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Is the CO_2 Emissions Reduction from Scale Change, Structural Change or Technology Change? Evidence from Non-metallic Sector of 11 Major Economies in 1995-2009

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Abstract: The contribution of non-metallic sector to global CO_2 emissions is increasing. However, there are very few studies on non-metallic sector CO_2 emissions from international comparative perspective. This paper proposes an integrated model employing LMDI (Logarithmic Mean Divisia Index) decomposition technique and TOPSIS (the Technique for Order Preference by Similarity to Ideal Solution) method to contribute to the existing literature by filling the gap that the drivers of aggregate and national level non-metallic sector CO2 emissions and its impacts on CO2 emissions reduction have not been estimated by relevant models. First, we analyze drivers of non-metallic sector CO_2 emissions in BRIC countries and G7 countries using LMDI decomposition method. Second, we evaluate the low-carbon development of non-metallic sector in the 11 major economies from a comprehensive viewpoint of main drivers using TOPSIS assessment model. Finally, based on the results of the model, this paper presents some implications for the non-metallic sector CO2 emissions reduction and low-carbon development.

Keywords: CO_2 emissions; Non-metallic sector; Cement; Logarithmic mean divisia index decomposition; WIOD database

1. Introduction

The contribution of non-metallic sector (Manufacture of non-metallic mineral products) to global CO_2 emissions is increasing. During 1971-2010, CO_2 emissions of global non-metallic sector have skyrocketed from 0.6 billion tons to 2.6 billion tons with an average annual growth rates of 3.8%, while the average annual growth rates of global CO_2 emissions was a mere 2%. Meanwhile, the share of CO_2 emissions from non-metallic sector in global CO_2 emissions achieved 7.7% by 2010 relative to 4% in 1971（Source: CDIAC and IEA Database）(Boden et al., 2013) . The cement industry plays a vital role in non-metallic sector CO_2 emissions. Fig.1 depicts the structure of non-metallic sector CO_2 emissions in 2010. The global cement process CO_2 emissions achieve 1.65 billion tons, accounting for 64% of the direct CO_2 emissions in global non-metallic sector.

There is substantial progress with respect to urbanization rate especially in developing countries, demanding for more additional new floor space, housing reconstruction, and urban transportation infrastructure. In addition, the economic growth in developing countries depends on investment drivers which are mainly relevant to infrastructure construction (Chari and Henry, 2014). This economic growth pattern results in huge demand for non-metallic sector, causing a mass of CO_2 emissions.

Understanding the drivers behind aggregate and national level non-metallic sector CO_2 emissions has important policy implications. Given the importance of low-carbon development on global emissions reduction, assessing the overall performance of low-carbon development in non-metallic sector is also relevant.

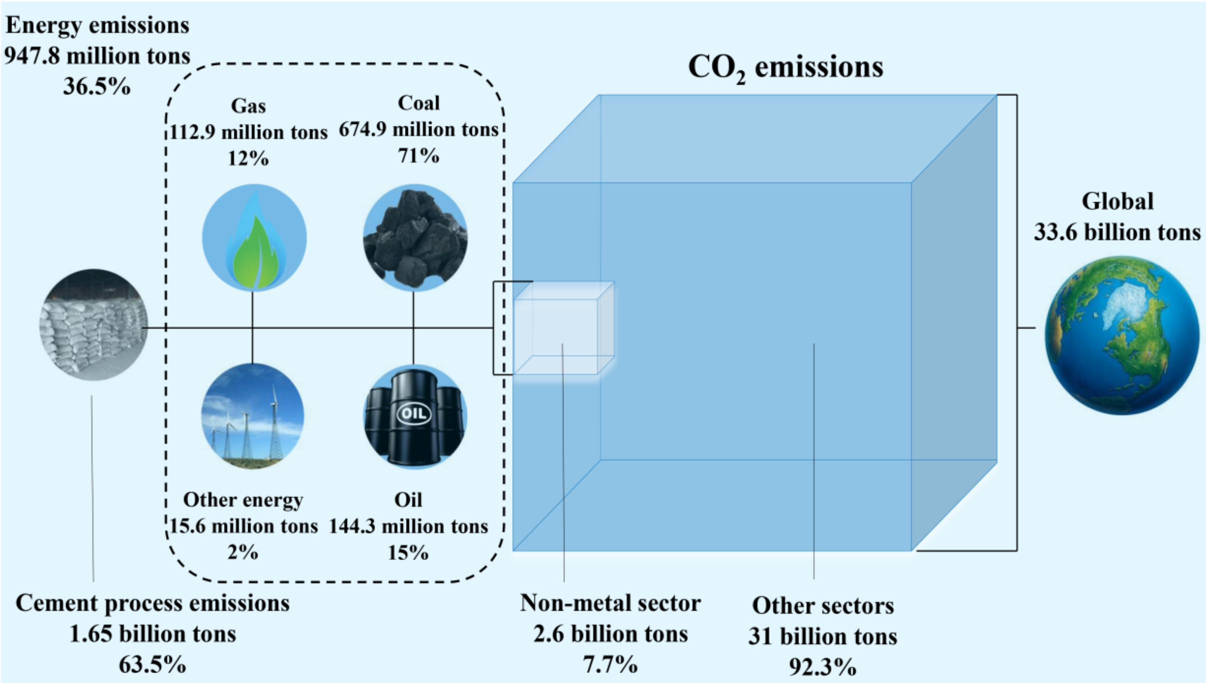


Fig.1. The global and non-metallic sector CO_2 emissions sources structure (in 2010).

However, to the best knowledge of the authors, there are very few studies on non-metallic sector CO_2 emissions from international comparative perspective using decomposition method. An important gap appear in the literature is that, apart from a few papers, the drivers of aggregate and national level non-metallic sector CO2 emissions and its impacts on non-metallic sector CO2 emissions reduction have not been estimated by relevant models. This paper proposes an integrated model employing LMDI decomposition techniques and TOPSIS assessment model to contribute to the existing literature by considering the gap.

Based on the data availability and regional distribution, 11 economies are chosen as research objects in this study, including four developing countries (namely Brazil, Russia, India and China), and seven developed countries (namely Canada, France, Germany, Italy, Japan, UK and U.S.). The reason why we choose BRIC and G7 countries is that these countries are important, in the sense that their non-metallic sector CO_2 emissions and cement process CO_2 emissions in 2010 account for 73.61% and 74.64% of that of the global pool, respectively.

This paper attempts to address three issues:

(1) What were the non-metallic sector CO_2 emissions trends of 11 major economies in 1995-2009?

(2) What are the performances of low-carbon development of non-metallic sector across countries in different time?

(3) Which were the main drivers accountable for non-metallic CO_2 emissions in aggregate and national level? What are the differences of main drivers across countries?

The remainder of this paper is structured as follows. Section 2 reviews the literature. Section 3 introduces the research framework and LMDI decomposition method and TOPSIS approach, and describes the collection and processing of data. Section 4 presents the results and discussions. Section 5 outlines the conclusions and policy implications for decision makers.

2. Literature review

2.1. Non-metallic sector energy use and CO_2 emissions

Due to the ever-increasing demand for infrastructure from emerging economies, the non-metallic sector, especially cement industry is now an issue drawing more and more attention in the context of global climate change (Ammenberg et al., 2015; Feiz et al., 2015a, b; Mi et al., 2016a, 2016b, 2015; Supino et al., 2016). Some research indicates the significance of non-metallic sector energy use in building energy use (Benhelal et al., 2013; Salas et al., 2016; Stafford et al., 2016). Zhang et al. (2015) applied life cycle approach to analyze China's building energy consumption and found that energy consumption of manufacturing building materials has boosted at a growth rate of 12.3% annually. In addition, suggested that energy efficiency of building materials, especially energy-intensive materials such as steel and cement, should be focused with preference. Oda et al. (2012) compared energy efficiency among countries in cement sector.

Non-metallic sector CO_2 emissions are the main source of construction and building CO_2 emissions, which mainly stems from building materials manufacturing stage according to some research (Ibn-Mohammed et al., 2013; Zhang and Wang, 2016). Giesekam et al. (2014) studied on the greenhouse gas emissions and mitigation options for materials used in UK construction, and identified the construction materials' low-carbon performance as a key to the UK's target of an 80% reduction in GHG emissions by 2050.

The cement industry plays an important role in non-metallic sector CO_2 emissions, where various actions are taken in a bid to reduce CO_2 emissions (Ishak and Hashim, 2015; Vargas and Halog, 2015). Wang et al. (2013) researched trajectory and drivers for GHG emissions in the cement industry in China and pointed out that the cement industry is important to low carbon development in China. Department of Energy and Climate Change (DECC) and Department for Business, Innovation and Skills (BIS), UK (2015) published the report *Industrial Decarbonisation And Energy Efficiency Roadmaps To 2050 – Cement*, and points out the key technology for emissions reduction including Electricity Grid Decarbonisation, Fuel and Feedstock Availability (including biomass), Energy Efficiency and Heat Recovery, Carbon Capture. UK Mineral Products Association (2013) pointed out that the UK cement industry aimed in 2013 to reduce greenhouse gases by 81% by 2050 and stressed that government should vigorously encourage cement production enterprises to use waste-derived fuels and biomass fuels. European Cement Association (2013) analyzed the role of cement industry in the 2050 low-carbon economy, indicating that most of the emissions in cement industry were from the decomposition of the materials itself. And in order to reach the 80% reduction in the cement sector suggested by the European Commission, 81Mt of CO_2 is yet to be eliminated with the assumption that 85% of total clinker production will need to be equipped with carbon capture and storage (CCS) technology.

2.2. LMDI method for CO_2 emissions decomposition analysis

Index decomposition analysis has been widely employed in energy consumption studies and firstly introduced to CO_2 emissions studies by Torvanger (1991) in his study about manufacturing sector CO_2 emissions of OECD countries. Xu & Ang (2013) conducted a literature survey of 80 publications using IDA method and found 45 percent papers of the sample used LMDI method. The results also showed that LMDI method allows more flexible decomposition with more drivers and indicated that researchers preferred the LMDI method to other decomposition methods. In addition, some publications revealed three advantages of LMDI method (Ang, 2004; Ang et al., 1998; Dietzenbacher and Los, 1998; Hoekstra and Van den Bergh, 2003; Kesicki, 2012; Sun, 1998): (1) Giving no residual. (2) Accommodating the value zero in the data set. (3) Low computational complexity relative to low-residual Adaptive Weighting Division (AWD).

LMDI decomposition method is a popular tool in the field of CO_2 emissions. Voigt et al. (2014) analyzed energy intensity trends and drivers in 40 major economies using the WIOD database and explored the role of structural change or technical progress in the energy intensity developments for different time and countries. Ren et al. (2014) studied the total CO_2 emissions from China's manufacturing industry during the period of 1996–2010 and explored the main drivers namely industry structure, energy structure, economic output, energy intensity, and emission factors, revealing four decoupling stages of China’s manufacturing industry. Wang et al. (2011) analyzed the transport sector CO_2 emissions over the period 1985–2009 and concluded that the transportation intensity effect and transportation services share effect played a significant role in CO_2 emissions reduction in China.

3. Methodology

3.1. Research framework

Energy Technology Perspectives 2015 was published by IEA (2015), and it outlines the important indicators of cement industry development, including cement production, energy intensity and fossil fuel structure, etc. In addition, the report shows that the share of cement process emissions in direct CO_2 emissions achieved 64% in global cement industry. Given the feature of CO_2 emissions in non-metallic sector, especially in cement industry ($B_{Total} = B_{Cement} + B_{Energy}$), this paper decomposes CO_2 emissions from cement process and energy combustion. By analyzing the decomposition at aggregate level, the main drivers of non-metallic sector CO_2 emissions of main economies are revealed. The multiple criteria decision making (MCDM) approach is also applied to discuss the overall low-carbon development of non-metallic sector in the 11 major economies. Based on the results of low-carbon development assessment, the authors classify the 11 economies under two categories and explore the differences of drivers at national level. Fig.2 illustrates the research framework in this study.

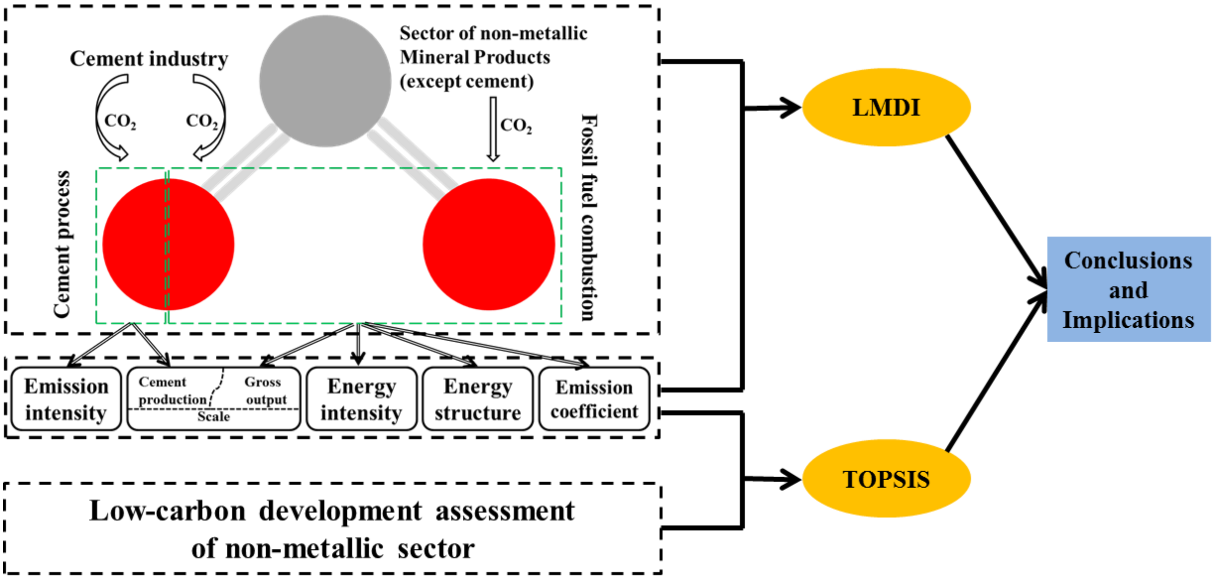


Fig.2. Research framework of CO_2 emissions decomposition from non-metallic sector.

3.2. LMDI decomposition method

3.2.1. CO_2 emissions from cement process

Based on the Kaya decomposition, we aggregate the total CO_2 emissions from cement process at time t across 11 countries:

$$B_C^t = \sum_i \frac{B_{Ci}^t}{P_i^t} \times \frac{p_i^t}{p^t} \times p^t = \sum_i S_i^t \times M_i^t \times P^t$$

(1)

Where:

B_C^t : aggregate total CO_2 emissions from cement process in Period t,

B_{Ci}^t : aggregate total CO_2 emissions from cement process in Period t, country i,

P_i^t : cement production in Period t, country i,

p^t : aggregate total cement production in Period t,

S_i^t : emission intensity in Period t, country i,

M_i^t : share of country i in aggregate total cement production in Period t,

The three factor additive decomposition of changes in aggregate total CO_2 emissions from cement process between Period t and Period $t+1$ is described by

$$\Delta B_C^{t+1} = B_C^{t+1} - B_C^t = \Delta B_C S^{t+1} + \Delta B_C M^{t+1} + \Delta B_C P^{t+1}$$

(2)

$\Delta B_C S^{t+1}$ is the estimated impact of emission intensity change on aggregate total CO_2 emissions in Period $t+1$. $\Delta B_C M^{t+1}$ is the estimated impact of cement production regional structural change in Period $t+1$ which can be explained by a change in the share of the corresponding country. $\Delta B_C P^{t+1}$ is the estimated impact of scale change in Period $t+1$, which can be explained by the cement production change on the aggregate level. The formulae for the log mean Divisia index decomposition are thus:

$$\Delta B_C S^{t+1} = \sum_i L(B_{Ci}^{t+1}, B_{Ci}^t) \ln(\frac{B_C S_i^{t+1}}{B_C S_i^t})$$

(3)

$$\Delta B_C M^{t+1} = \sum_i L(B_{Ci}^{t+1}, B_{Ci}^t) \ln(\frac{B_C M_i^{t+1}}{B_C M_i^t})$$

(4)

$$\Delta B_C P^{t+1} = \sum_i L(B_{Ci}^{t+1}, B_{Ci}^t) \ln(\frac{B_C P^{t+1}}{B_C P^t})$$

(5)

Where:

$$L(B_{Ci}^{t+1}, B_{Ci}^t) = \frac{B_{Ci}^{t+1} - B_{Ci}^t}{\ln(B_{Ci}^{t+1} / B_{Ci}^t)}$$

(6)

3.2.2. CO_2 emissions from fossil fuel combustion

Based on the Kaya decomposition, we aggregate total CO_2 emissions from fossil fuel combustion at time t across 11 countries:

$$B_E^t = \sum_{ij} \frac{B_{Eij}^t}{E_{ij}^t} \times \frac{E_{ij}^t}{E_i^t} \times \frac{E_i^t}{G_i^t} \times \frac{G_i^t}{G^t} \times G^t = \sum_{ij} F_{ij}^t \times T_{ij}^t \times I_i^t \times K_i^t \times G^t$$

(7)

Where:

B_E^t : aggregate total CO_2 emissions from fossil fuel combustion in Period t,

B_{Eij}^t : aggregate total CO_2 emissions from fossil fuel combustion in Period t, country i, fuel type j,

E_{ij}^{t}: energy use in Period t, country i, fuel type j,

E_{i}^{t}: total energy use in Period t, country i,

G_{i}^{t}: gross output in Period t, country i,

G^{t}: aggregate total gross output in Period t,

F_{ij}^{t}: CO_2 emission factor of fuel j, country i, Period t,

T_{ij}^{t}: energy mix ratio for fuel j, country i, Period t,

I_{i}^{t}: energy intensity for country i, Period t,

K_{i}^{t}: share of country i in aggregate total gross output in Period t,

The five factor additive decomposition of changes in aggregate total CO_2 emissions from fossil fuel combustion between the Period t and Period $t+1$ is described by

$$\Delta B_E^{t+1} = B_E^{t+1} - B_E^{t} = \Delta B_E F^{t+1} + \Delta B_E T^{t+1} + \Delta B_E I^{t+1} + \Delta B_E K^{t+1} + \Delta B_E G^{t+1}$$

(8)

$\Delta B_E F^{t+1}$ is the estimated impact of changes in the average emission factor of energy use on aggregate total CO_2 emissions from fossil fuel combustion in Period $t+1$, for country i, fuel type j. $\Delta B_E T^{t+1}$ is the estimated impact of energy structural change in Period $t+1$ which can be explained by a change in the share of the corresponding fuel type j, country i. $\Delta B_E I^{t+1}$ is the estimated impact of energy intensity change in Period $t+1$. $\Delta B_E K^{t+1}$ is the estimated impact of gross output regional structural change in Period $t+1$ which can be explained by a change in the share of the corresponding country. $\Delta B_E G^{t+1}$ is the estimated impact of scale change in Period $t+1$, which can be explained by the gross output change at aggregate level. The formulae for the log mean Divisia index decomposition are thus:

$$\Delta B_E F^{t+1} = \sum_{ij} L(B_{Eij}^{t+1}, B_{Eij}^{t}) \ln(\frac{B_E F_{ij}^{t+1}}{B_E F_{ij}^{t}})$$

(9)

$$\Delta B_E T^{t+1} = \sum_{ij} L(B_{Eij}^{t+1}, B_{Eij}^{t}) \ln(\frac{B_E T_{ij}^{t+1}}{B_E T_{ij}^{t}})$$

(10)

$$\Delta B_E I^{t+1} = \sum_{ij} L(B_{Eij}^{t+1}, B_{Eij}^{t}) \ln(\frac{B_E I_i^{t+1}}{B_E I_i^{t}})$$

(11)

$$\Delta B_E K^{t+1} = \sum_{ij} L(B_{Eij}^{t+1}, B_{Eij}^{t}) \ln(\frac{B_E K_i^{t+1}}{B_E K_i^{t}})$$

(12)

$$\Delta B_E G^{t+1} = \sum_{ij} L(B_{Eij}^{t+1}, B_{Eij}^{t}) \ln(\frac{B_E G^{t+1}}{B_E G^{t}})$$

(13)

Where:

$$L(B_{Eij}^{t+1}, B_{Eij}^{t}) = \frac{B_{Eij}^{t+1} - B_{Eij}^{t}}{\ln(B_{Eij}^{t+1} / B_{Eij}^{t})}$$

(14)

Given the combination of above two aspects, CO_2 emissions in non-metallic sector can be expressed in the following form:

$$\begin{aligned} B_{Total} &= B_{Cement} + B_{Energy} \\ &= \left(\Delta B_C S^{t+1} + \Delta B_C M^{t+1} + \Delta B_C P^{t+1}\right) + \left(\Delta B_E F^{t+1} + \Delta B_E T^{t+1} + \Delta B_E I^{t+1} + \Delta B_E K^{t+1} + \Delta B_E G^{t+1}\right) \end{aligned}$$

(15)

Due to the cement production and gross output driving the sector scale, the scale effect is expressed as follows

$$\Delta BC^{t+1} = \Delta B_C P^{t+1} + \Delta B_E G^{t+1}$$

(16)

Due to the cement production regional structure and gross output regional structure driving the sector regional structural changes, the regional structural effect is expressed as follows

$$\Delta BD^{t+1} = \Delta B_C M^{t+1} + \Delta B_E K^{t+1}$$

(17)

So, the formulae for six factor additive decomposition is described by

$$B_{Total} = \Delta BC^{t+1} + \Delta BD^{t+1} + \Delta B_C S^{t+1} + \Delta B_E F^{t+1} + \Delta B_E T^{t+1} + \Delta B_E I^{t+1}$$

(18)

3.3. Technique for order preference by similarity to an ideal solution

TOPSIS was first proposed by Hwang and Yoon (1981) to determine the best alternative by embracing the concept of the compromising solution. The principle of the compromising solution is to choose the solution with the shortest Euclidean distance from the positive ideal solution and the farthest Euclidean distance from the negative ideal solution (Mi et al., 2014; Wang et al., 2014).

This research explores the non-metallic sector CO_2 emissions in 11 main economies over 15 years. A set of alternatives can be expressed as $X=\{x_1,x_2,...,x_i,...,x_m\}$ （$m=11\times15$）. Based on the drivers from LMDI decomposition, this study chooses five cost-effective criteria (smaller is better), namely CO_2 emissions per cement production, energy structure (the share of conventional energy consumption), energy intensity (energy consumption per gross output of non-metallic sector), cement process CO_2 emissions, energy combustion CO_2 emissions in non-metallic sector. a set of criteria can be therefore described as $Y=\{y_1,y_2,y_3,y_4,y_5\}$. where $Z=\{y_{i1},y_{i2},y_{i3},y_{i4},y_{i5}\,|\,i=1,...,165\}$ denotes the set of performance ratings and $W=\{w_1,w_2,w_3,w_4,w_5\}$ is the set of weights. In this research, five criteria have been given the same weight with a fair consideration. Applying the procedures of TOPSIS, the low-carbon development assessment indicator can be derived as: $N_i^*=l_i^-/\left(l_i^-+l_i^+\right)$, $i=1,...,m$, where l_i^- is the separation from the negative ideal solution and l_i^+ is the separation from the positive ideal solution. Finally, the preferred orders can be obtained by ranking the N_i^* scores where a higher value shows a country with better performances in low-carbon development in non-metallic sector.

3.4. Data collection and processing

The main data source for gross output of non-metallic sector (a key indicator) is the newly released World Input–Output Database (WIOD), so the period of 1995-2009 is selected in this research. Energy intensity can be defined as the ratio between energy use and value-added. There is also another justified form that the ratio between energy use and gross output. However, with the theoretical as well as practical reasons from some references, the use of gross output is selected in our context (Diewert, 1973; Gollop et al., 1987; Voigt et al., 2014).

The data of cement process CO_2 emissions come from the Carbon Dioxide Information Analysis Center (CDIAC). The data of non-metallic sector CO_2 emissions from the energy combustion come from WIOD database, where the code of non-metallic sector is 26 (Other non-metallic Mineral). The authors summarize sources of fossil fuel emissions as four categories: coal, oil, natural gas and other. And the CO_2 emissions from cement process and energy combustion are summed up to get the data of total non-metallic sector CO_2 emissions. The data of cement production is included in U.S. Geological Survey (USGS). The relevant data about energy use and gross output of non-metallic sector are included in the Environmental Accounts and Socio Economic Accounts which are satellite accounts to the WIOD database (Timmer et al., 2012; Timmer et al., 2015). The raw data of gross output (GO) are expressed in monetary units in basic 1995 prices applying price deflators and converted to million US$ (1995) using market exchange rates.

4. Results and discussions

4.1. Aggregate level CO_2 emissions from non-metallic sector between 1995 and 2009

At the aggregate level, the trend of non-metallic sector CO_2 emissions can be described clearly as two stages. First, the period of 1995-2002 is a moderate growing stage with an average annual growth rates of 1.4%. Second, the period of 2002-2009 is a rapid growing stage where non-metallic sector CO_2 emissions skyrocketed from 1.02 billion to 1.813 billion with an average annual growth rates of 8.6%. Fig.3(a) illustrates the non-metallic sector CO_2 emissions structure that the share of cement process emissions is over 50% and counting. This structural change may be one important reason responsible for the faster growth of CO_2 emissions.

During1995-2009, with the increasing trend of gross output and CO_2 emissions in non-metallic sector, CO_2 emissions per gross output follows a growth trajectory (Fig.3(b)). With the decrease of gross output in non-metallic sector, the CO_2 emissions intensity exhibits the increasing trend, while the authors obtain the two performances of CO_2 emissions intensity change under the condition of gross output increasing. On the one hand, as the growth rate of gross output relative to the year before was smaller than the growth rate of CO_2 emissions in the year of 2003, 2004, 2006 and 2008, the CO_2 emissions intensity became higher than the year before. On the other hand, the CO_2 emissions intensity was relatively small, when the growth rate of gross output compared the year before was higher than the growth rate of CO_2 emissions, as is shown in the year of 2005 and 2007.

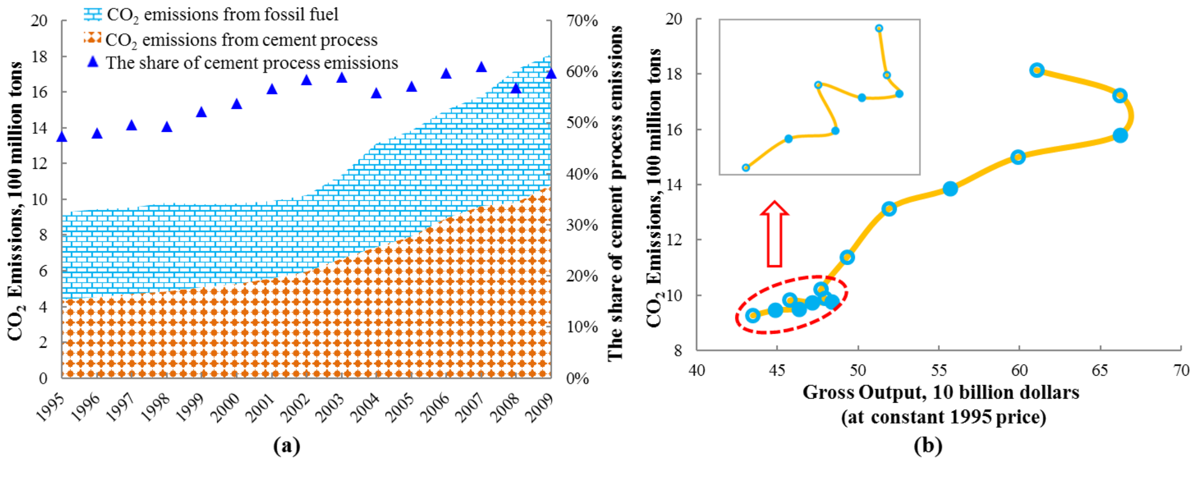


Fig.3. CO_2 emissions structure and emission intensity on the aggregate level (1995-2009).

Notes: (1) Fig.3. (a) depicts the CO_2 emissions from 1995 to 2009. (2) Fig.3. (b) describes the relationship between CO_2 emissions and Gross Output from 1995 to 2009. Solid dots denote that the CO_2 emissions per gross output (CO_2 emissions intensity) was smaller than the year before, and hollow dots denote that the CO_2 emissions intensity became higher than the year before.

4.2. National level CO_2 emissions from non-metallic sector between 1995 and 2009

On the national level, there are obvious differences in the trends of non-metallic sector CO_2 emissions between developing countries and developed countries, as is shown in Fig.4. The trends of non-metallic sector CO_2 emissions in developing countries are presented as increasing, while the trends of developed countries are in low level, with the falling trend derived from the financial crisis in 2008.

The trajectory of non-metallic sector CO_2 emissions of China is on a high level. We observe two phases with respect to growth of China's non-metallic sector CO_2 emissions, with the demarcation point being the year of 2002. The first phase (during 1995-2002) witnessed an increase in CO_2 emissions in a moderate trend with an average annual CO_2 emissions growth rate of 1.41%. In second phase, during 2002-2009, the CO_2 emissions grew more rapidly with an average annual growth rates of 12.89%, which was basically due to a large number of infrastructure construction started since 2002.

Fig.4(b) shows the decrease of non-metallic sector C O_2 emissions in developed countries after the financial crisis in 2008. By observing the trend of the 7 sample countries, we group developed countries in the three categories presented as follows. First, CO_2 emissions for U.S. with a high emission level and low growth rates. Second, CO_2 emissions for Japan with a high emission level and a declining trend. Third, CO_2 emissions for countries with low emission levels and moderate trends.

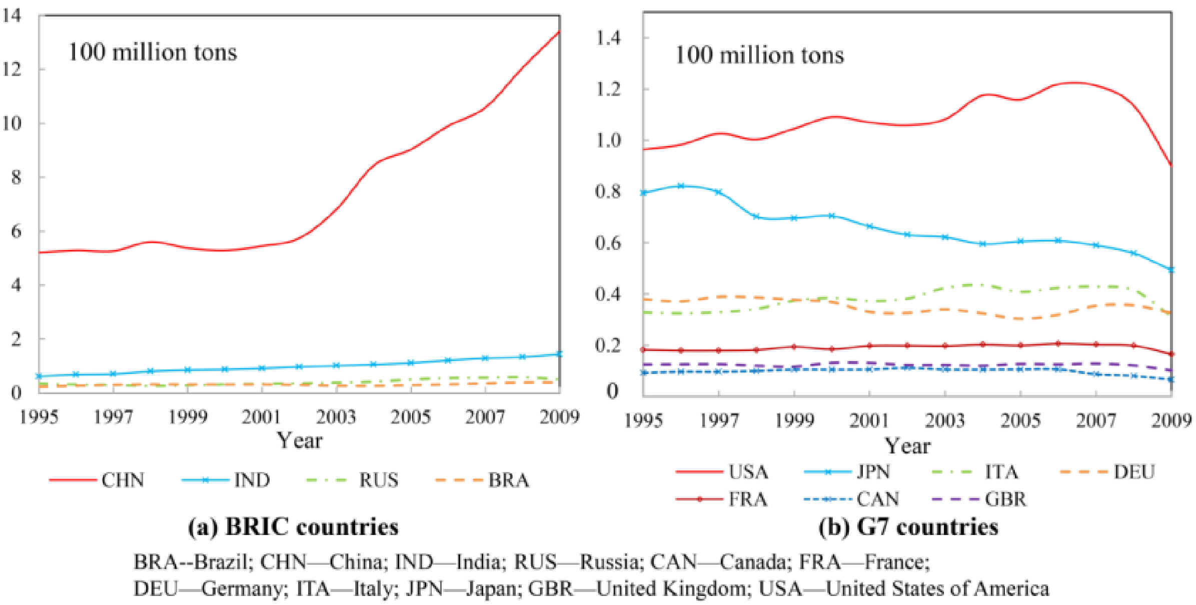


Fig.4. CO_2 emissions developments during 1995-2009.

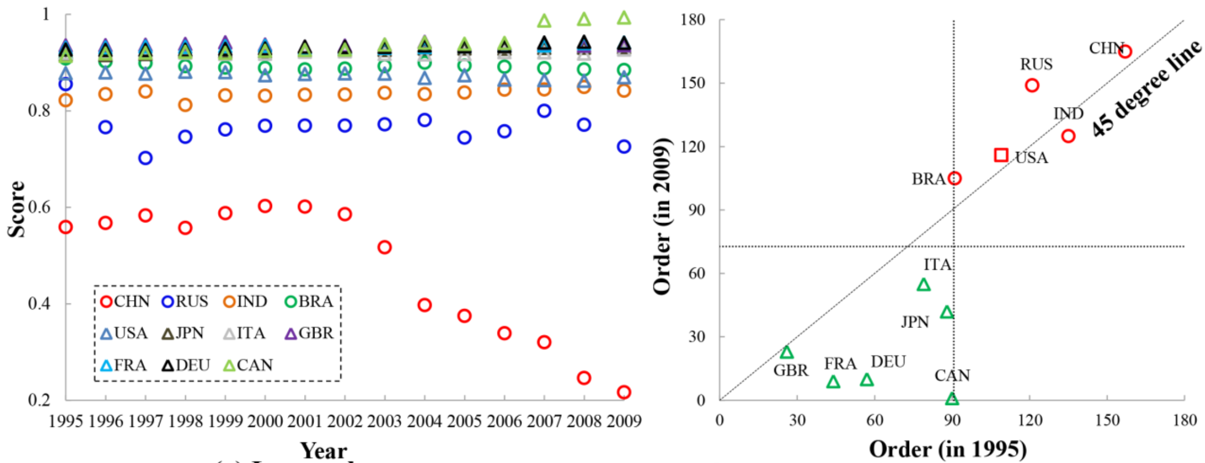
4.3. Low-carbon development assessment of non-metallic sector

By employing TOPSIS method, the authors evaluate the performance of low-carbon development in non-metallic sector amidst the 11 studied countries during 15 years. The results are presented in Fig.5(a).

Based on the performance scores of the national dimension, we conclude the differences among 11 countries. First, on average, developed countries perform better than developing countries. Canada is in the leader position potentially due to its advantages of a cleaner energy structure. During 1995-2009, with the decrease trend, the Canada's share of conventional energy consumption declined to 40% by 2009. The average share of conventional energy consumption of Canada was around 74%, relative to U.S.'s 85% and Japan's 78%. Second, Brazil seems to outperform other developing countries in terms of low-carbon, followed by India, Russia and China. We can observe that the performance of low-carbon development of Russia and China are obviously lower than developed countries, while the performance of Brazil is equal to developed countries' level. Coincidentally, results from the clean energy system (the average share of conventional energy consumption is about 57%), the average level of Brazil's scores is higher than U.S.

From perspective of time, the authors can obtain the variation and the volatility of performance scores from 1995 to 2009 for each countries. During 1995-2009, develop d countries and Brazil and India performed better，maintaining a good momentum. The performance scores of Russia are slightly lower than the developed countries with distinct volatility. The non-metallic sector of Canada got a good low-carbon trend and the performance scores increased visibly since 2007. This fact is supported by the cleaner energy structure and decreasing energy use per gross output in Canada. While China's low-carbon performance of non-metallic sector seems to relatively fall behind and deteriorated sharply since 2002. The reason for this is related to a rapid growth of CO_2 emissions in China resulting from a large number of infrastructure construction since 2002.

Combining the two dimensions, countries and time, the low-carbon development of non-metallic sector for 11 sample countries from 1995-2009 can be categorized in two, as is shown in Fig.5(b). First, U.S.-BRIC pattern (countries with poor performance). In the year of 1995 and 2009, the performance scores of U.S. and BRIC countries (Brazil, Russia, India and China) ranked below average. The ranks of U.S., Brazil, Russia and China in 2009 fell behind relative to the corresponding ranks in 1995, while the rank of India improved in 2009 relative to that in 1995. Second, developed countries pattern (countries with good performance). The G7 countries ranked above average except for U.S. during 1995-2009. In addition, the countries in this pattern have a better performance of ranking in 2009 than 1995. What is also worth noticing is that the low-carbon development in non-metallic sector of Canada is the benchmark in 2009 with the most palpable improvement.



(a) Low carbon score (b) Order correlation between 1995 and 2009

Fig.5. Low-carbon development assessment based on TOPSIS.

Notes: (1) The dotted lines divide sample countries into four groups according to whether they are located above or below the average rank in 1995 and 2009. (2) The 45 degree line identifies the countries with equal rank position in the two years.

4.4. Impact of regional structural change on aggregate level non-metallic sector CO_2 emissions fluctuation

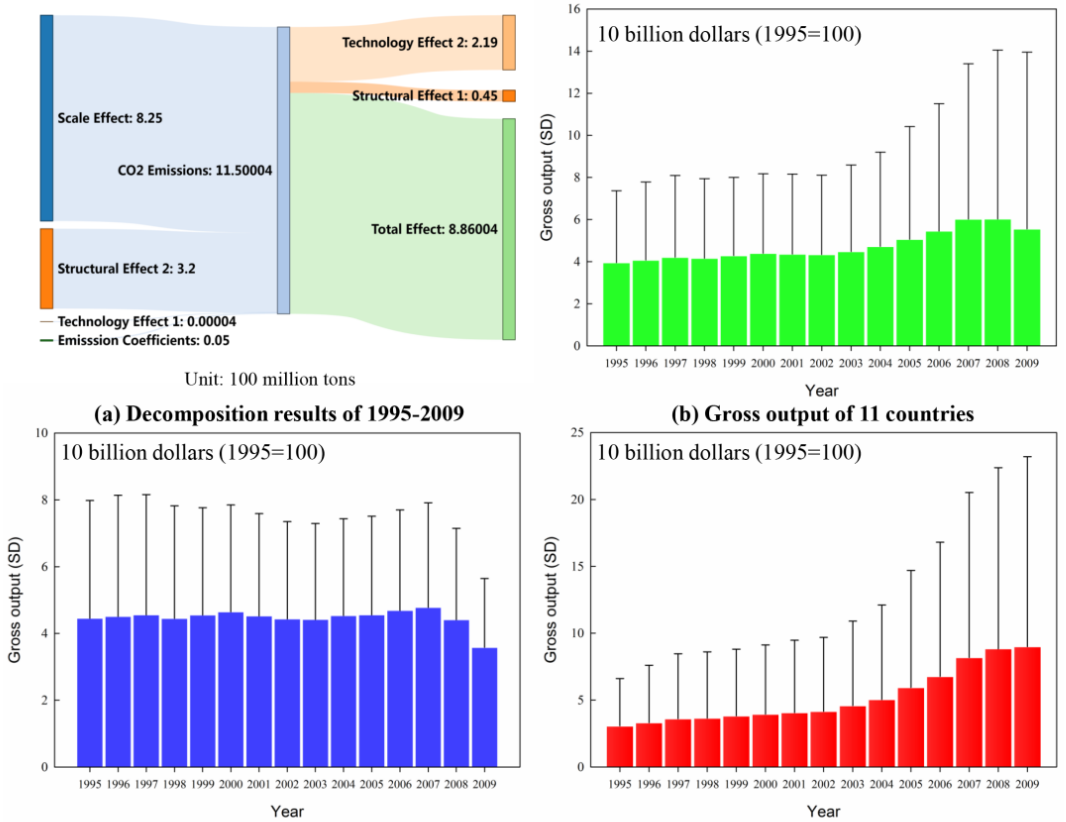
Fig.6 highlights the contribution of the scale effect, structural effect (including regional structure and energy structure) and technology effect (including energy use per gross output and CO_2 emissions per cement production) on aggregate level CO_2 emissions fluctuation. Based on the Eqs.(1) to (18), the authors present the decomposition results as follows.

The growth of non-metallic sector CO_2 emissions between 1995 and 2009 is described as Fig.6(a). The contribution from scale expansion and non-metallic industry transfer among countries is relatively higher. Energy use per gross output decreases results from technical progress, which results in obvious CO_2 emissions reduction. In addition, the effects of CO_2 emissions per cement production, CO_2 emission factor and energy structure are very limited.

The industry transfer in non-metallic sector draws the authors' attention. Fig.6(a) shows that the contribution of industry transfer to CO_2 emissions fluctuation from 1995 to 2009 is around 320 million tons. The volume is approximately equal to the accumulative non-metallic sector CO_2 emissions over the period of 1995-2009 in France (290 million tons), and also two times as much as the volume of Canada (150 million tons).

This analysis shows that regional structural change plays an important role in CO_2 emissions fluctuation on the aggregate level, suggesting that the trend of regional structure results from the transfer of gross output and cement production from developed countries to the BRIC countries, as is shown in Fig.6(b), (c) and (d). Looking at the transfer of gross output in non-metallic sector, the authors find that in the period of 1995-2009, the share of G7 countries' total gross output in aggregate has decreased from 72%

to 41%. For example, for countries with advanced technology such as U.S. and Japan, this share has declined by 7% and 14% respectively. However, China receives most plant capacity from G7 countries, improving the share of gross output in aggregate by 30%. Similarly, over the years between 1995 and 2009, the share of cement production of G7countries in aggregate has decreased by 21%. Conversely, the share of China has increased by 21.8%.



(a) Decomposition results of 1995-2009 (b) Gross output of 11 countries

(c) Gross output of developed countries (d) Gross output of BRIC countries

Fig.6. Regional structural change of gross output and aggregate level non-metallic sector CO2 emissions.

Notes:

(1)Technology effect 1 is CO_2 emissions per cement production change；Technology effect2 is energy use per gross output change；Structural effect 1 is energy structure change；Structural effect 2 is regional structural change.

(2) In the (b), (c) and (d), the bar heights presents the mean value of gross output and the error bars shows the standard deviation.

4.5. Influence of scale effect on CO_2 emissions fluctuation to the countries with poor performance

In this research, the authors find that scale effect is a main driver of the CO_2 emissions fluctuation to the underperforming countries with U.S.-BRIC pattern, as is shown in Fig.7(a).

Over the years of 1995 to 2009, the CO_2 emissions of China, India and Brazil increased sharply, which can be attributed mainly to the scale growing rapidly. However, there are some differences among the three countries, as is shown in Fig.7(b). For China and India, the CO_2 emissions reduction of non-metallic sector benefit from technical progress and energy structure change, while the climbing energy use per gross output and unreasonable energy structure result in the rising CO_2 emissions in Brazil.

The CO_2 emissions reduction in U.S. is mainly related to scale reduction. U.S. reduced approximately 6.5 million tons CO_2 emissions from non-metallic sector in the year of 2009, relative to the 1995 level. The contribution of scale reduction and cleansing of energy structure to the CO_2 emissions reduction were around 16 million tons and 4.6 million tons respectively.

For Russia, the non-metallic sector CO_2 emissions increase mainly due to the growth of energy use per gross output, while scale effects lead to slight CO_2 emissions reduction. Specifically, non-metallic sector CO_2 emissions in Russia increased by 16 million tons in 2009 relative to that in 1995. And 17 million tons CO_2 emissions increasing results from technology change. 0.87 million tons of CO_2 emissions reduction benefits from scale decreasing, while 0.74 million tons due to energy structure optimization.

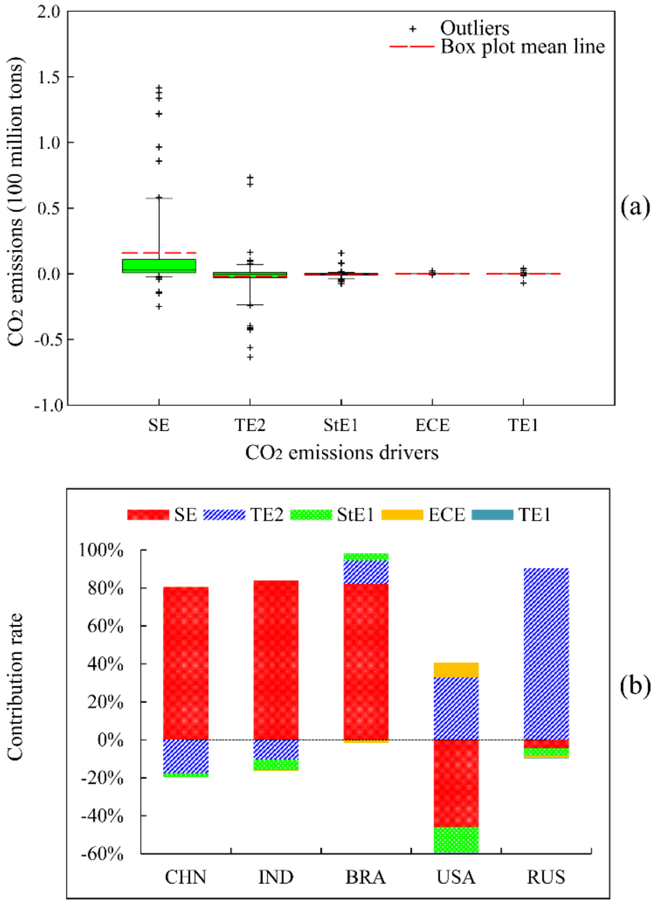


Fig.7. The LMDI decomposition of countries with poor performance.

Notes:

(1) SE is scale effect; TE1 (Technology effect 1) is CO_2 emissions per cement production change; TE2 (Technology effect2) is energy use per gross output change; ECE is emission coefficients effect; StE1 (Structural effect 1) is energy structure change.

(2) In Fig 7(a), the Box is sourced from the decomposition results of above 5 countries year by year in the period of 1995-2009.

(3) In Fig 7(b), the contribution rate is calculated according to the decomposition result of above 5 countries between 1995 and 2009.

4.6. Three patterns of CO_2 emissions reduction to the countries with good performance

During 1995-2009, the well-performing countries in terms of low-carbon development had a better trend of non-metallic sector CO_2 emissions reduction. Based on the decomposition results, the reduction pattern can be categorized in three, as is shown in Fig.8.

(1) United Kingdom, Germany and Japan achieve non-metallic sector CO_2 emissions reduction by scale reduction

United Kingdom, Germany and Japan reduced CO_2 emissions 2.35 million tons, 5.32 million tons and 30 million tons in 2009 respectively, relative to the 1995 level. The key driver of this reduction is scale reduction which has chopped CO_2 emissions by 2.8 million tons, 7.13 million tons and 31.63 million tons respectively for the three countries. In addition, this group of countries also benefited from cleaner energy structure which provided CO_2 emissions reduction of 0.2 million tons, 3.31 million tons and 2.46 million tons respectively for the three countries during 1995-2009, mainly because the share of conventional energy consumption for three countries decreased by 2%, 12% and 5% in the same period.

(2) Technical progress is the main driver of non-metallic sector CO_2 emissions reduction in France and Canada

In the period of 1995-2009, non-metallic sector CO_2 emissions in France and Canada climbed due to scale expansion. However, the two countries achieved more CO_2 emissions reduction through technical progress. So, from a comprehensive view, CO_2 emissions of two countries decrease. Relative to the 1995 level, France and Canada reduced non-metallic sector CO_2 emissions about 3.58 million tons and 4 million tons in 2009. The reason may be the fact that the non-metallic sector energy use per gross output declined by 2.7 TJ/million dollars and 10 TJ/million dollars, respectively.

(3) Non-metallic sector CO_2 emissions reduction of Italy is mainly due to the cleansing of its energy structure

Between 1995 and 2009, Italy witnessed a decrease trend of non-metallic sector CO_2 emissions due to its efforts on improving their low-carbon development. In this period, the share of conventional energy consumption declined by approximately 7%, achieving non-metallic sector CO_2 emissions reduction around 1.2 million tons benefiting from the cleansing of the energy structure (compared with total effects as 1.57 million tons). In addition, Italy also reduced CO_2 emissions by cutting down non-metallic sector scale, resulting in 1.82 million tons of emissions reduction in 2009, relative to the 1995 level.

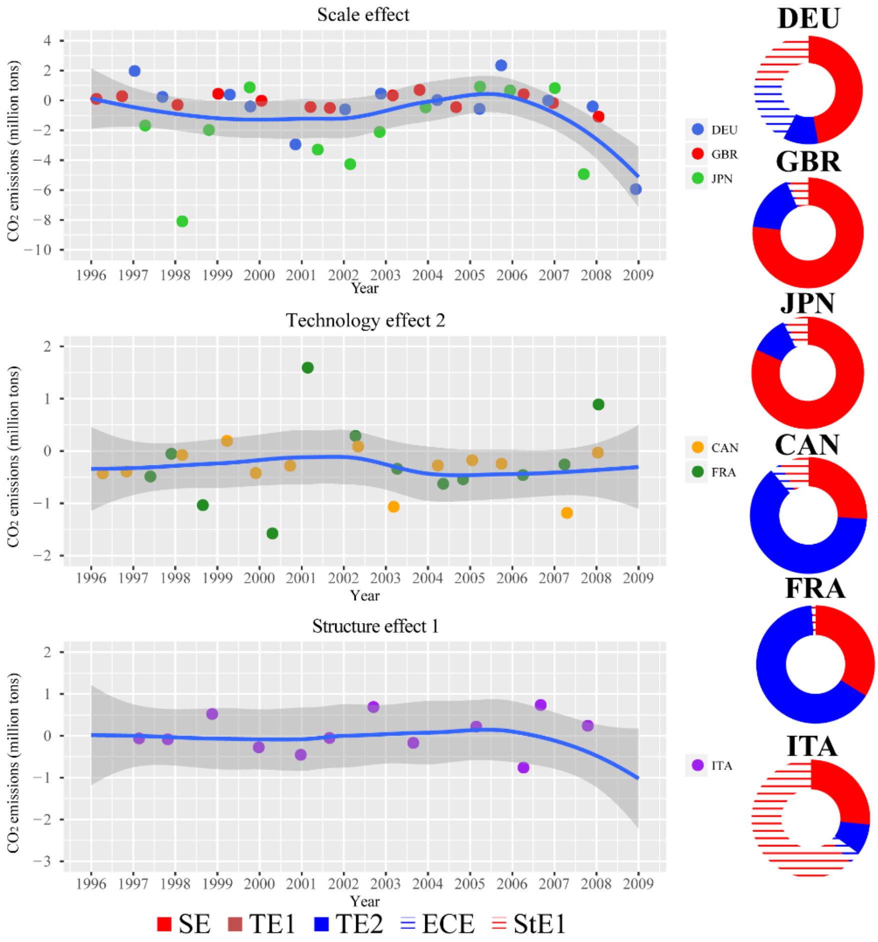


Fig.8. The LMDI decomposition of countries with good performance.

Notes:

(1) SE is scale effect; TE1 (Technology effect 1) is CO_2 emissions per cement production change； TE2 (Technology effect2) is energy use per gross output change； ECE is emission coefficients effect; StE1 (Structural effect 1) is energy structure change.

(2) The blue solid curve shows the loess smoother fit for the trend and confidence interval (gray envelopes).

5. Conclusions and policy implications

5.1. Conclusions

From the comprehensive analysis carried out in our research, the authors argue the following conclusions.

(1) The analysis on the aggregate level indicates that there are two phases with respect to sustaining growth of non-metallic sector CO_2 emissions (with an average annual growth rates is 5%), with the year of 2002 as a distinct demarcation point. In addition, with the increasing trend of non-metallic sector CO_2 emissions, the share of cement process emissions and CO_2 emissions per gross output are in climbing trend. On the other hand, the national level analysis reveals that developing countries obviously emit more CO_2 than developed countries.

(2) The low-carbon development assessment of non-metallic sector for 11 sample countries shows that

the developed countries outperform developing countries with Canada in the leader position. Combining the two dimensions across countries and time horizon, the low-carbon development of non-metallic sector can be categorized in the two. First, U.S.-BRIC pattern (underperforming countries). Second, developed countries pattern (well-performing countries).

(3) The decomposition results on the aggregate level demonstrate that regional structural change plays an important role in CO_2 emissions fluctuation on the aggregate level. Over the period of 1995-2009, non-metallic sector achieved 320 million tons CO_2 emissions due to non-metallic industry transfer. The results suggest that the trend of regional structure results from the transfer of gross output and cement production from developed countries to the BRIC countries.

(4) The study finds that scale effect is a main driver of the CO_2 emissions fluctuation to the underperforming countries with U.S.-BRIC pattern. Over the years of 1995-2009, the non-metallic sector CO_2 emissions of China, India and Brazil skyrocketed, which can be mainly attributed to the rapid scale growth. Conversely, the CO_2 emissions reduction of U.S. was mainly due to scale reduction.

(5) In this research, the authors also conclude that the well-performing countries in terms of low-carbon development can be categorized in three patterns. First pattern, UK, Germany and Japan achieve non-metallic sector CO_2 emissions reduction by reducing scale. Second pattern, technical progress is the main driver of non-metallic sector CO_2 emissions reduction in France and Canada. Third pattern, non-metallic sector CO_2 emissions reduction of Italy mainly depends on the cleansing of its energy structure.

5.2. Policy implications

According to the results of LMDI decomposition model and non-metallic sector low-carbon development assessment employing TOPSIS method, some important implications for non-metallic sector CO_2 emissions reduction for the world are presented below.

(1) More emphasis should be laid on the scale reduction and production transfer across the regions in non-metallic sector, which is of vital importance to the achievement of non-metallic sector CO_2 emissions reduction for the main economies in the world. In order to boost the performance of regional as well as global low-carbon development, a wide range of policies should be deployed, such as curbing the growth rate of non-metallic industry scale, preemptively cutting excessive production capacity, and reasonably transferring capacity of non-metallic materials mainly including cement, glass and clay building materials, by such cooperation among regions as “the Silk Road Economic Belt and the 21st-Century Maritime Silk Road” proposed by China.

(2) It is imperative that the government of economies conduct valid measures and regulations for

restructuring the energy system and obtaining the potential CO_2 emissions reduction with cleaner energy structure. Drawing the experience from Italy (a good example of energy structure optimization), countries should increase the share of renewable energy use and enhance the CO_2 emissions reduction capacity of clean energy structure to abate CO_2 emissions growth.

(3) Considering the increasing importance of technical progress, more generalized CO_2 emissions reduction technology should be deployed and strengthened. The CO_2 emissions reduction technology in non-metallic sector mainly include four aspects， as is shown in follows. First, logistics technology amidst regions should be retrofitted to ensure that the production capacity of non-metallic sector can achieve flexible delivery and elimination. Second, the development and application of large scale energy storage technology should be enhanced to provide more possibility of widespread use of renewable energy. Third, in terms of environmental policies and regulations, it is advisable for economies to adopt and popularize clinker substitutes, which can offer both favorable product characteristics as well as environmental benefits (Güereca et al., 2015; Paris et al., 2016). For example, with a careful collaborative design, some materials of domestic refuse can be usable as a constituent in cement. Fourth, economies should upgrade the technology of production line for non-metallic sector (especially for cement industry), in order to cut back the energy use per gross output.

With respect to the directions for future research, there are some interesting extensions, including: (1) Exploring the effects of non-metallic mineral products structure on CO_2 emissions, by collecting data on the products level. (2) Conducting a case study analysis of those countries with a significant impact of production capacity transfer (namely regional structural effect).

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