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Extreme events and carbon emissions: What we could learn from decomposition of national- and sector-carbon emission

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1. Introduction

The outbreak of COVID-19 pandemic brings an unprecedented challenge to human being with great uncertainty. The pandemic exerted a severe impact on human activities, and then in turn caused substantial changes in energy consumption and carbon dioxide emissions [1]. Liu et al. [2] discovered that global fossil emission decreased by 5.8% (542 Mt CO2) in the first quarter of 2020. Le Quéré et al. [3] found global energy-related emission reduced by 2.6 Gt in 2020 appropriately. Moreover, industrial carbon emission also suffered severe hit, like power sector, which will be 6.8% lower than that in 2019 [4].

However, the plunge of carbon emission will not last, since it is more caused by temporary lockdown measures, which do not alter the pattern of economy, energy system at all [5]. In addition, there is a great potential for carbon emission to get a retaliatory rebound [6]. According to International Energy Agency, global energy-related emission appeared a strong rebound in late 2020 due to economic recovery [7]. In order to achieve carbon reduction globally, it is necessary to curb potential retaliatory rebound of carbon emission especially when extreme event happens. Consequently, this paper is developed to analyze changes in carbon emissions by learning lessons from the most recent extreme event, 2008 global financial crisis.

Achieving global carbon reduction needs efforts from countries all over the world. In addition, different countries have different situations and take different measures when confronting the COVID-19 pandemic. Hence, it is of great importance to investigate how carbon emission changes and what factors influence carbon emission changes among different countries. We select 42 countries, considering major developing and developed countries and aim to uncover similarities and differences among countries. To be honest, only national carbon emission research is not enough for formulating targeted carbon reduction measures. In this context, we decide to further take industrial carbon emission changes into consideration. According to statistics from the World Input-Output Database (WIOD), annual data for 56 sectors are

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provided. However, due to data deficiency, we reclassify these sectors into 21 major sectors. By investigating industrial carbon emissions, we expect to find out how industrial carbon emissions change and the impact of various factors on industrial carbon emissions, which can help a country achieve carbon reduction as soon as possible. By doing above study, we are able to figure out similarities and differences in carbon emission trends across countries and industries, and then provide scientific suggestions for achieving national and global carbon reduction.

The remaining parts of this research are arranged as follows. Section 2 presents relevant literature review. Section 3 describes the methodology and data sources. Section 4 conducts results analysis and discussion from the perspective of nation and industry. Section 5 comes to some conclusions and proposes some scientific and practical policy implications.

2. Literature review

As a major contributor to global warming, carbon emission gets eyes of numerous scholars [8–11]. In reality, there are a great deal of literatures closely connected with carbon emission focusing on two aspects: region and industry. From the perspective of region, some scholars prefer to focus on city level [12–14]. Yu and Zhang [15] studied the causal relationship between low-carbon city pilot policy and carbon efficiency of 251 Chinese cities in 2003–2018. Wang et al. [16] constructed an integrated spatial estimating framework to investigate spatial distribution of carbon emission on city scale. In addition, some scholars switched eyes to provincial carbon emission [17–19]. Applying a threshold regression model, Zhang et al. [20] aimed to figure out how do environmental regulation and foreign investment behavior influence carbon intensity of 30 Chinese provinces. Moreover, some scholars extended to carbon emission research on country level, whether on single country [21–23] or multi-country level [24–27]. Erdogan et al. [28] selected 14 countries from G20 to study the impact of innovation on sectoral emission with the Environmental Kuznets Curve hypothesis applied. They found the increase of innovation brings emission reduction. Ehigiamusoe et al. [29] conducted a panel and country-specific analysis in 64 middle-income countries. Wang et al. [30] intended to study per-capita carbon emission of 147 countries by taking various factors into consideration.

Through the above literature review, it is clear that previous scholars have done enough work on regional carbon emissions, but relatively few studies have taken COVID-19 into account. As a sudden global extreme event, the COVID-19 pandemic has caused varying degrees of damage to the economy and environment of many countries. Hence, this paper attempts to draw lessons from the most recent extreme event, the 2008 global financial crisis, analyze changes in carbon emissions before and after the financial crisis using historical data, and investigate the key factors behind these changes. The findings could provide practical insights for curbing carbon emissions during and after the pandemic.

However, only studying carbon emission on country level is not helpful to formulate and implement targeted carbon reduction measures. Consequently, what we need further is to investigate industrial carbon emission. From the perspective of industrial carbon emission, previous scholars have made a great contribution to numerous industries, like transport [31–33], manufacturing industry [34,35], construction industry [36–38], logistics industry [39,40], coal chemical industry [41], power sector [42,43], metallurgy [44] and do on. In addition, some scholars tended to study carbon emission of multi-industry, so as to reveal the characteristics of carbon emissions in different sectors. For instance, Liu and Wei [45] classified 42 sectors into four categories and analyzed the spillover effects of intersectoral carbon emissions. Wu et al. [46] selected six high-energy-consuming industry to assess their carbon reduction potential. They found that electric power industry owns the greatest potential to reduce carbon emission. Actually, previous researches focused more on single industry, and multi-industry still need further research. In this context, we aims to consider as more industries as possible, so as to figure out similarities and differences of carbon emission changes among industries, which is conducive to establishing specific carbon reduction policies.

All in all, under the background of COVID-19 pandemic, this paper aims to figure out what and how carbon emission changes, and provide scientific references for further controlling carbon emission retaliatory rebound after the pandemic by taking a lesson from 2008 global financial crisis. To this end, decomposition analysis and comparative analysis are introduced in this paper. This paper is devoted to studying national carbon emission changes in 42 countries, including major developing and developed countries. Furthermore, this paper takes a step forward to study industrial carbon emission changes by classifying 56 sectors into 21 major sectors (3 sectors is excluded due to data deficiency), so as to figure out more detailed information. Through a detailed analysis of national and industrial carbon emission changes, this paper is able to provide helpful suggestions for controlling carbon emission in the future.

3. Methods and data sources

3.1. Carbon emission decomposition at national level

Understanding changes and major influencing factors of national carbon emission is conducive to formulating and implementing carbon reduction policies nationally. In order to do that successfully, both kaya identity and LMDI decomposition methods are introduced. The complete procedure about national carbon emission decomposition has been exhibited in Fig. 1.

Regarding to kaya identity, national carbon emission (C) has been decomposed into five driving forces: carbon intensity, energy intensity, economic structure, economic level, and population scale. Moreover, C, E, IAV refer to carbon emission, energy consumption, and gross output of industry i; IAV, P respectively refer to gross output and population nationally. The ratio of carbon emission and energy consumption (C/E) indicates carbon emission per unit energy consumption, namely, carbon intensity; The ratio of energy consumption and gross output (E/P) indicates energy consumption per unit economic output, namely, energy intensity; The ratio of gross output of industry i in total gross output (IAV/P) indicates economic structure; The ratio of total gross output and population (IAV/P) indicates gross output per capita, in a word, economic level.

On the basis of kaya identity [47], LMDI multiplicative decomposition form has been used to figure out what and how factors drive carbon emission to change. Among all decomposition methods, LMDI method is easy to operate, handle zero value, and leaves no residuals. The carbon emission changes (D) from base year (t) to target year (t+1) has also been decomposed into five factors: D_{\text{G0}}^{\text{t+1}}, D_{\text{T0}}^{\text{t+1}}, D_{\text{IAC1}}^{\text{t+1}}, D_{\text{IAC2}}^{\text{t+1}}, D_{\text{IAC3}}^{\text{t+1}}, referring to national carbon emission changes caused by carbon intensity effect, energy intensity effect, economic structure effect, economic level effect, and population scale effect in a single period, respectively.

In addition, single-period decomposition is only available to report the impact of factors on carbon emission changes year by year. However, multi-period decomposition is available to report the impact of factors on carbon emission changes in a specific period. In this context, multi-period decomposition is deemed as a supplementary. Hence, based on single-period decomposition, we further obtain the impact of these five corresponding factors on national carbon emission changes in a multi-period, which are carbon intensity effect (D_{\text{G0}}^{\text{t+1}}), energy intensity effect (D_{\text{T0}}^{\text{t+1}}), economic structure effect (D_{\text{IAC1}}^{\text{t+1}}), economic level effect (D_{\text{IAC2}}^{\text{t+1}}), and population scale effect (D_{\text{IAC3}}^{\text{t+1}}), respectively.

3.2. Carbon emission decomposition at industrial level

Understanding changes and major influencing factors of industrial
carbon emission promotes formulation and implementation of specific and targeted carbon reduction policies. Therefore, after national carbon emission decomposition analysis, we continue to conduct industrial carbon emission decomposition analysis. Prior to decomposition analysis, it is necessary to make it clear what industries shall be considered. There are 56 original industries according to the World Input-Output Database (WIOD), but data deficiency exists in some industries.

In order to solve that problem, this research attempts to reclassify these industries into 21 industries in accordance with International Standard Industrial Classification revision 4 (ISIC Rev. 4). However, industry R (arts, entertainment and recreation), industry T (Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use), and industry U (Activities of extraterritorial organizations and bodies) are still bothered by data limitation. Therefore, these three industries are excluded in this research. The involved industries have been displayed in following Table 1, and more information about original industries please see Appendix A in supporting material.

After making industry classification clear, it is able to explore industrial carbon emission changes and underlying factors. Initially, it decomposes industrial carbon emission into effect of carbon intensity, energy intensity, economic level, and population scale according to kaya identity as shown in the following equation [47].

\[
C_i = \frac{C_i}{E_i} \times \frac{IAV_i}{P} = c_{int} \times e_{int} \times isca \times psca
\] (1)

Where \(C_i\) refers to carbon emission of industry \(i\). \(c_{int}\), \(e_{int}\), \(isca\), and \(psca\), respectively refer to carbon intensity, energy intensity, industrial level, and population scale of industry \(i\), and \(P\) represents the base year (\(t\)) to targeted year (\(t + 1\)). \(\Delta C_{int}^{new}\), \(\Delta C_{eint}^{new}\), \(\Delta C_{isca}^{new}\), and \(\Delta C_{psca}^{new}\) respectively represents the contribution of industrial carbon intensity effect, industrial energy intensity effect, industrial economic level effect, and population effect made to industrial carbon emission changes, which can be obtained according to Eq. (3) - Eq. (7)

\[
\Delta C_{int}^{new} = \sum L(C_i^t, C_i^{t+1}) \times \ln \left( \frac{c_{int}^{t+1}}{c_{int}^t} \right)
\] (3)

\[
\Delta C_{eint}^{new} = \sum L(C_i^t, C_i^{t+1}) \times \ln \left( \frac{e_{int}^{t+1}}{e_{int}^t} \right)
\] (4)

Fig. 1. National carbon emission decomposition procedure.
This research aims to observe carbon emission changes and further uncover what and how factors drive carbon emission changes nationally and industrially from 2000–2014. For the sake of comprehensive and comparable discussion, this research involves 42 countries, which contain major developed and developed countries. Regarding to data, like carbon emission, energy consumption, gross output, come from the WIOD [48]. Furthermore, economic data has been adjusted to 2010 level like carbon emission, energy consumption, gross output, come from the comparable discussion, this research involves 42 countries, which and industrially during 2000–2014.

3.3. Data sources

Table 2 shows the carbon emission and gross output changes of 42 countries in Table 2. It is obvious that almost one third of the countries achieve carbon reduction, while the rest two third did not. Specifically, developing countries tend to increase carbon emission, like the top two developing countries China and India, whose carbon emission respectively increased by 195% and 124%, which confirmed the results of Liu et al. [49]. Moreover, Yao et al. [50] found developing countries still tended to increase carbon emission as economic output grows, while developed countries did not. That proved our findings to some extent.

On the contrary, developed countries tend to reduce carbon emission, which is in line with the research of Wang and Wang [51]. However, though most of developed countries successfully reduce carbon emission, the reduction is not remarkable enough. As for economic development, only Brazil and Turkey experience negative economic growth during 2000–2014. Gross output of developing countries maintains a high-speed growth which corresponds to carbon emission changes. Relatively speaking, gross output of developed countries tends to increase carbon emission. Relatively speaking, gross output of developed countries tends to increase carbon emission.
to grow at a stabilized middle-speed, especially the highly developed countries. Furthermore, the outbreak of 2008 global financial crisis had a serious impact on both carbon emission and economic development. For most developed and developing countries, both carbon emission and gross output initially decrease and then rebound to varying degrees.

4.2. Industrial carbon emissions and gross output

We choose China, India, Russia, and Brazil as typical developing countries, so as to study industrial carbon emission changes and identify driving factors (in Table 3). Obviously, there is only one industry achieved carbon reduction, which is industry L in China and Brazil, industry F in India. Moreover, carbon emission of these industries does not fall as steep as enough. The remaining industries in China, India, and Brazil all witness carbon increase during 2000–2014, among them, industry N in China and India, industry D in Brazil see a sharp average annual growth rate, which reach 24.53%, 14.43%, and 9.04%, respectively. In addition, industry C in China, and industry D in India and Brazil increase the most when it comes to actual amount. Generally speaking, parts of the industries of China and India show a much steeper carbon emission increase, while those of Brazil show a relatively moderate increase which is limited to less than 10%. For Russia, carbon emission in almost all industries increase during 2000–2014.

Gross output of China and Brazil holds a constant and steady uptrend in all industries, while India and Russia present an increasing trend in most industries during 2000–2014. As we can see, Chinese industrial gross output grows at a pretty high speed, which is much higher than the other three developing countries. Furthermore, Chinese industrial gross output grows faster than carbon emission. However, growth rate of Indian industrial gross output lags behind carbon emission, which demonstrates that India shall make more efforts to curb carbon emission when developing economy. Brazil and Russia have a relatively low industrial output growth, but their output grows a little faster than carbon emission.

As for developed countries (Table 4), we also consider economic growth and carbon emission. In this context, we choose four typical countries, the United States, Japan, Germany, and Canada, as the research object. In this way, we hope to study industrial carbon emission changes and identify driving factors. Carbon emission and gross output changes of these four countries have been displayed in Table 3. Compared with developing countries, developed countries successfully reduce carbon emission in over two third of the industries. Overall, industrial carbon emission of the United States, Japan, and Canada does not fall as steep as enough, while that of Germany fall remarkably, especially the industry N, the average annual growth rate of which reaches −10.1%. What is consistent in the four developed countries is that industry C, industry G, industry I, industry K, industry L, industry N, and industry S all reduce carbon emission during 2000–2014. As for gross output, it cannot be ignored that over half of the industries present negative growth in Japan. Canada always maintains positive economic growth in all industries during 2000–2014. The United States and Germany achieve positive industrial economic growth, except one or two industries. Moreover, economic growth rate of developed countries is relatively smaller than developing countries, especially the United States.

4.3. National carbon emission decomposition analysis

Regarding to national carbon emission decomposition analysis, we decide to conduct both single-period and multi-period decomposition analysis and hope to provide complete and helpful references about what and how factors influence national carbon emission changes.

4.3.1. Single-period decomposition analysis

Table 5 presents the contribution of various factors on carbon emission in 42 countries containing developed and developing countries. Obviously, carbon emission of all countries are varied. Both developed and developing countries experience six states: marginal carbon increase, moderate carbon increase, drastic carbon increase, marginal carbon decrease, moderate carbon decrease, and drastic carbon decrease. For specific influencing factors, there is no doubt that energy intensity plays a dominate role in promoting carbon emission reduction.

On the contrary, economic level plays a dominate role in promoting an increase in carbon emission. The studies of Ma et al. [52], Wang and Feng [53], Chang et al. [54] came to the same conclusions with us. Weaker than energy intensity, economic structure and population scale mainly slightly boost the decrease of carbon emission. Specifically, there exist great differences and imbalances about economic development among all selected countries, which lead to the different contributions of economic structure effect. Moreover, population scale mainly accelerates a slight decrease or a moderate increase in carbon emission due to the relative rapid growth of population in developing countries [55]. Carbon intensity has both positive and negative impact on carbon emission. It is worthy to mention that moderate and drastic carbon decrease are more common in developed countries.

Representative developing and developed countries varies on carbon emission as well as influencing factors (see Fig. 2). Most of them achieve carbon reduction compared to the previous year, except the two developing country, India and Russia, and the two developed country, the United States and Canada. Actually, impacted by the 2008 global financial crisis, carbon emission of developed countries (except Germany, Australia and Korea) initially drops and then rebounds. On the contrary, developing countries still show an uptrend in terms of carbon emission (except Russia). Surprisingly, energy intensity always facilitates carbon reduction in China, and so does is in most years of other developing as well as developed countries. Moreover, due to the global financial crisis, the impact of energy intensity on carbon emission turns from positive to negative in Australia, Canada, Germany, the United Kingdom, the United States, and Russia during 2007–2019. Korea and India seem to delay the shock of the global financial crisis, whose impact turns positive during 2007–2010.

Economic level effect always has negative impact on carbon reduction in China and most years of other countries. Economic level effect of India and Russia drives carbon reduction during 2011–2014, which is closely connected with their declining economic output. Developed countries like Canada and the United Kindom, gradually weaken the negative impact of economic level effect and get some achievements. The effect of carbon intensity and economic structure is weaker than energy intensity and economic level. The former exerts a moderate positive impact on carbon reduction in Australia, Canada, Germany, Korea, the United States, Russia, China, while negative impact on India and the United Kingdom overall. The latter put carbon emission in a worse position than the former except India and the United States. More specifically, economic structure effect hinders carbon reduction in Australia, Germany, the United Kingdom, and Korea totally. Population scale effect plays a negligible positive role in boosting carbon increase in both chosen developed and developing countries.

4.3.2. Multi-period decomposition analysis

The accumulated contribution of five influencing factors on carbon emission between 2000 and 2014 has been displayed in Table 6. Most developed countries successfully decrease carbon emission, but there are still a few developed countries (AUS, CAN, EST, KOR, LTU, MLT) whose carbon emissions have increased dramatically, so the overall increase is not incredible. Oppositely, developing countries still struggle with carbon increase, like China, India, whose carbon emission increase to two or even three times in less than 15 years. Regarding to specific influencing factors, energy intensity effect significantly drives carbon reduction in developing countries.

However, carbon emission of some countries witnesses a remarkable drop, like SVK, LTU, MLT etc., while other countries witness a relatively
Table 3
Carbon emissions and gross output change in representative developing countries.

| Industry | Carbon emission in Kt | Gross output in billion US$ |
|----------|-----------------------|----------------------------|
|           | China 2000 | China 2014 | 00-14 R | India 2000 | India 2014 | 00-14 R | Brazil 2000 | Brazil 2014 | 00-14 R | Russia 2000 | Russia 2014 | 00-14 R |
| A 98024  | 187319  | 89295  | 4.73%  | 52708  | 79442  | 26734  | 2.97%  | 27104  | 32607  | 5503  | 1.33%  | 34596  | 27063  | −7533  | −1.74%  |
| B 108903 | 229360  | 120457 | 5.46%  | 47716  | 159345 | 111628 | 8.99%  | 8069  | 18027  | 9598  | 5.91%  | 111419 | 92043  | −19376 | −1.36%  |
| C 137888 | 463927  | 326416 | 9.05%  | 252248 | 684235 | 413987 | 7.39%  | 154941 | 207971 | 53030 | 2.12%  | 365334 | 462905 | 97571  | 1.71%   |
| D 147256 | 4141215 | 2668652 | 7.67%  | 446007 | 924741 | 478734 | 5.35%  | 23730  | 79702  | 55972 | 9.04%  | 730783 | 733032 | 2249   | 0.02%   |
| E 21404  | 55359   | 39955  | 7.02%  | 2232   | 5669   | 3347   | 6.58%  | 261    | 576    | 316   | 5.83%  | 358373 | 358373 | 2249   | 0.02%   |
| F 27590  | 71633   | 44043  | 7.05%  | 16997  | 441488 | −2513  | −1.14% | 6176   | 70246  | 4070  | 3.68%  | 7580   | 13827  | 6246   | 4.39%   |
| G 27051  | 71363   | 44043  | 7.05%  | 16997  | 441488 | −2513  | −1.14% | 6176   | 70246  | 4070  | 3.68%  | 7580   | 13827  | 6246   | 4.39%   |
| H 141646 | 266954  | 123508 | 4.63%  | 59196  | 87085  | 27889  | 2.80%  | 63454  | 89510  | 26055 | 2.49%  | 105213 | 124276 | 19063  | 1.20%   |
| I 10035  | 3528    | 2.18%  | 15007  | 40999  | 25002  | 7.27%  | 3101   | 4929   | 1827  | 3.36%  | 1656   | 1810   | 154    | 0.64%   |
| J 1399   | 2337    | 3.73%  | 10007  | 40999  | 25002  | 7.27%  | 3101   | 4929   | 1827  | 3.36%  | 1656   | 1810   | 154    | 0.64%   |
| K 1587   | 7784    | 6197   | 12.03% | 943    | 2041   | 1098   | 5.67%  | 877    | 1285   | 6348  | 2.98%  | 358373 | 358373 | 2249   | 0.02%   |
| L 10132  | 6164    | −3968  | −3.49% | 982    | 4530   | 3548   | 11.54% | 460    | 397    | −63   | −1.04% | 4582   | 4976   | 394    | 0.59%   |
| M 3640   | 37020   | 33830  | 18.02% | 1212   | 4709   | 3496   | 10.18% | 2468   | 2875   | 407   | 1.10%  | 730783 | 733032 | 2249   | 0.02%   |
| N 111    | 2384    | 2274   | 24.53% | 5      | 35     | 30     | 14.43% | 2210   | 5224   | 3015  | 6.38%  | 2556   | 4425   | 6246   | 4.39%   |
| O 12191  | 61515   | 49324  | 12.03% | 1520   | 2374   | 854    | 3.23%  | 3836   | 5497   | 1661  | 2.60%  | 5114   | 5869   | 755    | 0.99%   |
| P 28340  | 56638   | 28298  | 5.07%  | 1092   | 3684   | 2592   | 9.07%  | 3282   | 6285   | 3003  | 4.75%  | 5006   | 5467   | 461    | 0.63%   |
| Q 7612   | 63468   | 55857  | 16.36% | 556    | 1503   | 946    | 7.36%  | 2044   | 4014   | 1970  | 4.94%  | 3793   | 4634   | 841    | 1.44%   |
| S 25158  | 63726   | 38507  | 6.86%  | 2912   | 4745   | 1833   | 3.55%  | 2311   | 5104   | 2793  | 5.82%  | 5229   | 4540   | −689   | −1.00%  |

Q. Wang et al.
Table 4
Carbon emission and gross output change in representative developed countries.

| Industry | the United States | Japan | Germany | Canada |
|----------|------------------|-------|---------|--------|
| A        | 55251            | 57008 | 1757    | 0.22%  |
| B        | 103269           | 130773| 27504   | 1.70%  |
| C        | 1014476          | 728312| –281614 | –2.34% |
| D        | 2488369          | 2094483| –393886 | –1.22% |
| E        | 34474            | 26415 | –8509  | –1.88% |
| F        | 53858            | 62942 | 9089    | 1.12%  |
| G        | 139681           | 102075| –38606  | –2.28% |
| H        | 472357           | 534160| 61803   | 0.88%  |
| I        | 67197            | 61085 | –6112  | –0.68% |
| J        | 19729            | 18277 | –1452  | –0.54% |
| K        | 36566            | 26099 | –10468 | –2.38% |
| L        | 15267            | 12913 | –2354  | –1.19% |
| M        | 51795            | 49202 | –2593  | –0.37% |
| N        | 79146            | 59695 | –19452 | –1.90% |
| O        | 279646           | 242418| –37228 | –1.02% |
| P        | 15732            | 21931 | 6198   | 2.40%  |
| Q        | 82476            | 84405 | 1936   | 0.17%  |
| R        | 46446            | 57008 | –8167  | –1.60% |

Gross output in billion US$

| Industry | the United States | Japan | Germany | Canada |
|----------|------------------|-------|---------|--------|
| A        | 308              | 450   | 142     | 2.74%  |
| B        | 274              | 614   | 340     | 5.94%  |
| C        | 5375             | 5725  | 350     | 0.45%  |
| D        | 448              | 372   | –7     | –1.32% |
| E        | 75               | 97    | 22      | 1.88%  |
| F        | 1155             | 1109  | –46     | –0.29% |
| G        | 2502             | 2993  | 492     | 1.29%  |
| H        | 748              | 985   | 236     | 1.98%  |
| I        | 650              | 822   | 172     | 1.69%  |
| J        | 1529             | 1717  | 188     | 0.83%  |
| K        | 1837             | 2017  | 173     | 0.64%  |
| L        | 1908             | 2559  | 651     | 2.12%  |
| M        | 1438             | 1957  | 536     | 2.29%  |
| N        | 799              | 1901  | 202     | 1.62%  |
| O        | 2475             | 3167  | 692     | 1.78%  |
| P        | 182              | 295   | 112     | 3.49%  |
| Q        | 1228             | 1922  | 694     | 3.25%  |
| S        | 559              | 695   | 136     | 1.57%  |

| Year | Value | Year | Value | Year | Value | Year | Value | Year | Value |
|------|-------|------|-------|------|-------|------|-------|------|-------|
| 2000 | 22628 | 2000 | 22372 | 2000 | 2327 | 2000 | 11066 |
| 2014 | 616   | 2014 | 630   | 2014 | 5364 | 2014 | 5414  |
| 00   | –1511 | 00   | –8234 | 00   | 10.68% | 00   | 4.25%  |
| 14   | 23934 | 14   | 395535| 14   | 1.45%  | 14   | 6.50%  |
| 14   | 29298 | 14   | 36972 | 14   | –1.26% | 14   | 2.17%  |
| 14   | 5364  | 14   | 165933| 14   | 0.4%   | 14   | 2.01%  |
| 14   | 23618 | 14   | 471378| 14   | 2.44%  | 14   | 2.19%  |
| 14   | 132511| 14   | 15321 | 14   | 1.28%  | 14   | 1.49%  |
| 14   | 2743  | 14   | 6944  | 14   | 6.86%  | 14   | 2.08%  |
| 14   | 4202  | 14   | 1245  | 14   | 1.28%  | 14   | 1.26%  |
| 14   | 4597  | 14   | 69651 | 14   | 1.28%  | 14   | 1.26%  |
| 14   | 8280  | 14   | 5961  | 14   | 1.10%  | 14   | 2.69%  |
| 14   | 10635 | 14   | 16479 | 14   | 2.89%  | 14   | 2.01%  |
| 14   | 8388  | 14   | 2744  | 14   | 1.26%  | 14   | 1.26%  |
| 14   | 30049 | 14   | 8234  | 14   | 2.34%  | 14   | 1.26%  |
| 14   | 11531 | 14   | 8283  | 14   | 2.01%  | 14   | 1.26%  |
| 14   | 1248  | 14   | 13921 | 14   | 1.26%  | 14   | 1.26%  |
| 14   | 4107  | 14   | 13172 | 14   | 1.26%  | 14   | 1.26%  |
| 14   | 2074  | 14   | 17019 | 14   | 1.26%  | 14   | 1.26%  |
| 14   | 772   | 14   | 7114  | 14   | 1.26%  | 14   | 1.26%  |
| 14   | 2280  | 14   | 7303  | 14   | 1.26%  | 14   | 1.26%  |
| 14   | 6087  | 14   | 16716 | 14   | 1.26%  | 14   | 1.26%  |
| 14   | 42076 | 14   | 91781 | 14   | 1.26%  | 14   | 1.26%  |

Gross output in billion US$
small drop, like JPN, USA. The contribution of economic level effect on carbon emission has a negligible difference between developing and developed countries. Particularly, economic level effect has a far more overwhelming impact on carbon emission in China. The unprecedentedly drastic economic growth of China might explain that.

4.4. Industrial carbon emission decomposition analysis

4.4.1. Industrial carbon emission decomposition analysis of developing countries

This research chose four major developing countries (China, India, Russia, and Brazil) to explore industrial carbon emission changes and underlying factors in Table 7 (see Fig D1-D4 in Appendix C).

China, the largest developing country, gets all industrial carbon emission increased (except industry L whose emission decreased by 116.25%). Among all driving factors, without any doubt, industrial economic level effect and energy intensity effect are the dominant promotor and inhibitor to carbon emission increase, but the latter has a weaker impact than the former for all industries of China. According to study of Hang et al. [56], energy intensity can promote carbon emission to decouple from economic growth, which means when economy grows, carbon emission grows slower or even declines. In this way, it confirms our results again. Industries accounting for a large ratio in total emission, like industry C and industry D, see great carbon emission increase too, and economic level and energy intensity effect performed strongly. The results of study of Tian et al. [35] coincides with ours, which presents that shaping the production pattern is good for controlling carbon emission in industry C. Moreover, industrial carbon intensity has a negative impact on carbon emission increase, especially industry J and industry G. Furthermore, population scale always accelerates industrial carbon emission increase, though its impact is quite minor.

India, another major developing country, also gets all industrial carbon emission increased (except industry F whose emission decreased by 14.78%). Different from China, energy intensity significantly promotes carbon emission increase for most industries in India, and economic level effect promotes carbon emission increase for over 70% industries. In reality, there exists great difference among industries in India, which means that Indian government shall make it a priority to formulate and implement specific and targeted carbon reduction policies.

Different from China and India, one fourth of the industries achieve carbon emission reduction, though the reduction is not significant in...
Russia. Similar to China, economic level dominantly promotes carbon emission increase, while energy intensity significantly inhibits carbon emission increase for most industries.

Like China and India, Brazil also gets all industrial carbon emission increased (except industry L whose emission decreased by 13.67%). Economic level effect remarkably boosts carbon emission increase all the time for all industries of Brazil. Energy intensity effect makes a positive and great contribution to curbing carbon emission increase for most industries. It is worthy to mention that energy intensity inhibits emission reduction in industry D, industry N, and industry S, especially in industry D, energy intensity imposes a stronger impact on emission than economic level effect. Similar to Russia, carbon intensity effect has both positive and negative impact on emission, and it inhibits emission reduction for one fourth of the industries.

4.4.2. Industrial carbon emission decomposition analysis of developed countries

In order to discuss industrial carbon emission decomposition results of developed countries, this research chose the United States, Japan, Germany, and Canada as objects. Different from developing countries, over two thirds of the industries got industrial carbon emission decreased (Table 8).

Specifically speaking, energy intensity effect makes a great contribution to industrial carbon emission reduction for almost all industries and its impact is much stronger than economic level effect such as industry G, industry J. However, energy intensity switches to inhibiting carbon emission reduction in industry D, industry F, and industry P. Carbon intensity effect both promotes and inhibits industry carbon emission decrease in the United States, but it strongly drives emission decrease and becomes the dominate promoter to emission reduction in industry J and industry P. Like previous discussed countries, population scale effect drives emission increase in all industries.

For Japan, energy intensity effect significantly drives emission decrease in most industries, economic level effect significantly drives emission increase in nearly one third of the industries. Moreover, economic level effect has a negative impact on emission increase in half of the industries of Japan, which means Japanese economic development does not bring carbon emission definitely. Carbon intensity effect promotes carbon emission increase in two thirds of the industries. Particularly in industry D, industry E, industry F, and industry N, carbon intensity effect is the primary contributor to emission increase. Population scale effect has positive impact on emission increase, but its impact is negligible.

In Germany, as a primary promotor, energy intensity effect successfully promotes emission reduction in all industries (except industry A, industry E, and industry M). Economic level effect always promotes carbon emission increase in all industries (except industry A). In addition, the impact of energy intensity on industrial carbon emission is stronger than (like industry B) economic level, or weaker (like industry H), or nearly equal to it (like industry C). Carbon intensity effect has a positive impact on emission reduction in over 60% industries and its impact is quite important. In addition, population scale effect always drives emission decrease, but its impact is quite negligible.

In Canada, energy intensity effect promotes industrial carbon emission decrease reduction all the time and makes itself the primary contributor to emission reduction. Economic level and population scale effect always inhibit emission reduction and neither economic level nor population scale has a negligible impact. For most industries, carbon intensity effect has a positive impact on emission reduction, but its impact is much weaker than energy intensity effect.

5. Conclusions and policy implications

5.1. Conclusions

This research is developed to uncover carbon emission changes and the underlying factors from the perspectives of nation and industry. Moreover, this research involves 42 nations covering major developing and developed countries and considers 18 industries. Our main findings are as follows:
Accumulated decomposition results in 2000–2014.

| country | Carbon intensity | Energy intensity | Economic structure | Economic level | Population scale | Total effect |
|---------|-----------------|-----------------|-------------------|----------------|------------------|-------------|
| AUS     | 0.9273          | 0.4813          | 1.0266            | 1.8830         | 1.2256           | 1.0577      |
| AUT     | 0.7356          | 0.5396          | 1.0458            | 1.7084         | 1.0667           | 0.7445      |
| BEL     | 0.8090          | 0.5627          | 0.9113            | 1.5569         | 1.0934           | 0.7062      |
| BGR     | 0.9195          | 0.4689          | 0.8885            | 2.7444         | 0.8843           | 0.9301      |
| CAN     | 0.9100          | 0.6664          | 0.9717            | 1.5716         | 1.1548           | 1.0694      |
| CHE     | 0.5438          | 0.6745          | 1.0203            | 2.1542         | 1.1308           | 0.9191      |
| CHN     | 0.9407          | 0.4576          | 0.9612            | 6.4520         | 1.0805           | 2.9459      |
| CYP     | 0.9935          | 0.4389          | 1.1088            | 1.3566         | 1.2213           | 0.8016      |
| CZE     | 0.6645          | 0.3912          | 1.0058            | 2.5287         | 1.0263           | 0.6791      |
| DDK     | 0.8325          | 0.5076          | 1.1907            | 1.6443         | 0.9851           | 0.8256      |
| DNK     | 0.8752          | 0.6143          | 1.0921            | 1.6248         | 1.0569           | 0.9571      |
| ESP     | 0.8468          | 0.4313          | 1.3177            | 1.4265         | 1.1456           | 0.7868      |
| EST     | 1.0208          | 0.4516          | 1.0171            | 2.9126         | 0.9410           | 1.2857      |
| FIN     | 0.7426          | 0.5399          | 1.0785            | 1.6198         | 1.0550           | 0.7398      |
| FRA     | 0.8028          | 0.5573          | 0.9626            | 1.5266         | 1.0886           | 0.7162      |
| GBR     | 0.9989          | 0.5585          | 1.0101            | 1.2721         | 1.0969           | 0.7792      |
| GRC     | 0.6567          | 0.5040          | 1.3534            | 1.2113         | 1.0080           | 0.5475      |
| HRV     | 1.0476          | 0.3507          | 1.0951            | 1.9429         | 0.9486           | 0.7432      |
| HUN     | 0.8129          | 0.6355          | 0.9770            | 1.5502         | 0.9663           | 0.7562      |
| IDN     | 1.0585          | 0.8146          | 1.1092            | 1.4255         | 1.2061           | 1.6452      |
| IND     | 1.0533          | 1.6314          | 0.7577            | 1.4048         | 1.2238           | 2.2328      |
| IRL     | 1.0986          | 0.4076          | 1.1828            | 1.5238         | 1.2238           | 0.9858      |
| ITA     | 0.8129          | 0.5964          | 1.0873            | 1.2928         | 1.0675           | 0.7274      |
| JPN     | 1.2020          | 0.8114          | 1.0169            | 0.9927         | 1.0034           | 0.9879      |
| KOR     | 0.9392          | 0.5664          | 1.2117            | 1.7997         | 1.0795           | 1.2289      |
| LTT     | 1.4225          | 0.2980          | 1.0887            | 3.5962         | 0.8384           | 1.3982      |
| LUX     | 0.7373          | 0.4501          | 0.8407            | 2.4208         | 1.2744           | 0.8628      |
| LVA     | 0.7276          | 0.5903          | 0.9662            | 2.6869         | 0.8423           | 0.9391      |
| MEX     | 0.9438          | 1.1337          | 1.0220            | 0.8724         | 1.2169           | 1.1607      |
| MLY     | 1.0641          | 0.3796          | 1.2381            | 2.0449         | 1.1139           | 1.1393      |
| NLD     | 1.3964          | 0.4206          | 1.0019            | 1.5357         | 1.0590           | 0.9571      |
| NOR     | 0.6716          | 0.6144          | 0.8457            | 2.0293         | 1.1437           | 0.8107      |
| POL     | 0.9354          | 0.4206          | 1.0322            | 2.3139         | 0.9935           | 0.9344      |
| PRT     | 0.7920          | 0.5475          | 1.2295            | 1.3331         | 1.0108           | 0.7183      |
| ROU     | 0.9128          | 0.5992          | 0.9108            | 1.7614         | 0.8872           | 0.7591      |
| RUS     | 0.9824          | 0.6211          | 0.9983            | 1.8111         | 0.9811           | 1.0824      |
| SVK     | 0.8322          | 0.3211          | 1.0301            | 2.8497         | 1.0056           | 0.7890      |
| SVN     | 0.8906          | 0.5927          | 1.2375            | 1.4704         | 1.0367           | 0.9968      |
| SWE     | 0.7951          | 0.5088          | 0.9648            | 1.6382         | 1.0927           | 0.6992      |
| TUR     | 0.8602          | 4.1767          | 1.0489            | 0.3245         | 1.2210           | 1.4911      |
| USA     | 0.9419          | 0.9037          | 0.8327            | 1.0758         | 1.1281           | 0.8601      |

(i) Almost one third of the selected countries achieve carbon reduction, while the remaining two third do not. Moreover, developing countries such as China, India, are still struggling with carbon emission since their carbon emission is increasing rapidly. Developed countries like Germany, the United Kingdom, successfully reduce carbon emission though the reduction is not remarkable enough.

(ii) Different from carbon emission, economic output tends to increase in almost all studied countries. Developed countries, especially highly developed countries, hold a middle-speed increase, such as the United States. However, for developing countries, they not only have a large absolute quantity, but also a high-speed increase in economic output. Energy intensity is regarded as the dominate inhibitor to carbon emission drop. For example, in China, economic level has a far more overwhelming impact on carbon emission than other factors. Furthermore, developed countries exert efforts to weaken the negative impact of economic level and get some achievements, for example, in Canada, the United Kingdom. Carbon intensity has both positive and negative impact on carbon emission drop, generally negative impact in developing countries. Population scale mainly causes carbon emission to slightly decrease or moderately increase in developing countries owing to the relative rapid growth of population.

(iii) For industrial carbon emission in developing countries, almost all industries get carbon emission increased, especially industry N in China, industry L in India, industry D in Brazil, and industry F in Russia. Moreover, industrial carbon emission of China, Brazil, and Russia grows lower than industrial economic output. On the contrary, India’s carbon emission grows faster than industrial economic output. Over two third of the industries achieve carbon reduction in developed countries. In addition, industrial carbon emission of Germany reduces remarkably, particularly the industry N. Besides, growth rate of industrial economic output in developed countries is relatively lower than that in developing countries, especially the United States. Energy intensity significantly drives industrial carbon emission reduction, while economic level effect remarkably inhibits emission reduction both in developing and developed countries. However, the latter has a weaker impact than the former in developed countries, while stronger in developing countries.

5.2. Policy implications

In accordance with above conclusions, it is necessary to propose some scientific and practical policy implications so as to effectively curb carbon emission. Specific policy implications are shown as follows:
Table 7
The impact of various factors on carbon emission of major developing countries (%).

| Industry | China | India | Russia | Brazil |
|----------|-------|-------|--------|--------|
|          | Δc^c | Δc^c | Δc^c | Δc^c | Δc^c | Δc^c | Δc^c | Δc^c | Δc^c |
| A        | −5   | −116 | 201  | 12   | 91   | −12 | 54   | −14 | 23   | 51   |
| B        | −10  | −216 | 324  | 12   | 111  | 29  | 222  | −53 | 35   | 234  |
| C        | −8   | −236 | 428  | 17   | 236  | 20  | 93   | 25  | 33   | 171  |
| D        | −16  | −135 | 318  | 15   | 181  | 6   | 112  | −38 | 107  | −9   | −61 | 72   | −2   | 0   |
| E        | 5    | 38   | 102  | 14   | 159  | −52 | 213  | −49 | 31   | 14   |
| F        | −28  | −177 | 352  | 13   | 160  | −76 | −3   | 46  | 19   | −15  |
| G        | −64  | −68  | 173  | 8    | 49   | −30 | 57   | 98  | 37   | 162  |
| H        | −9   | −127 | 214  | 11   | 88   | −4  | −2   | 30  | 23   | 47   |
| I        | −87  | −142 | 253  | 12   | 35   | 53  | 35   | 42  | 36   | 167  |
| J        | −226 | −70  | 351  | 12   | 67   | −28 | 27   | 96  | 36   | 131  |
| K        | −42  | −200 | 612  | 20   | 390  | −32 | 69   | 44  | 36   | 116  |
| L        | −54  | −116 | 125  | 6    | −39  | −1  | 264  | 56  | 43   | 361  |
| M        | −46  | −376 | 1296 | 43   | 917  | −14 | 98   | 155 | 50   | 288  |
| N        | 81   | −1104| 3009 | 71   | 2057 | 402 | −22  | 124 | 55   | 560  |
| O        | −31  | −151 | 234  | 23   | 405  | 0   | 36   | −4  | 24   | 56   |
| P        | −8   | −159 | 256  | 11   | 100  | 14  | 147  | 40  | 37   | 237  |
| Q        | −4   | −228 | 933  | 33   | 734  | 41  | 77   | 17  | 35   | 170  |
| S        | −51  | −72  | 264  | 13   | 153  | −8  | 33   | 16  | 22   | 63   |

Table 8
The impact of various factors on carbon emission of major developing countries (%).

| Industry | the United States | Japan | Germany | Canada |
|----------|-------------------|-------|---------|--------|
|          | Δc^c | Δc^c | Δc^c | Δc^c | Δc^c | Δc^c | Δc^c | Δc^c | Δc^c |
| A        | 10   | −48  | 28   | 13   | 3    | −19 | −45 | −10 | 1    | −73  |
| B        | −4   | −57  | 75   | 12   | 27   | 7   | 5   | 10  | 0    | 22   |
| C        | −3   | −31  | −6   | 10   | −28  | 1   | −17 | −1  | 0    | −16  |
| D        | −12  | −12  | −28  | 11   | −16  | 63  | −24 | −1  | 0    | 40   |
| E        | 3    | −44  | 9    | 9    | −23  | 116 | 57  | −30 | 20   | 153  |
| F        | −1   | −19  | −16  | 15   | 17   | 8   | −18 | −15 | 0    | −26  |
| G        | 11   | −55  | 5    | 11   | −28  | −14 | −13 | −10 | 1    | −36  |
| H        | 0    | −13  | 15   | 11   | 13   | 0   | −28 | 0   | 0    | −27  |
| I        | 19   | −51  | 12   | 12   | −9   | −13 | −17 | 6   | 0    | −23  |
| J        | 42   | −58  | −2   | 11   | −7   | 1   | −34 | 4   | 1    | −28  |
| K        | 9    | −47  | −1   | 11   | −29  | −3  | −19 | −8  | 0    | −30  |
| L        | 57   | −102 | 118  | 18   | −15  | 10  | −23 | 5   | 0    | −28  |
| M        | 6    | −42  | 19   | 11   | −5   | 8   | −20 | 3   | 0    | −9   |
| N        | −1   | −41  | 7    | 10   | −25  | 6   | −24 | −14 | 0    | −32  |
| O        | 2    | −41  | 14   | 12   | −13  | 1   | −32 | 21  | 0    | −10  |
| P        | −235 | 222  | 38   | 13   | 39   | −76 | 235  | −48 | 0    | 110  |
| Q        | 11   | −55  | 94   | 12   | 2    | 8   | −35 | 24  | 35   | −2   |
| S        | 5    | −45  | 9    | 11   | −20  | 2   | −21 | −3  | 0    | −21  | 70   | −135 | 36   | −2   | −30  | −12  | −61  | 50   | 13   | −10  |
• Carbon reduction policies shall be formulated according to economic developing phase. In different economic development phase, major targets may be different. The formulation and implement of carbon reduction policies in accordance with economic phase may achieve the largest emission reduction at the least cost.

• All developing countries should pay attention to carbon emission. Developing countries, like China and India shall put it as a priority due to their extreme large absolute quantity and high-speed growth. Moreover, developing countries need more efforts to coordinate carbon emission and economic growth since they are in the course of high-speed economic development.

• All countries need to formulate and implement targeted carbon reduction measures according to their reality since differences exist among countries and industries. For example, India shall make more efforts than other developing countries to curb carbon emission while developing economy; industry N in China, industry L in India, industry D in Brazil, and industry F in Russia need more attention paid to reduce carbon emission.

• Energy intensity shall be further improved. Energy intensity significantly promotes carbon emission drop in developed countries, while promotes carbon emission increase in some developing countries. Hence, developing countries shall emphasize technological innovation, which is conducive to developing carbon-reduction and energy-savings technologies. Moreover, developing countries can cooperate with developed countries and introduce advanced technologies from outside.

• Energy structure should be optimized. In the future, more clean, renewable, and low-carbon energy shall be used and the ratio of carbon-intensive energy such as coal in total energy consumption system shall be further lowered. In order to achieve that effectively, it is necessary to stabilize the supply of low-carbon energy and at the same time lower the cost.

Actually, we have researched similarities and differences among countries and industries, while have not given enough attention to similarities and differences among regions of one particular country. Hence, in the near future, we intend to research regional inequality of particular developing countries like China, and particular developed countries like the United States. Moreover, when we have solid foundation of regional study, we intend to investigate regional inequality of single or multi-industries of particular country.

Author contribution statement

Rongrong Li: Methodology, Software, Data curation, Investigation Writing – original draft, Writing- Reviewing and Editing. Qiang Wang: Conceptualization, Methodology, Software, Data curation, Writing – original draft preparation, Supervision, Writing- Reviewing and Editing. Min Su: Methodology, Data curation, Investigation Writing – original draft, Writing- Reviewing. Shasha Wang: Methodology, Data curation, Investigation Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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