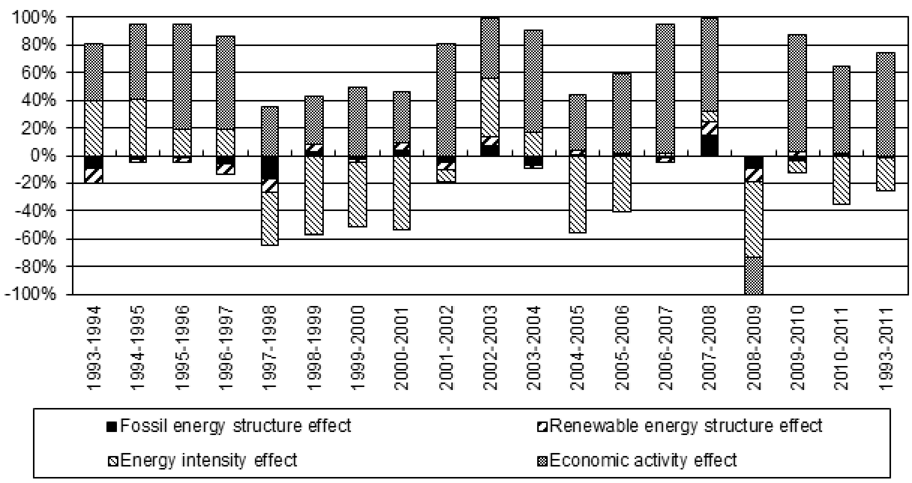

Figure 1: Complete decomposition of energy-related CO_2 emission change in percentage

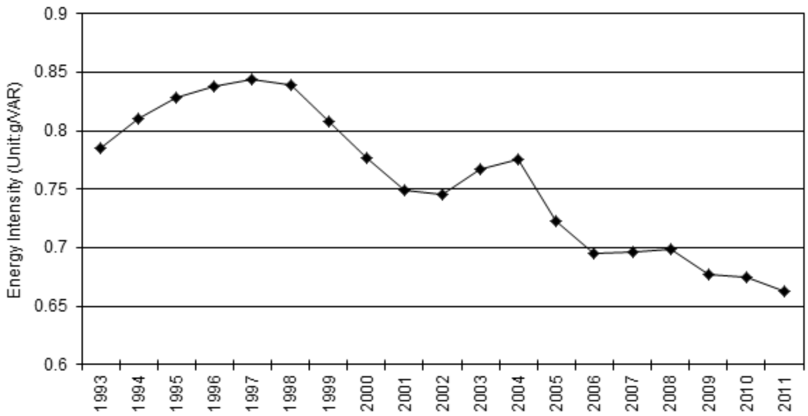

Figure 2: The change of South Africa's energy intensity over 1993-2011

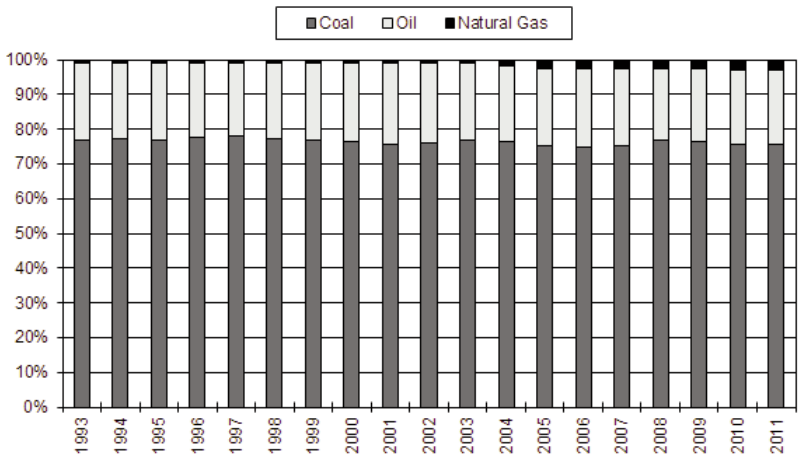

Figure 3: The tendency of fossil energy consumption structure over 1993-2011

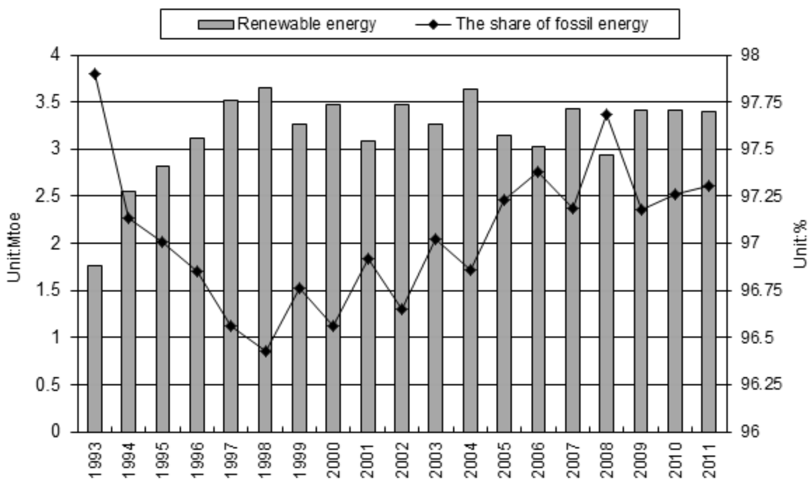

Figure 4: The tendency of the share of fossil energy consumption and renewable energy

total CO_2 emission change in absolute value. The tendency of the share of fossil energy consumption and renewable energy consumption over the period 1993-2011 is presented in Figure 4. During the study period, renewable energy consumption (including hydro power, nuclear power and other renewable energy) increased from 1.76Mtoe in 1993 to 3.39Mtoe in 2011, representing an annual average growth rate of 3.72%. That growth rate is faster than that of fossil energy (2.27%). Figure 4 also shows that the share of the fossil energy to total energy consumption declined from 97.89% in 1993 to 97.30% in 2011 (authors' calculation based on Statistical Review of World Energy, 2012). Though renewable energy increased quickly over 1993-2011, the decrease of the share of fossil energy was very small, which is the reason for the minor impact of renewable energy.

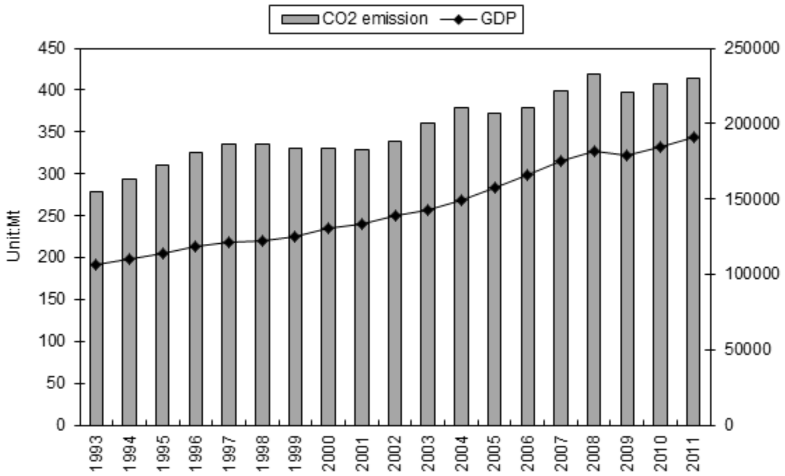

Figure 5: GDP and energy-related CO_2 emission in South Africa over 1993-2011

Our results show that economic activity is the critical factor in the growth of energy-related CO_2 emissions in South Africa. During 1993-2011, the economic activity effect made a continual increase of CO_2 emission except 2008-2009, as shown in Table 2. The accumulated (period-wise) effect is an increase of 206.13Mt, so accounts for about 152.89% of the total change in absolute value. The economic activity of South Africa (GDP) and energy-related CO_2 emissions are presented in Figure 5, which show an upward trend both in CO_2 emissions and GDP over this period. South Africa has experienced stable economic growth, with its GDP increasing at an average annual rate of about 3.27% over 1993-2011. Along with the economic development, energy –related CO_2 emission rose from 278.13Mt in 1993 to 414.32Mt in 2011, representing an annual average growth rate of 2.23%.

4. Conclusions

Global warming is considered among the most important environmental problems. How to relieve CO_2 emissions has become an urgent task of each country. South Africa has become one of the most developing countries in the world. Studying the driving forces governing energy-related CO_2 emissions may help to draw energy saving and a carbon reduction policy. Thus, the LMDI method is used to analyse the contribution of the factors which influence energy-related CO_2 emissions in South Africa over the period 1993-2011. The main conclusions drawn from the present study may be summarized as follows:

1. The energy intensity effect plays the dominant role in decreasing of CO_2 emissions, followed by the fossil energy structure effect and renewable energy structure effect; the economic activity is the critical factor in the growth of energy-related CO_2 emission in South Africa.
2. The change of South Africa's energy intensity illustrated a general decrease tendency during the study period, which also presented three different stages.
3. The tendency of the fossil energy consumption structure presented a substitution between the increasing share of natural gas and a decreasing share of coal during the study period. During the study period, renewable energy consumption increased faster than that of fossil energy.
4. During the 1993-2011, South Africa has experienced significant economic growth. Along with the economic development, energy–related CO_2 emission rose from 278.13Mt in 1993 to 414.32Mt in 2011.

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