Decomposition and measures of the driving factors for China's industrial air pollution emissions at the prefectural level

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Abstract. The decomposition and measures of industrial air pollution emissions’ driving forces in China are helpful to sustainable development. They are also instructive for the Chinese government to functionally formulate policies for energy conservation and emission reduction, as well as to deal with climate change in practice. This study, for the first time, has applied Kaya identity and LMDI index decomposition method to empirically decompose and measure the driving factors of China's industrial air pollution emissions based on prefecture-level cities. The results suggest that, over the past ten years, the per capita industrial air pollution emissions have increased from both state and regional perspective. The main reason for the increasing trend is the economy’s scale effects. Meanwhile, the technological effects and structural effects reduce pollution emissions in the long term. However the environmental-beneficial technology and structural effects are smaller than the scale effects, therefore such an increasing trend cannot be offset by the technological effects.

1. Introduction

In China, the industrial pollution emissions account for more than 80% of the total pollution emissions generated by various energy sectors [1]. Therefore, research on the pollution emissions of the industrial sector can be taken as an important reference to China’s energy conservation, emission reduction, and sustainable development. The environmental Kuznets curve (EKC) serves as a theoretical foundation and analyzing tool for policy agenda on sustainable issues. The critics of EKC argue that the EKC model is a “black box” that ignores environmental impact factors other than economic development and does not fully describe the mechanism by which economic growth affects environmental quality [2]. Supporters of EKC theory responded to such criticism by decomposing the EKC, they claimed that the formation of the EKC curve can be summarized as the comprehensive result of structural, scale and technological effects (environmental impacts = economy (structure, scale, technology)) [3]. This study systematically decomposed, measured and discussed economic structural change, economic scale as well as technological advancement, these three driving forces’ effects on the variation of regional air pollution discharge level in China through 2003-2015.

This research technically applied Kaya Identity and LDMI index decomposition approaches to decompose the annual variation of industrial air pollutant emission level (total effects) into the driving forces (i.e., scale effects, technological effects, and structural effects) for the entire country and its’ east, central, west regions, and then calculate these effects’ value in each year. After that, the research made comparisons between the regions. This is the first research that has empirically decomposed and measured the driving factors of industrial air pollution emissions based on Chinese prefecture-level
cities. The policy purpose of this research is to offer theoretical support and make constructive suggestions for China’s coordinated, sustainable development and environmental protection of all regions.

2. Methodology and data
Before the formal analysis, this section briefly introduces the methodology and empirical model applied in the remaining part of this paper.

2.1. Kaya identity
Kaya Identity was firstly presented by the Japanese scholar Yoichi Kaya at the IPCC\(^1\) conference [4]. Kaya Identity is usually used to analyze and measure changes in carbon dioxide emissions and the driving factors at the macro aspects, such as national or regional aspects. Its equation expression is as follow:

\[
CO_2 = \frac{CO_2}{E} \times \frac{E}{GDP} \times \frac{GDP}{P} \times P
\]

In Eq.1, \(CO_2\) indicates the carbon dioxide emission; \(GDP\) is the gross domestic product; \(E\) refers to the energy consumption; \(P\) is the total population of a region/city (population size). One can decompose \(CO_2\) to the carbon intensity of energy structure \((CO_2/E)\), energy intensity \((E/GDP)\), per capita GDP \((GDP/P)\), and population size \((P)\) by factorization. Thus, Kaya Identity combines carbon dioxide emissions and GDP, energy consumption and population size, and provides a theoretical basis for quantitative analysis of the influence of these factors on \(CO_2\). The practical and theoretically based Kaya Identity has been widely used in carbon and various pollutant emissions researches. Furthermore, Eq. 1 can be converted to Eq. 2:

\[
\frac{CO_2}{P} = \frac{GDP}{P} \times \frac{E}{GDP} \times \frac{CO_2}{E}
\]

Eq.2 shows that one can decompose per capita \(CO_2\) emission to the product of per capita GDP, energy intensity and energy structural intensity. Namely, per capita \(CO_2\) emission can be explained by these three factors: personal income, technological advancement, and structural change. According to environmental economic theory, the energy and resource consumption of economy expansion inevitably increase pollution emission levels and environmental pressure (scale effects); the industrial structure varies as the economy growths: the proportion of the secondary industry in the total economic scale rose first and then fell, which could alleviate the aggravation of environmental pollution (structural effects); the technological advancement brought by economic growth will profoundly affect the level of environmental quality as well (technological effects) [5]. Accordingly, the three terms on the right-hand side of Eq.2 also represent the core factors in the economy-environment relation: scale effects, technological effects and structural effects [3].

2.2. Logarithmic mean divisia index decomposition
In the next section, the empirical analysis applies LDMI\(^2\) introduced by Ang B.W. [6] to further decompose Eq. 2 for investigating the factors’ influence on the increment of pollution emissions (the sizes and signs). Essentially, the LDMI approach incrementally decomposes the concerned indicators according to relevant theories and quantify the structural changes’ contribution to the increment of indicators after decomposition. Thus, the effects of each factor on the change of emissions can be obtained. The advantage of LDMI decomposition is that it can decompose all driving factors without residuals, it does not generate residuals without explanation during the decomposition process. Therefore, it is a complete decomposition of driving forces. Compare to other decomposition

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\(^1\) Intergovernmental Panel on Climate Change
\(^2\) LMDI, Logarithmic Mean Divisia Index Decomposition.
approaches that have residuals, LDMI approach has more powerful explanatory power for decomposition results [7].

E.q.2 can be generalized to E.q.3:

\[ Emission = \sum_i Scale_i \times Tech_i \times Struct_i \]  

In E.q.3, Emission indicates a specific per capita air pollutant emission level (pollution emissions/population) in a country \(i\) and \(Scale_i\), \(Tech_i\), as well as \(Struct_i\) refers to scale effects, technological effects and structural effects, these three driving forces. Mark the change in the total amount of pollutant discharge in the country or regions from the base year, that is, the period T-1 to T as \(\Delta E\). Here, \(\Delta E\) is also the total effects of LDMI decomposition results and \(\Delta E\) consists of scale effects (\(\Delta Scale\)), technological effects (\(\Delta Tech\)) and structural effects (\(\Delta Struct\)). Thus, it can be described by E.q.4.

\[ \Delta E = E_T - E_{T-1} = \Delta Scale + \Delta Tech + \Delta Struct \]  

Based on the additive decomposition of LDMI\(^4\), the calculations of \(\Delta Scale\), \(\Delta Tech\), and \(\Delta Struct\) are listed below [3, 6]:

\[ \Delta Scale = \sum_i \frac{\Delta E_i}{E_i^T - E_i^{T-1}} \ln \left( \frac{Scale_i}{Scale_{i-1}} \right) \]  

\[ \Delta Tech = \sum_i \frac{\Delta E_i}{E_i^T - E_i^{T-1}} \ln \left( \frac{Tech_i}{Tech_{i-1}} \right) \]  

\[ \Delta Struct = \sum_i \frac{\Delta E_i}{E_i^T - E_i^{T-1}} \ln \left( \frac{Struct_i}{Struct_{i-1}} \right) \]  

Besides, \(\Delta Scale\), \(\Delta Tech\), and \(\Delta Struct\) also subject to the following formula:

\[ \frac{\Delta Scale}{\Delta E} + \frac{\Delta Tech}{\Delta E} + \frac{\Delta Struct}{\Delta E} = 1 \]  

As shown in Eq.8, the sum of scale, technological and structural effects over the total change of emissions levels equal to 1 [8].

2.3. Data
Considering the quality and availability of the indices, this study applies the prefectural level data (2003-2015) obtained from China City Statistical Yearbook. The annual industrial soot discharge is applied to reflect the industrial pollution emission level. It is the dependent variable in Eq.3 and Eq.4. Because the comprehensive energy consumption index (such as the standard coal consumption) of prefectural cities is not available, this study takes the intensity of electricity consumption intensity\(^5\) (electricity consumption/industrial GDP) as the indicator of technological effects. The personal income of the industrial sector (industrial GDP/population) and energy structural intensity (industrial soot discharge/electricity consumption) refer to the scale effects and structural effects respectively.

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\(^3\) Here, it is different from E.q.2 because the left term of this equation does not only represent CO2 emission level.

\(^4\) There are mainly two kinds of LDMI decomposition methods: additive and multiplication decomposition, and their decomposition results are consistent.

\(^5\) The reason of choosing electricity consumption is because it is one of the important indicators of Li Keqiang index, its data are more complete, standard and reliable [9].
3. Results and discussion
Table 1 illustrates the variation of pollution emissions from the whole country’s perspective (268 prefecture-level cities). The scot discharge slightly declined in most years during the period of 2003 to 2015. However, due to the increase in 2010-2011 shot up, the reducing effects of emissions in most years are offset. Therefore, industrial pollution has accumulatively leveled up by 4.283. The industrial scale effects have the maximum absolute value among these three driving forces. This is because the expansion of industrial-scale requires more natural and ecological resources for consumption and production [10]. Further, the waste and pollutants generated in the production process will also increase. As shown in table 1, the scale effect of each year drives the industrial sector to emit more pollutants. On the other hand, the technological effects in the industrial sector drive the reduction of industrial pollution emissions every year, so the cumulative effects of technology are negative at the end. The structural effects are negative in most years, and their cumulative effect is ultimately negative. Because of the scale, structural as well as technological effects, the total effects (ΔE, indicates the annual variation) have an increasing trend with fluctuation during the 13 years period. The sequence of the absolute value of the three driving factors is scale effects > technological effects > structural effects.

Table 1. Driving forces at the national level.

| National level | ΔScale | ΔTech | ΔStruct | ΔE | ΔScale (%) | ΔTech (%) | ΔStruct (%) |
|----------------|--------|-------|---------|----|------------|-----------|------------|
| 2003-2004      | 1.464  | -0.661| -0.434  | 0.368| 3.973      | -1.794    | -1.179     |
| 2004-2005      | 1.970  | -1.014| -0.449  | 0.507| 3.886      | -2.001    | -0.885     |
| 2005-2006      | 1.602  | -0.947| -1.256  | -0.601| -2.665     | 1.575     | 2.090      |
| 2006-2007      | 1.352  | -0.682| -1.587  | -0.917| -1.475     | 0.744     | 1.731      |
| 2007-2008      | 0.860  | -0.674| -0.842  | -0.655| -1.313     | 1.028     | 1.285      |
| 2008-2009      | 0.907  | -0.779| -0.730  | -0.602| -1.508     | 1.294     | 1.214      |
| 2009-2010      | 0.526  | -0.006| -0.590  | -0.070| -7.563     | 0.080     | 8.483      |
| 2010-2011      | 1.223  | -0.691| 6.420   | 6.952| 0.176      | -0.099    | 0.923      |
| 2011-2012      | 1.769  | -1.530| -0.757  | -0.518| -3.413     | 2.952     | 1.460      |
| 2012-2013      | 1.057  | -0.587| -1.759  | -1.289| -0.820     | 0.456     | 1.365      |
| 2013-2014      | 0.676  | -0.549| -0.190  | -0.063| -10.751    | 8.737     | 3.014      |
| 2014-2015      | 0.396  | -0.795| 1.569   | 1.169| 0.338      | -0.680    | 1.341      |
| 2003-2015      | 16.548 | -10.162| -2.103  | 4.283| 3.864      | -2.373    | -0.491     |

Note: Data in the table are rounded up/down. ΔScale (%) = (Scale T - Scale T-1)/ScaleT-1, ΔTech (%) = (Tech T - Tech T-1)/TechT-1, ΔStruct (%) = (Struct T - Struct T-1)/StructT-1, which indicating the relative rate of changes. Hereinafter the same.

Table 2. Driving forces in the eastern region.

| East | ΔScale | ΔTech | ΔStruct | ΔE | ΔScale (%) | ΔTech (%) | ΔStruct (%) |
|------|--------|-------|---------|----|------------|-----------|------------|
| 2003-2004 | 1.096 | -0.499| -0.529  | 0.068| 16.111     | -7.332    | -7.779     |
| 2004-2005 | 1.398 | -0.699| -0.250  | 0.450| 3.111      | -1.555    | -0.556     |
| 2005-2006 | 1.129 | -0.724| -0.842  | -0.437| -2.583     | 1.656     | 1.927      |
| 2006-2007 | 0.955 | -0.495| -0.855  | -0.394| -2.422     | 1.255     | 2.167      |
| 2007-2008 | 0.581 | -0.669| -0.286  | -0.374| -1.554     | 1.789     | 0.765      |
| 2008-2009 | 0.685 | -0.510| -0.627  | -0.451| -1.518     | 1.129     | 1.389      |
| 2009-2010 | 0.322 | -0.320| -0.420  | -0.068| -4.746     | -0.439    | 6.185      |
| 2010-2011 | 0.650 | -0.373| 3.090   | 3.368| 0.193      | -0.111    | 0.918      |
| 2011-2012 | 1.010 | -0.766| -0.798  | -0.554| -1.821     | 1.382     | 1.440      |
| 2012-2013 | 0.622 | -0.249| -0.005  | 0.368| 1.690      | -0.676    | -0.014     |
| 2013-2014 | 0.407 | -0.212| 2.816   | 3.012| 0.135      | -0.070    | 0.935      |
| 2014-2015 | 0.383 | -0.489| 1.782   | 1.676| 0.228      | -0.292    | 1.064      |
| 2003-2015 | 13.806 | -8.223| 1.078   | 6.662| 2.073      | -1.234    | 0.162      |
As shown in Table 2, in the industrial sector of eastern prefectoral cities, the scale effects were positive all through the 13 years, while the technological effects kept negative in most years except for 2009-2010. So technological advancement is basically beneficial to the industrial pollution emission abatement. In the beginning years, the structural effects kept reducing the per capita industrial emissions level, however, it boosted up the emissions level in 2010-2011 and 2013-2015. Affected by the three effects, the total effects also have an increasing trend during the 13 years, and its cumulative effect is 6.662 which means compared to 2003, there is a certain increase of per capita emissions by the year 2015. Similar to the national level, in eastern regions, the sequence of the absolute value of the three driving factors is scale effects > technological effects > structural effects.

The technological effects of the central region reduce the per capita industrial pollution emissions every year (Table 3). During the 13 years, the accumulated reduction of per capita emissions in the central region is more than the eastern region (-16.671 vs. -8.223). The other difference is that although the structural factor of the industrial sector in the central region exerts different effects in different years i.e. positive in some years and negative in the other years, its overall effects lowered the per capita emissions in the end. Besides, the accumulated value of the scale effects of the central region is larger than the east.

Table 3. Driving forces in the central region.

| Year    | ΔScale | ΔTech | ΔStruct | ΔE   | ΔScale (%) | ΔTech (%) | ΔStruct (%) |
|---------|--------|-------|---------|------|------------|-----------|-------------|
| 2003-04 | 1.760  | -1.064| -0.194  | 0.501| 3.514      | -2.126    | -0.388      |
| 2004-05 | 2.516  | -1.819| 0.144   | 0.840| 2.993      | -2.165    | 0.172       |
| 2005-06 | 2.280  | -1.178| -1.339  | -0.236| -9.657     | 4.987     | 5.669       |
| 2006-07 | 2.107  | -0.885| -2.495  | -1.273| -1.655     | 0.695     | 1.960       |
| 2007-08 | 1.694  | -0.801| -1.849  | -0.956| -1.771     | 0.838     | 1.934       |
| 2008-09 | 1.325  | -1.464| -0.551  | -0.690| -1.920     | 2.122     | 0.799       |
| 2009-10 | 1.025  | -0.147| -1.369  | -0.491| -2.086     | 0.300     | 2.786       |
| 2010-11 | 1.904  | -1.449| 4.398   | 4.853| 0.392      | -0.299    | 0.906       |
| 2011-12 | 2.696  | -2.643| 9.284   | 9.337| 0.289      | -0.283    | 0.994       |
| 2012-13 | 2.090  | -1.859| -4.674  | -4.443| -0.470     | 0.418     | 1.052       |
| 2013-14 | 0.971  | -0.823| -5.448  | -5.300| -0.183     | 0.155     | 1.028       |
| 2014-15 | 0.855  | -2.091| 3.532   | 2.296| 0.372      | -0.911    | 1.538       |
| 2003-15 | 23.383 | -16.671| -2.275  | 4.438| 5.269      | -3.757    | -0.513      |

The situation in the western region is similar to that in central China (Table 4): overall, the industrial scale effects led the per capita emission level went up during the 13 years; technological and structural effects (their accumulated values through the 13 years are -9.926 and -5.978) lowered the emissions level of per capita at most years and finally reduced pollution emissions in the western region by 2015. Note that the total change of emissions in the western region is only 0.635, less than the eastern and central regions. In other words, the per capita industrial emissions in western cities only increased slightly during the 13 years.

One can conclude that no matter on the national level or regional level, the scale effects in the industrial sectors play the dominant roles. It determines the variation and trend of industrial pollutant discharge. Other than that, both the technology and structural effects are not as effective as the scale effects. The sequence of (1) the scale effects at regional level are center > west > east; (2) the technological effects (in absolute value): center > west > east; (3) the structural effects: west > center > east; (4) the total effects: east > center > west. The reasons behind these findings could be that (1) the income growth at the central area prevails the west area, and there are fewer cities in the east area than in the central area; (2) the investment of R&D in the central and western areas continue to increase while the R&D investment in the east has saturated, so its’ marginal effects are not significant [11]; (3) the marginal effects of industrial structure reform is more significant in less developed areas (west and center) than in the developed areas (east) [9].
Table 4. Driving factors in the western region.

| West         | ΔScale | ΔTech | ΔStruct | ΔE   | ΔScale (%) | ΔTech (%) | ΔStruct (%) |
|--------------|--------|-------|---------|------|------------|-----------|-------------|
| 2003-2004    | 1.578  | -0.359| -0.573  | 0.646| 2.442      | -0.556    | -0.886      |
| 2004-2005    | 2.287  | -0.840| -1.193  | 0.254| 9.011      | -3.310    | -4.701      |
| 2005-2006    | 1.817  | -1.076| -1.974  | -1.232| -1.475    | 0.873     | 1.602       |
| 2006-2007    | 1.522  | -1.005| -1.753  | -1.235| -1.233    | 0.813     | 1.419       |
| 2007-2008    | 0.920  | -0.461| -1.164  | -0.706| -1.304    | 0.654     | 1.650       |
| 2008-2009    | 1.064  | -0.958| -0.818  | -0.712| -1.495    | 1.346     | 1.149       |
| 2009-2010    | 0.618  | -0.109| -0.074  | 0.435| 1.422     | -0.251    | -0.170      |
| 2010-2011    | 2.343  | -0.877| 13.501  | 14.967| 0.157     | -0.059    | 0.902       |
| 2011-2012    | 1.913  | -1.980| -11.987 | -12.054| -0.159    | 0.164     | 0.994       |
| 2012-2013    | 0.877  | -0.513| -0.487  | -0.123| -7.142    | 4.176     | 3.967       |
| 2013-2014    | 1.202  | -1.353| 1.485   | 1.334| 0.901     | -1.014    | 1.113       |
| 2014-2015    | -0.077 | -0.372| -0.490  | -0.939| 0.082     | 0.396     | 0.522       |
| 2003-2015    | 16.539 | -9.926| -5.978  | 0.635| 26.055    | -15.638   | -9.417      |

The relatively high energy intensity and the structure of coal-based energy consumption should be responsible for the dominance of scale effects [12]. The common environment-beneficial impacts of structural and technical effects may be attributed to the Chinese government’s industrial structure reform and upgrade policy as well as continuous investment on the environmental protection technology over the past ten years [11].

4. Conclusions
To sum up, industrial pollution emissions of per capita have accumulatively rose up during the past decade at both regional (prefectural cities) and national level. Based on Chinese economic development in recent years, the key driver of such an increasing trend of emissions is the scale effects brought by economic development and urban expansion. In the long term, the technological and structural effects that are closely related to economic development always mitigate the rise of pollution discharge. However, the sum of their absolute values is always less than the scale effects, therefore the increasing trend cannot be reversed in the near future.

Based on the findings, the central government is expected to fully take advantages of the beneficial technological and structural effects for the improvement of environmental quality and energy use efficiency with a continuous high speed of economic growth. For the purpose of sustainability and environmental protection, the local governors in different areas are expected to better coordinate for the emissions reduction and efficient energy consumption when accelerating the industrial reform and advancing the technological progress.

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