Tracking Key Industrial Sectors for CO\(_2\) Mitigation through the Driving Effects: An Attribution Analysis

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**Abstract:** The heavy pressure to improve CO\(_2\) emission control in industry requires the identification of key sub-sectors and the clarification of how they mitigate CO\(_2\) emissions through various actions. Focusing on 30 Chinese provincial regions, this study quantifies the contribution of each industrial sector to regional CO\(_2\) mitigation by combining the logarithmic mean Divisia index with attribution analysis and extract the key sectors of CO\(_2\) mitigation for each region. Results indicate that during 2010–2019, significant emission reduction was achieved through energy intensity (74%) in Beijing, while emission reductions were attained through industrial structure changes for Anhui (50%), Henan (45%), and Chongqing (45%). The contribution to emission reduction through energy structures is not significant. The production and supply of power and heat (PSPH) is a central factor in CO\(_2\) mitigation through all three inhibitive factors. Petroleum processing and coking (PPC) generally contributes to emission reduction through energy structures, while the smelting and pressing of ferrous metals (SPMF) through changes in industrial structures and energy intensity. PSPH and SPMF, in most regions, have not achieved the emission peak. Except in the case of coal mining and dressing (CMD), CO\(_2\) emissions in other key sectors have almost been decoupled from industrial development. CMD effectively promotes CO\(_2\) mitigation in Anhui, Henan, and Hunan, with larger contribution of PPC in Tianjin, Xinjiang, Heilongjiang, and that of smelting and pressing of nonferrous metals in Yunnan and Guangxi. The findings help to better identify key sectors across regions that can mitigate CO\(_2\) emissions, while analyzing the critical emission characteristics of these sectors, which can provide references to formulating region- and sector-specific CO\(_2\) mitigation measures for regions at different levels of development.

**Keywords:** CO\(_2\) emissions; industry; attribution analysis; key sectors; emission peak

1. Introduction

Facing the increasingly severe threat of global climate change, active measures are being invoked around the world to meet this realistic challenge of reducing CO\(_2\) emissions [1–3]. With rapid global industrialization, industry has become the main source of CO\(_2\) emissions. As the International Energy Agency (IEA) reported, existing industrial plants and coal-fired power plants around the world will emit about 600 billion tons of CO\(_2\) over the next five years [4]. In the context of meeting more stringent climate targets, the control of industrial CO\(_2\) emissions should be placed at a prioritized position.

At present, studies on industrial CO\(_2\) emissions have mainly focused on the influencing factors of emissions and the prediction of emission peak. A great number of studies employed the methods, such as logarithmic mean Divisia index (LMDI) [5,6], stochastic impacts by regression on population, affluence, and technology (STIRPAT) [7,8] and structural decomposition analysis (SDA) [9,10] to identify the influencing factors of industrial CO\(_2\) emissions. The promotive and inhibitive drivers of emissions were explored at the...
national [11,12], provincial [13,14], regional [15,16], and sectoral levels [17,18]. The main factors identified included: economic growth, industrial structure, energy structure, energy intensity, population, urbanization, and so on [19–22]. Economic growth is considered as a primary contributor to increasing emissions, while energy intensity significantly inhibits emissions [23,24]. In addition, other factors, such as energy-saving technology, production efficiency, and research and development (R&D) efficiency, have also been gradually incorporated by researchers into the critical factors [25,26].

Recently, CO₂ emission peak has been frequently described and analyzed in the prediction of emissions in the scenarios of future economic development. Most studies believe that the CO₂ emissions of China could reach the peak before 2030 [27–29], and industry plays a leading role in controlling emissions, as well as in achieving an earlier peak [30]. Industrial CO₂ emissions have a potential to peak by 2025 through policies such as optimizing the industrial structure and eliminating overcapacity [31,32]. More subdivided industrial sectors, such as nonferrous metals industry [33], chemical industry [34], power generation industry [35], and steel and cement industries [36] have been estimated to reach the peak of their emissions in different years, and show diverse emission reduction potentials. In numerous scenario analyses, the growth and differences of energy consumption and CO₂ emissions were predicted and compared under different settings of evolution of socioeconomic situations, for which corresponding policy suggestions were put forward. Ref. [37] believed that under the current policy scenario, the emissions of the power industry in China cannot reach their peak before 2030, the findings of which align with that of Meng et al. [38] based on the prediction of power industry’s emissions in a variety of scenarios. Li et al. [39] assessed the CO₂ reduction potential of the iron and steel industries in China in six scenarios, providing a feasible path for the industries to achieve the emission reduction goal by 2030.

Reducing industrial CO₂ emissions is the key to reaching the peak of the whole country’s emissions at an earlier date, which requires a combination of technological innovation and policy guidance. Specific to various sectors, clean coal technology can provoke cleaner power generation development by improving the efficiency of coal utilization for thermal power generation [40]. Waste heat energy recovery technology, hydrogen-based steelmaking, and iron-ore electrolysis technologies are effective ways for sustainable green iron and steel manufacturing [41]. Technology is only one part of the blueprint for emission control, and putting in place the right policies can provide incentives for technology deployment and accelerate emission reduction. For example, the carbon emission trading scheme can stimulate effective responses across all channels, which is an effective approach to achieving emission reduction targets at a sub-national scale [42,43]. The effects of carbon pricing on critical earth system processes have also been explored, as well as the impact on CO₂ emissions [44]. Given the continuous transformation of development mode and the adjustment of industrial structures, the emission characteristics of different subdivided industrial sectors are diverse. Technological innovation and policy formulation targeting the key sectors are the guarantee of achieving the emission peak as soon as possible. Thus, identifying which sectors deserve prioritized attention is the prerequisite for addressing these issues.

Based on the multiplicative decomposition of LMDI, the attribution analysis traces the change of decomposition factors in various sub-sectors, and, thus, quantifies the contribution of various sectors to variations in CO₂ emissions, which provides a methodological support for the identification of the “key sectors”. At present, this method has been used to identify the key sectors in terms of energy intensity [45,46], CO₂ intensity [47,48], air pollutant emissions [49], etc. When evaluating the emission performance of regional energy-related activities, for example in power generation, regional attribution analysis was also used to highlight regional differences of emission reduction [50]. Attribution analysis can ascribe the contributions of the driving factors to some individual components, such as sub-sectors or sub-regions, laying a foundation for the formulation of differentiated policies for different sectors or regions.
The ability of the industry to reach the peak of CO₂ emissions ahead of schedule is the key to China’s commitment to address climate change. Some problems remain to be further explored, beyond a number of extant studies on industrial CO₂ emissions. First, the urgency to mitigate emissions should be differentiated among industrial sectors. Identifying the key sectors in terms of larger contribution to CO₂ mitigation is the basis for an orderly emission reduction route. However, the identification of the key sectors in existing studies mainly relies on qualitative analysis or direct observation based on numerical results, lacking a methodological basis. In addition, industrial energy consumption and technological level vary considerably across the provincial regions as a result of different levels of industrial development and relevant policies. This leads to differences in the key sectors across regions, as well as in the emission characteristics of these sectors, including the decoupling from industrial development and the emission peaking status (having peaked or not). The inadequacy in clarification of the above hinders the formulation of pertinent mitigation measures for industrial CO₂ emissions.

In light of the above, the CO₂ emissions of industry in China’s 30 provincial regions are sorted into contributions from six major influencing factors through the LMDI method, and those inhibiting emissions in each region are identified. Then, the contributions of industrial sectors to variations in the inhibitive effects are quantified by the attribution analysis to extract the key sectors that significantly contribute to CO₂ mitigation. Finally, the emission characteristics of the key sectors in terms of the decoupling from industrial development and peaking status in each region are analyzed. The novelty of this paper lies in (1) tracking the key industrial sectors through the inhibitive driving effects on CO₂ mitigation in each provincial region in China; (2) inventorying the critical emission characteristics of the key sectors in terms of larger contribution to CO₂ emissions to facilitate the formulation of differentiated emission control measures.

2. Methods

2.1. Divisia Decomposition Analysis

The LMDI decomposition method has two forms: addition and multiplication [51]. Compared with other index decomposition methods, LMDI has the advantages of wider application scope and easier interpretation of results [52]. In order to conduct the attribution analysis, the LMDI multiplication decomposition method proposed by Choi and Ang [53] is adopted here. The CO₂ emissions are decomposed into the Kaya identity [54] expressed as:

\[ C = \sum_i \sum_j C_{ij} = \frac{C_{ij}}{E_{ij}} \times \frac{E_i}{Q_i} \times \frac{Q_i}{P_i} \times P \]

(1)

where C is total CO₂ emissions of the industry; i denotes an industrial sector and j denotes an energy type; E is energy consumption; Q_i is the industrial output of sector i and Q is total industrial output of a region; P is population of a region; C_{ij}/E_{ij} denotes the CO₂ emission coefficient of energy j in sector i (ED_{ij}); E_i/Q_i denotes the energy structure of sector i (ES_{i}); E_i/Q_i denotes the energy intensity of sector i (EI_i); Q_i/P_i denotes industrial structure (IS_i); Q/P denotes per capita industrial development level (IO).

The variations in total CO₂ emission over the period \([t-1, t]\) can be calculated as follows:

\[ \frac{C_t}{C_{t-1}} = D_{ED}^{t-1, t} \times D_{ES}^{t-1, t} \times D_{EI}^{t-1, t} \times D_{IS}^{t-1, t} \times D_{IO}^{t-1, t} \times D_P^{t-1, t} \]

(2)

where \(D_{ED}^{t-1, t}, D_{ES}^{t-1, t}, D_{EI}^{t-1, t}, D_{IS}^{t-1, t}, D_{IO}^{t-1, t}\) and \(D_P^{t-1, t}\) denote the variations in CO₂ emissions induced by emission coefficient, energy structure, energy structure, energy intensity, industrial structure, per capita industrial development level, and population, respectively. The variables in Equation (2) are calculated as follows:

\[ D_{ED}^{t-1, t} = \exp \left( \sum_{i=1}^{I} \sum_{j=1}^{J} \omega_{ij}^{t-1, 0} \ln \left( \frac{ED_{ij,t}}{ED_{ij,t-1}} \right) \right) \]

(3)
where

\[ D_{ES}^{t-1} = \exp \left( \sum_{i=1}^{J} \sum_{j=1}^{I} \omega_{ij}^{t-1} \ln \left( \frac{ES_{ij,t}}{ES_{ij,t-1}} \right) \right) \]

\[ D_{EI}^{t-1} = \exp \left( \sum_{i=1}^{J} \sum_{j=1}^{I} \omega_{ij}^{t-1} \ln \left( \frac{EI_{ij,t}}{EI_{ij,t-1}} \right) \right) \]

\[ D_{IS}^{t-1} = \exp \left( \sum_{i=1}^{J} \sum_{j=1}^{I} \omega_{ij}^{t-1} \ln \left( \frac{IS_{ij,t}}{IS_{ij,t-1}} \right) \right) \]

\[ D_{IO}^{t-1} = \exp \left( \sum_{i=1}^{J} \sum_{j=1}^{I} \omega_{ij}^{t-1} \ln \left( \frac{IO_{ij,t}}{IO_{ij,t-1}} \right) \right) \]

\[ D_{IP}^{t-1} = \exp \left( \sum_{i=1}^{J} \sum_{j=1}^{I} \omega_{ij}^{t-1} \ln \left( \frac{IP_{ij,t}}{IP_{ij,t-1}} \right) \right) \]

where

\[ \omega_{ij}^{t-1} = \frac{L(C_{ij,t}/C_{ij,t-1}/C_{t-1})}{\sum_{i=1}^{J} \sum_{j=1}^{I} L(C_{ij,t}/C_{ij,t-1}/C_{t-1})} \]

and \( L(A, B) = (A - B)/(\ln A - \ln B) \) represents the logarithmic mean function.

The multi-period divisia decomposition expresses total emission variations over the period \([0, T]\), which can be expressed as:

\[
\frac{C_T}{C_0} = \prod_{t=1}^{T} \frac{C_t}{C_{t-1}} = \prod_{t=1}^{T} \left( D_{ED}^{t-1} \times D_{ES}^{t-1} \times D_{EI}^{t-1} \times D_{IS}^{t-1} \times D_{IO}^{t-1} \times D_{IP}^{t-1} \right)
\]

\[ = D_{ED}^{0,T} \times D_{ES}^{0,T} \times D_{EI}^{0,T} \times D_{IS}^{0,T} \times D_{IO}^{0,T} \times D_{IP}^{0,T} \]

where \( D_{ED}^{0,T}, D_{ES}^{0,T}, D_{EI}^{0,T}, D_{IS}^{0,T}, D_{IO}^{0,T}, \) and \( D_{IP}^{0,T} \) denote the corresponding cumulative products of single-period decomposed variables.

2.2. Attribution Analysis

Attribution analysis is used to further explore the contribution of individual components to the effects of influencing factors [53]. Based on the results of the LMDI multiplicative decomposition, this method can attribute the variations in decomposition factors’ effects to all terminal sectors. For example, the single-period attribution results of energy intensity can be expressed as:

\[
\frac{E_{i,t}}{E_{i,t-1}} - 1 = \sum_{i=1}^{I} \sum_{j=1}^{J} r_{ij} \left( \frac{E_{i,t}}{E_{i,t-1}} - 1 \right)
\]

\[ r_{ij} = \frac{\omega_{ij}^{t-1} E_{i,t-1}}{\sum_{j=1}^{J} \sum_{i=1}^{I} \omega_{ij}^{t-1} E_{i,t-1}} \]

where \( \sum_{j=1}^{J} r_{ij} \left( \frac{E_{i,t}}{E_{i,t-1}} - 1 \right) \) represents the contribution of sector \( i \) to the variation of energy intensity over the period \([t - 1, t]\); \( r_{ij} \) denotes the weight of energy type \( j \) in sector \( i \).

According to the single-period attribution results, the contribution of each sector to variations in energy intensity over the period \([0, T]\) are expressed as:
Due to the absence of economic data for subdivided areas, Equations (11) and (12) can be used to describe the contribution of a sector to variations in other influencing factors.

\[
\frac{EI_t}{EI_{t-1}} - 1 = \sum_{j=1}^{J} \sum_{i=1}^{I} \frac{EI_{t-1}}{EI_{t}} r_{ij,t-1,t} (\frac{EI_{t}}{EI_{t-1}} - 1)
\]

\[
r_{ij,t-1,t} = \frac{\sum_{i=1}^{I} \sum_{j=1}^{J} \omega_{ij} \frac{EI_{t-1}}{EI_{t}}}{\sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{t=1}^{T} EI_{t-1}}
\]

where \( \sum_{j=1}^{J} \sum_{i=1}^{I} \frac{EI_{t-1}}{EI_{t}} r_{ij,t-1,t} (\frac{EI_{t}}{EI_{t-1}} - 1) \) represents the contribution of sector \( i \) to the multi-period variations in energy intensity effect over the period \([t - 1, t]\). Similarly, Equations (11) and (12) can be used to describe the contribution of a sector to variations in other influencing factors.

2.3. Decoupling Index

Most researchers have applied the decoupling model to confirm whether environmental issues have been decoupled from economic growth [55–57]. At present, there are two widely used models in this field. Compared with the Organization for Economic Co-operation and Development (OECD) decoupling model, the Tapio decoupling model is more widely used due to low data requirements, simple operation, and clear results. The Tapio decoupling model is used in this study to analyze if CO\(_2\) emissions of these key sectors have been decoupled from industrial output.

\[
\gamma = \frac{\Delta C}{\Delta Y} / Y
\]

where \( \gamma \) denotes the decoupling index between CO\(_2\) emissions and industrial output; \( Y \) represents industrial output; \( \Delta C \) and \( \Delta Y \) denote the variations in CO\(_2\) emissions and industrial output, respectively. Different levels of decoupling state are presented in Table 1.

| \( \Delta C/C \) | \( \Delta Y/Y \) | \( \gamma \) | Decoupling State |
|-----------------|----------------|------|-----------------|
| <0 | >0 | \( \gamma < 0 \) | Strong decoupling |
| >0 | >0 | \( 0.8 > \gamma \geq 0 \) | Weak decoupling |
| >0 | >0 | \( 1.2 \geq \gamma \geq 0.8 \) | Expansive coupling |
| >0 | >0 | \( \gamma > 1.2 \) | Expansive decoupling |
| >0 | <0 | \( \gamma < 0 \) | Strong negative decoupling |
| <0 | <0 | \( 0.8 > \gamma \geq 0 \) | Weak negative decoupling |
| <0 | <0 | \( 1.2 \geq \gamma \geq 0.8 \) | Recessive coupling |
| <0 | <0 | \( \gamma < 0 \) | Recessive decoupling |

2.4. Data and Study Area

The study period ranges from 2010 to 2019 considering the availability of the latest data for each provincial region. Overall, the study period can reflect the situations in the 12th and 13th five-year plan periods. Due to the absence of economic data for subdivided industrial sectors, LMDI-attribution analysis and decoupling analysis are only carried out until 2017. The data on energy consumption and CO\(_2\) emissions during this period are obtained from the datasets published by China Emission Accounts and Datasets (CEADs) inventory [59–61]. The data on industrial output and population of 30 provincial regions are gathered from the China Statistical Yearbooks [62]. To accommodate the price inflation, the industrial output data are normalized at the 2010 constant price.
The level of industrial development in China is uneven across regions, with Guangdong, Jiangsu, Shandong, Zhejiang, and other eastern coastal regions having a higher level than the central and western regions. However, the pace of industrial development in the central and western regions has been accelerated, in part supported by enhanced policies and capital investment. Meanwhile, each region has its own primary resources for development, for example, coal mining resources are concentrated in Shanxi, Inner Mongolia, Shaanxi, and other regions; Heilongjiang, Shandong, and Liaoning are richer in oil resources. In general, there are regional differences in the economy and resources; as a result, it is of great significance to analyze key sectors at the provincial level.

3. Results

3.1. Decomposition Analysis of Industrial CO$_2$ Emissions

The industrial CO$_2$ emissions of 30 regions are decomposed by LMDI method according to Equations (1)–(10). The results show that, in most regions, industrial development and population have positive effects, while energy intensity and industrial structure have negative effects, as illustrated in Figure 1. Industrial development is the most important driver of emissions. The regions where the contribution of industrial development is larger include Anhui, Guizhou, Jiangxi, Ningxia, Shaanxi, etc. These regions have a weaker economic base, but are relatively rich in resources to boost industrial development. However, the growth rate of industrial output of the developed regions, such as Beijing, Guangdong, Shanghai, and Zhejiang, is slowing down due to stronger economic foundation. The promotive effects of industrial development in these regions are not very obvious. The contribution of population is weaker than that of industrial development. Except for Heilongjiang, Jilin, and Liaoning, population contributes positively to emissions in most regions. In recent years, the low birth rate and serious outflow of population in the Northeast China are responsible for this situation.

Figure 1. LMDI decomposition results of industrial CO$_2$ emissions of regions during 2010–2017. ES: energy structure; IS: industrial structure; EI: energy intensity; IO: per capita industrial development level; P: population.
Attributed to the goals for energy intensity and CO$_2$ emission intensity control proposed successively in the 11th and 12th five-year plans, the effects on energy conservation and emission reduction are gradually emerging, which impels the inhibitive effect of energy intensity in most regions (except Heilongjiang and Qinghai) during the study period. Industrial structure is also an inhibitive factor in most regions. However, industrial structure in regions, such as Hainan, Liaoning, and Xinjiang, promotes emissions. Taking Liaoning as an example, the contribution rate of industrial structure is as high as 53%. This is possibly triggered by that the heavy industrial sectors with larger emissions, such as SPFM, have an upward trend in industrial output (the abbreviations of sectors are provided in Table 2). Meanwhile, the proportion of industrial output of the light industrial sectors is declining. As a result, industrial structure has a great promotive effect in Liaoning. As for energy structure, the inhibitive effect is slightly obvious in regions rich in renewable energy, such as Qinghai, Guangxi, and Yunnan. However, seen overall, the effect of energy structure is insignificant.

Table 2. Sector classification and abbreviation.

| Code | Sector                                      | Abbreviation |
|------|---------------------------------------------|--------------|
| 1    | Coal Mining and Dressing                    | CMD          |
| 2    | Petroleum and Natural Gas Extraction        | PNGE         |
| 3    | Ferrous Metals Mining and Dressing          | FMMD         |
| 4    | Nonmetal Minerals Mining and Dressing       | NMMD         |
| 5    | Food Processing                             | FPS          |
| 6    | Food Production                             | FP           |
| 7    | Beverage Production                         | BP           |
| 8    | Tobacco Processing                          | TP           |
| 9    | Textile Industry                            | TI           |
| 10   | Garments and Other Fiber Products           | GOFP         |
| 11   | Leather, Furs, Down and Related Product     | LFDRP        |
| 12   | Timber Processing, Bamboo, Cane, Palm Fiber, and Straw Products | TPBCP |
| 13   | Furniture Manufacturing                     | FM           |
| 14   | Papermaking and Paper Products              | PP           |
| 15   | Printing and Record Medium Reproduction     | PRMR         |
| 16   | Cultural, Educational and Sports Articles   | CESA         |
| 17   | Petroleum Processing and Coking             | PPC          |
| 18   | Raw Chemical Materials and Chemical Products | RCMCP    |
| 19   | Medical and Pharmaceutical Products         | MPP          |
| 20   | Chemical Fiber                              | CF           |
| 21   | Rubber and Plastic Products                 | RPP          |
| 22   | Nonmetal Mineral Products                   | NMP          |
| 23   | Smelting and Pressing of Ferrous Metals     | SPFM         |
| 24   | Smelting and Pressing of Nonferrous Metals  | SPNM         |
| 25   | Metal Products                              | MP           |
| 26   | Ordinary Machinery                          | OM           |
| 27   | Equipment for Special Purposes              | ESP          |
| 28   | Transportation Equipment                    | TE           |
| 29   | Electric Equipment and Machinery            | EEM          |
| 30   | Electronic and Telecommunications Equipment | ETE          |
| 31   | Instruments, Meters, Cultural and Office Machinery | IMCOM |
| 32   | Other Manufacturing Industry                | OMI          |
| 33   | Scrap and waste                             | SW           |
| 34   | Production and Supply of Power and Heat     | PSPH         |
| 35   | Production and Supply of Gas                | PSG          |
| 36   | Production and Supply of Tap Water          | PSTW         |

3.2. Attribution Analysis of Sectors’ Contributions to CO$_2$ Mitigation

According to the results of LMDI decomposition, energy structure, industrial structure, and reduction in energy intensity contribute significantly to CO$_2$ mitigation in most regions. However, there are still some differences in specific inhibitive factors across regions. For example, the above three factors all have an inhibitive effect on CO$_2$ emissions in Anhui, while only industrial structures and reduction in energy intensity contribute to CO$_2$ mitigation in Guangdong. Therefore, 30 regions are divided into six groups according to the specific inhibitive factors for each region. On this basis, the variations in the effects of energy structure, industrial structure and energy intensity are further attributed to 36 subdivided...
industrial sectors in each region. Figure 2 combined with Tables S1–S3 in Supplementary Material shows the attribution results.

Figure 2. Attribution of CO₂ mitigation to the industrial sectors through energy structure, industrial structure, and energy intensity. (a) Group 1 (the inhibitive factors are energy structure, industrial structure, and energy intensity). (b) Group 2 (the inhibitive factors are industrial structure and energy intensity). (c) Group 3 (the inhibitive factors are energy structure and energy intensity). (d) Group 4 (the inhibitive factor is energy structure). (e) Group 5 (the inhibitive factor is industrial structure). (f) Group 6 (the inhibitive factor is energy intensity).

Regions in Group 1 include Anhui, Chongqing, Fujian, Guangxi, Jilin, Jiangsu, Shandong, Shaanxi, Shanghai, Sichuan, Tianjin, and Yunnan, in which energy structure, industrial structure, and energy intensity all make a contribution to emission reduction. The
contribution of PSPH is $-16.38\%$ though energy structure in Tianjin, and that of PPC is $-13.19\%$ in Shaanxi, which are obviously higher than that of other sectors. Sectors that significantly contribute to emission reduction through industrial structure in Group 1 appear to SPF in Guangxi ($-41.7\%$) and PSPH in Anhui ($-35.91\%$). Sectors contributing to the effects of energy intensity are basically concentrated in PSPH in each region, with the highest contribution in Guangxi ($-69.44\%$). Industrial structure and energy intensity contribute to CO$_2$ mitigation in regions in Group 2, including Guangdong, Guizhou, Hebei, Henan, Hubei, Hunan, Inner Mongolia, Jiangxi, Ningxia, and Shanxi. PSPH is the main contributor to the variations in industrial structure, followed by CMD in Henan ($-7.49\%$) and Hunan ($-10.15\%$), and SPF in Hebei ($-11.91\%$) and Hubei ($-11.85\%$). PSPH in Hunan ($-17.66\%$) makes a greater contribution to variations in energy intensity, while SPF in this group promotes CO$_2$ mitigation through energy intensity changes compared with Group 1. Group 3 includes Hainan, Liaoning, Xinjiang, and Zhejiang, where energy structures and energy intensity changes are the main inhibitive factors. Meanwhile, PPC in Liaoning ($-1.87\%$) and Xinjiang ($-2.62\%$) also have a great impact. Qinghai is the only one region in Group 4, where the contribution of PSPH to variations in energy structure is $-25.66\%$. PSPH ($-9.28\%$) and PPC ($-6.80\%$) in Heilongjiang contribute to CO$_2$ mitigation through industrial structure only, and this region is divided into Group 5. Energy intensity is the only inhibitive factor in Group 6. PSPH in Beijing ($-60.00\%$) and Gansu ($-28.72\%$) are the main contributors.

### 3.3. Key Industrial Sectors for CO$_2$ Mitigation

Sectors that considerably propel CO$_2$ mitigation through the inhibitive effects are defined as the key sectors in this study, which are the main forces of emission reduction deserving more attention in policy-making. However, the key sectors under different inhibitive factors are diverse, thus forming a combination of regional key sectors, as shown in Figure 3.

![Figure 3. Key industrial sectors for CO$_2$ mitigation in each region. (a) Group 1 (the inhibitive factors](image-url)
are energy structure, industrial structure and energy intensity). (b) Group 2 (the inhibitive factors are industrial structure and energy intensity). (c) Group 3 (the inhibitive factors are energy structure and energy intensity). (d) Group 4, 5, and 6 (the inhibitive factors are energy structure, industrial structure, and energy intensity, respectively). Each string of connected circles in the figure indicates that the sector (the smallest circle) has an inhibitive effect on regional (the middle circle) industrial CO$_2$ emissions through an inhibitive factor (the largest orange circle).

From the perspective of inhibitive factors, the key sectors under energy structure in Group 1 are concentrated in PPC and PSPH, while the key sectors under industrial structure and energy intensity are concentrated in SPFM and PSPH. The inhibitive factors of Group 2 are industrial structure and energy intensity, with the key sectors also concentrated in SPFM and PSPH. In Group 3, PSPH is the key sector for all regions under energy intensity, and the key sectors under energy structure also include PPC and PSPH. There is only one inhibitive factor in Group 3 to Group 5, with PSPH as the main key sector in three groups.

From the perspective of sectors, PSPH is the key sector for all regions, indicating that, with the development of low-carbon power supply and decarbonization technologies, CO$_2$ mitigation in PSPH is being promoted properly. It still has a great potential for further CO$_2$ mitigation that will be the main force for deepening emission reduction in energy system in the future. PPC and SPFM are also the key sectors for most regions. However, PPC generally contributes to emission reduction through energy structure, while SPFM through industrial structure and energy intensity. SPFM solidifies energy intensity improvement through energy-saving technological transformation, such as reducing the use of coal for iron making and smelting, and expanding clean energy use. PPC accelerates energy structure adjustment through eliminating outdated production capacity, combined with technological advancement, such as augmenting biofuel production. Other sectors, such as CMD in Anhui, Sichuan, Chongqing, Henan, and Hunan promote emission reduction mainly through industrial structure adjustment. NMP contributes to CO$_2$ mitigation mainly in Fujian, Sichuan, Chongqing, and Hubei through energy intensity changes. SPNM is the main promoter of emission reduction in Guangxi and Yunnan.

### 3.4. Emission Characteristics of the Key Sectors for CO$_2$ Mitigation

The critical emission characteristics, including decoupling from industrial development and the peaking status in each region are analyzed so as to better compare the emission status of the key sectors in different regions, with the results presented in Table 3. The two columns under each sector represent the two emission characteristics. Seen overall, in terms of either the number of key sectors that contribute to CO$_2$ mitigation or the emission characteristics, the performance of the economically developed eastern coastal regions is overall better than that of the economically underdeveloped central and western regions.

From the perspective of sector, except CMD whose emissions present recessive decoupling or negative decoupling, other key sectors in most regions have accomplished the decoupling of emissions from industrial development. However, through the comparison of the emission peaking status of regions, CMD is the one with the best situation among the key sectors, while SPFM and PSPH in most regions have not peaked the emissions, especially PSPH, whose emissions in most regions are still on the rise. From the perspective of region, Beijing and Shanghai have a small energy intensity although they have maintained the rapid growth in industrial output, and the decoupling from industrial development and the peaking status of the key sectors have been basically achieved through industrial restructure. Emissions of most key sectors in Fujian, Jiangsu, Sichuan, and Tianjin have been decoupled from industrial development, however without showing a clear trend towards peaking. Hebei, Hubei, Jilin, and Shaanxi are heavy industrial regions in need for transformation. The emissions of the key sectors have already turned a corner, but present weak negative decoupling due to the downward growth rate of industrial output. Some western regions, such as Guangxi and Xinjiang, fall behind in industrial development. Emissions of the key sectors are in a state of negative decoupling, and the emission peaking is yet to be realized.
Table 3. Critical emission characteristics of the key industrial sectors of regions.

| Group 1 | Anhui | Chongqing | Guangxi | Jilin | Jiangsu | Shandong | Shaanxi | Shanghai | Sichuan | Tianjin | Yunnan |
|---------|-------|-----------|---------|-------|---------|---------|---------|----------|---------|---------|--------|
| Coal Mining and Dressing | RC | WND | FD | EC | SD | END | RD | SD | SD | SD | SD |
| Petroleum Processing and Coking | WD | x | WD | x | SD | x | RD | x | SD | x | SD |
| Nonmetal Mineral Products | WD | x | WD | x | SD | x | RD | x | SD | x | SD |
| Smelting and Pressing of Ferrous Metals | WD | x | WD | x | SD | x | RD | x | SD | x | SD |
| Smelting and Pressing of Nonferrous Metals | WD | x | WD | x | SD | x | RD | x | SD | x | SD |
| Production and Supply of Power and Heat | WD | x | WD | x | SD | x | RD | x | SD | x | SD |

Group 2

| Guangdong | Guizhou | Hebei | Henan | Hubei | Hunan | Jiangxi | Inner Mongolia | Ningxia | Shanxi |
|-----------|---------|-------|-------|-------|-------|---------|----------------|---------|--------|
| Coal Mining and Dressing | SD | o | RC | o | SD | o | WD | x | SD |
| Petroleum Processing and Coking | WD | x | WD | x | SD | x | WD | x | WD |
| Nonmetal Mineral Products | WD | x | WD | x | SD | x | WD | x | WD |
| Smelting and Pressing of Ferrous Metals | WD | x | WD | x | SD | x | WD | x | WD |
| Smelting and Pressing of Nonferrous Metals | WD | x | WD | x | SD | x | WD | x | WD |
| Production and Supply of Power and Heat | WD | x | WD | x | SD | x | RD | x | SD |

Group 3

| Hainan | Xinjiang | Zhejiang |
|--------|----------|----------|
| Coal Mining and Dressing | RD | x | RC | x |
| Petroleum Processing and Coking | WD | x | WD | x |
| Nonmetal Mineral Products | WD | x | WD | x |
| Smelting and Pressing of Ferrous Metals | WD | x | WD | x |
| Smelting and Pressing of Nonferrous Metals | WD | x | WD | x |
| Production and Supply of Power and Heat | WD | x | WD | x |

Group 4

| Beijing | Gansu |
|--------|-------|
| Coal Mining and Dressing | RD | o |
| Petroleum Processing and Coking | WD | x |
| Nonmetal Mineral Products | WD | x |
| Smelting and Pressing of Ferrous Metals | WD | x |
| Smelting and Pressing of Nonferrous Metals | WD | x |
| Production and Supply of Power and Heat | WD | o |

Group 5

| Heilongjiang |
|--------------|
| Coal Mining and Dressing | RD |
| Petroleum Processing and Coking | WD |
| Nonmetal Mineral Products | WD |
| Smelting and Pressing of Ferrous Metals | WD |
| Smelting and Pressing of Nonferrous Metals | WD |
| Production and Supply of Power and Heat | WD |

Table 3. Critical emission characteristics of the key industrial sectors of regions.

| Group 1 | Anhui | Chongqing | Guangxi | Jilin | Jiangsu | Shandong | Shaanxi | Shanghai | Sichuan | Tianjin | Yunnan |
|---------|-------|-----------|---------|-------|---------|---------|---------|----------|---------|---------|--------|
| Coal Mining and Dressing | RC | WND | FD | EC | SD | END | RD | SD | SD | SD | SD |
| Petroleum Processing and Coking | WD | x | WD | x | SD | x | RD | x | SD | x | SD |
| Nonmetal Mineral Products | WD | x | WD | x | SD | x | RD | x | SD | x | SD |
| Smelting and Pressing of Ferrous Metals | WD | x | WD | x | SD | x | RD | x | SD | x | SD |
| Smelting and Pressing of Nonferrous Metals | WD | x | WD | x | SD | x | RD | x | SD | x | SD |
| Production and Supply of Power and Heat | WD | x | WD | x | SD | x | RD | x | SD | x | SD |

4. Discussion

The attribution analysis reveals that sectors contributing to CO₂ mitigation across regions are mainly concentrated in PSPH, SPFM, and PPC, which is attributed to reinforced government’s control over these sectors in recent years. Alongside energy efficiency improvement and renewable energy development, these key sectors have basically realized the decoupling from industrial development. While promoting CO₂ mitigation, PSPH also needs to meet the continuous growth of power demand. However, restricted by the coal-dominated energy structure, the emissions of PSPH lag far from the peak, which is in compliance with the results of Wen et al. [63]. The same situation happens to SPFM, which is the second largest emitter following PSPH due to its large scale and production process characteristics relying on fossil fuels.

There are differences in the key sectors and emission characteristics among regions. Beijing, Qinghai, Shanghai, and Sichuan are among the minority of regions where PSPH has achieved the emission peak. These regions are either at the forefront of economic development or rich in clean energy. The promotion of power trading markets, and the deployment of pumped storage and offshore power stations have prompted to improve power generation efficiency. CMD is the key sector for Anhui, Chongqing, Henan, Hunan, and other regions, in addition to the above sectors. The number of mines with small single wells in these regions have reduced since the implementation of coal supply-side reform because of the poor mining conditions. Meanwhile, the support of relevant policies, such as controlling the total number of coal mines in Hunan, resolving overcapacity in Henan, as well as putting forward coal-intelligence goals in Anhui and Henan, have also contributed to CO₂ mitigation in this sector. However, the decoupling status of CMD is mainly in recessive coupling, indicating that both CO₂ emission and industrial output are declining, which shows the main task of the sector in these regions is changing the development mode.
to realize the decoupling as soon as possible. PPC mainly contribute to CO\textsubscript{2} mitigation in the Northeast China and some oil-producing regions, such as Shaanxi, Tianjin, and Xinjiang, among which the decoupling has been achieved, except Jilin and Shaanxi. The long industrial chain, the wide variety of products, and the continuous growth of oil consumption pose severe challenges to low-carbon transition in this sector. Strengthening emission reduction in production process and alleviating energy consumption caused by raw materials to achieve deeper decarbonization is the key to reaching the peak for the sector. There are unique non-metallic resources in Hunan, Jiangxi, and Sichuan, and the industrial parks have been established successively in these regions. The development of energy efficient materials, implementation of access standards and establishment of R&D centers have facilitated a green manufacturing system, enabling \textit{NMP} to promote CO\textsubscript{2} mitigation in these regions. \textit{SPNM} undergoes high-quality development in regions rich in mineral resources, such as Yunnan and Guangxi, through technological breakthrough as in the case of aluminum electrolysis.

The methods presented in this paper that couple the inhibitive factors extracted from LMDI analysis with attribution analysis provide an approach capable of quantifying the contribution of industrial sectors to the drivers and extracting the key sectors that contributed to CO\textsubscript{2} mitigation. Complex network approach and input–output model have also been applied to analyze the different roles of various sectors to help decision-makers identify key sectors [64,65]. However, the key sectors identified in this study are those under the inhibitive factors that promote CO\textsubscript{2} mitigation in each region, meaning that these sectors are already contributing to emission reductions. Additionally, this is a better visualization of which factors of these sectors can be adjusted to mitigate regional CO\textsubscript{2} more effectively, and facilitate policymakers to develop more targeted emission reduction policies. Furthermore, this study analyzes the critical emission characteristics of the key sectors across regions, so as to provide reference to formulating differentiated emission reduction measures for regions with different levels of development, policies, and technological guidance. The methods can be extended to recognize the key sectors in terms of significant contribution to the emission and mitigation of air pollutants or water pollutants.

Some policy implications can be revealed through combing the strategic goal of China’s carbon peaking before 2030 with the findings of this study. Firstly, compared with other sectors, \textit{PSPH} and \textit{SPFM} in most regions have not yet achieved the peak. Renewable energy should be the priority for power generation in the future, meanwhile the energy storage technology and power market should be extended to promote an early emission peak for \textit{PSPH}. As for \textit{SPFM}, excessive and outdated production capacity is still the main problem faced by this sector. Secondly, while \textit{PPC} is undergoing prosperous development in Tianjin, Heilongjiang, Xinjiang, and other oil-producing regions, it still suffers from heavy emission control burden. In order to arrive at the emission peak earlier, adjusting the structure of refinery products and replacing with greener fuels is the prior mission. \textit{CMD} has made certain contribution to CO\textsubscript{2} mitigation in Anhui, Hunan, Henan, and other regions. However, this sector should be further focused on in Shanxi, Shaanxi, and Mongolia for the release of production capacity of mines under construction and the elimination of mines with poor endowments. Regions rich in mineral resources, such as Yunnan and Guangxi, should strengthen technological innovation and policy guidance in \textit{SPNM}. Finally, regions, such as Beijing, Guangdong, and Zhejiang, only have \textit{PSPH} as their key sector. As the first echelon leading China in achieving the carbon peaking and carbon neutrality goals, they should keep transforming their own advantages into the attractive force for the development of the surrounding regions and provide support to boost low-carbon development in surrounding regions.

5. Conclusions

In the context of pursuing earlier carbon peaking in China, CO\textsubscript{2} mitigation in industry, which the largest source of CO\textsubscript{2} emissions, is a foremost task. Using the LMDI-attribution method, this study identifies the key sectors that significantly contribute to CO\textsubscript{2} mitigation
in 30 provincial regions in China, and analyzes the emission characteristics, including
decoupling from industrial development and peaking status of these sectors. Several key
findings are summarized as follows:

Industrial development and population growth are the main drivers of emissions. Energy intensity and industrial structure inhibit emissions in most regions, but industrial
structure is a main factor promoting emissions in some regions as result of the increasing
share of energy-intensive sector. The effect of energy structures on emission reduction
in most regions is not obvious. According to the combinations of inhibitive factors, the
30 regions are divided into six groups. The key sectors that promote CO$_2$ mitigation in
each region are tracked through the inhibitive effects, mainly including: coal mining and
dressing, petroleum processing and coking, non-metal mineral products, smelting and pressing of
ferrous metals, smelting and pressing of nonferrous metals, and production and supply of power
and heat. Of these, production and supply of power and heat propels CO$_2$ mitigation through
all three inhibitive factors. Petroleum processing and coking generally contributes to emission
reduction through energy structure, while smelting and pressing of ferrous metals through
industrial structure and energy intensity.

The results of the study also show the emission characteristics of key sectors in each
region. Production and supply of power and heat is the key sector in all regions, followed by
smelting and pressing of ferrous metals, but these two sectors in most regions have not achieved
the emission peak. Except coal mining and dressing, the key sectors in most regions have
accomplished the decoupling of emissions from industrial development. In addition, coal
mining and dressing effectively promotes CO$_2$ mitigation in Anhui, Henan, and Hunan, with
a larger contribution of petroleum processing and coking in Tianjin, Xinjiang, Heilongjiang,
and other oil-producing regions, and that of smelting and pressing of nonferrous Metals
in Yunnan and Guangxi.

This study identifies the key sectors that contribute to regional emission reductions,
which are major areas for future industrial CO$_2$ mitigation; it also examines the critical
emission characteristics of these sectors. The level of development of the key sectors varies
from region to region, and the results of the study can provide assistance in formulating
regional emission reduction paths that are more suitable for local development. The
revealed policy implications can serve for better policy-making on sector-level and region-
level carbon mitigation practices. There are still some limitations in this paper. First of all,
due to the limitations of the research method of attribution analysis, the change of the total
amount can only be decomposed into one-dimensional factors, which makes it impossible
to explore the driving factors of the change of emissions from multiple dimensions, such
as different sectors and different energy types. Second, the key sectors discussed in this
study are those under the inhibitive factors of industrial CO$_2$ emissions, and the promotive
factors of emissions are not specific to the segmented sectors, which should be incorporated
into the further work.

**Supplementary Materials:** The following supporting information can be downloaded at:
https://www.mdpi.com/article/10.3390/ijerph192114561/s1, Table S1. Multi-period attribution
analysis of energy structure; Table S2. Multi-period attribution analysis of industrial structure; Table
S3. Multi-period attribution analysis of energy intensity.

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References

1. Rahut, D.B.; Aryal, J.P.; Marenya, P. Understanding climate-risk coping strategies among farm households: Evidence from five countries in Eastern and Southern Africa. *Sci. Total Environ.* 2021, 769, 145236. [CrossRef] [PubMed]

2. Rivas, S.; Urraca, R.; Bertoldi, P.; Thiel, C. Towards the EU Green Deal: Local key factors to achieve ambitious 2030 climate targets. *J. Clean. Prod.* 2021, 320, 128878. [CrossRef]

3. Dong, H.; Feng, Z.; Yang, Y.; Li, P.; You, Z.; Xiao, C. Sub-national climate change risk assessment: A case analysis for Tibet and its prefecture-level cities. *Sci. Total Environ.* 2022, 807, 151045. [CrossRef] [PubMed]

4. IEA. *Energy Technology Perspective 2020—Special Report on Carbon Capture Utilisation and Storage;* IEA: Paris, France, 2020.

5. Gao, C.; Ge, H. Spatiotemporal characteristics of China’s carbon emissions and driving forces: A Five-Year Plan perspective from 2001 to 2015. *J. Clean. Prod.* 2020, 248, 119280. [CrossRef]

6. Kouyakhi, N.R. CO₂ emissions in the Middle East: Decoupling and decomposition analysis of carbon emissions, and projection of its future trajectory. *Sci. Total Environ.* 2022, 845, 157182. [CrossRef]

7. Jiao, J.; Chen, C.; Bai, Y. Is green technology vertical spillovers more significant in mitigating carbon intensity? Evidence from Chinese industries. *J. Clean. Prod.* 2020, 257, 120354. [CrossRef]

8. Yu, X.; Chen, H.; Wang, B.; Wang, R.; Shan, Y. Driving forces of CO₂ emissions and mitigation strategies of China’s National low carbon pilot industrial parks. *Appl. Energy* 2018, 212, 1553–1562. [CrossRef]

9. Cheng, H.; Dong, S.; Li, F.; Yang, Y.; Li, S.; Li, Y. Multiregional Input-Output Analysis of Spatial-Temporal Evolution Driving Force for Carbon Emissions Embodied in Interprovincial Trade and Optimization Policies: Case Study of Northeast Industrial District in China. *Environ. Sci. Technol.* 2018, 52, 346–358. [CrossRef]

10. Tian, X.; Bai, F.; Jia, J.; Liu, Y.; Shi, F. Realizing low-carbon development in a developing and industrializing region: Impacts of industrial structure change on CO₂ emissions in southwest China. *J. Environ. Manag.* 2019, 233, 728–738. [CrossRef]

11. Ortega-Ruiz, G.; Mena-Nieto, A.; Golpe, A.A.; Garcia-Ramos, J.E. CO₂ emissions and causal relationships in the six largest world emitters. *Renew. Sustain. Energy Rev.* 2022, 162, 112435. [CrossRef]

12. Wang, Z.J.; Jiang, Q.Z.; Dong, K.Y.; Mubarak, M.S.; Dong, X.C. Decomposition of the US CO₂ emissions and its mitigation potential: An aggregate and sectoral analysis. *Energy Policy* 2020, 147, 111925. [CrossRef]

13. Wen, L.; Li, Z. Provincial-level industrial CO₂ emission drivers and emission reduction strategies in China: Combining two-layer LMDI method with spectral clustering. *Sci. Total Environ.* 2020, 700, 134374. [CrossRef]

14. Zhu, Q.; Li, X.; Li, F.; Zhou, D. The potential for energy saving and carbon emission reduction in China’s regional industrial sectors. *Sci. Total Environ.* 2020, 716, 135009. [CrossRef]

15. De Oliveira-De Jesus, P.M. Effect of generation capacity factors on carbon emission intensity of electricity of Latin America & the Caribbean, a temporal IDA-LMDI analysis. *Renew. Sustain. Energy Rev.* 2019, 101, 516–526.

16. Zhang, Y.; Wang, Y.; Hou, X. Carbon Mitigation for Industrial Sectors in the Jing-Jin-Ji Urban Agglomeration, China. *Sustainability* 2019, 11, 6383. [CrossRef]

17. Talaei, A.; Gecmechu, E.; Kumar, A. Key factors affecting greenhouse gas emissions in the Canadian industrial sector: A decomposition analysis. *J. Clean. Prod.* 2020, 246, 119026. [CrossRef]

18. Xie, P.; Yang, F.; Mu, Z.; Gao, S. Influencing factors of the decoupling relationship between CO₂ emission and economic development in China’s power industry. *Energy* 2020, 209, 118341. [CrossRef]

19. Dong, J.; Li, C.; Wang, Q. Decomposition of carbon emission and its decoupling analysis and prediction with economic development: A case study of industrial sectors in Henan Province. *J. Clean. Prod.* 2021, 321, 120019. [CrossRef]

20. Kopidou, D.; Diakoulaki, D. Decomposing industrial CO₂ emissions of Southern European countries into production- and consumption-based driving factors. *J. Clean. Prod.* 2017, 167, 1325–1334. [CrossRef]

21. Lin, B.; Benjamin, N.I. Determinants of industrial carbon dioxide emissions growth in Shanghai: A quantile analysis. *J. Clean. Prod.* 2019, 217, 776–786. [CrossRef]

22. Lu, L.; Zhou, L.; Zhang, H.; Weng, Y. The effects of industrial energy consumption on energy-related carbon emissions at national and provincial levels in China. *Energy Sci. Eng.* 2018, 6, 371–384. [CrossRef]

23. Lu, Q.; Yang, H.; Huang, X.; Chuai, X.; Wu, C. Multi-sectoral decomposition in decoupling industrial growth from carbon emissions in the developed Jiangsu Province, China. *Energy* 2015, 82, 414–425. [CrossRef]

24. Román-Collado, R.; Morales-Carrion, A.V. Towards a sustainable growth in Latin America: A multiregional spatial decomposition analysis of the driving forces behind CO₂ emissions changes. *Energy Policy* 2018, 115, 273–280. [CrossRef]

25. Avenyo, E.K.; Tregenna, F. Greening manufacturing: Technology intensity and carbon dioxide emissions in developing countries. *Appl. Energy* 2022, 324, 119726. [CrossRef]

26. Wang, M.; Feng, C. Impacts of oriented technologies and economic factors on China’s industrial climate mitigation. *J. Clean. Prod.* 2019, 233, 1016–1028. [CrossRef]

27. Fang, K.; Tang, Y.Q.; Zhang, Q.F.; Song, J.N.; Wen, Q.; Sun, H.P.; Ji, C.Y.; Xu, A.Q. Will China peak its energy-related carbon emissions by 2030? Lessons from 30 Chinese provinces. *Appl. Energy* 2019, 255, 113852. [CrossRef]

28. Jiang, J.; Ye, B.; Liu, J. Research on the peak of CO₂ emissions in the developing world: Current progress and future prospect. *Appl. Energy* 2019, 235, 186–203. [CrossRef]

29. Xu, G.Y.; Schwarz, P.; Yang, H.L. Adjusting energy consumption structure to achieve China’s CO₂ emissions peak. *Renew. Sustain. Energy Rev.* 2020, 122, 109737. [CrossRef]
30. Wu, R.; Geng, Y.; Cui, X.; Gao, Z.; Liu, Z. Reasons for recent stagnancy of carbon emissions in China’s industrial sectors. *Energy* **2019**, *172*, 457–466. [CrossRef]

31. Yu, S.; Zheng, S.; Li, X.; Li, L. China can peak its energy-related carbon emissions before 2025: Evidence from industry restructuring. *Energy Econ.* **2018**, *73*, 91–107. [CrossRef]

32. Zhou, S.; Wang, Y.; Yuan, Z.; Ou, X. Peak energy consumption and CO2 emissions in China’s industrial sector. *Energy Strategy Rev.* **2018**, *20*, 113–123. [CrossRef]

33. Li, M.; Mi, Z.; Coffman, D.M.; Wei, Y.M. Assessing the policy impacts on non-ferrous metals industry’s CO2 reduction: Evidence from China. *J. Clean. Prod.* **2018**, *192*, 252–261. [CrossRef]

34. Lu, C.; Li, W.; Gao, S. Driving determinants and prospective prediction simulations on carbon emissions peak for China’s heavy chemical industry. *J. Clean. Prod.* **2020**, *251*, 119642. [CrossRef]

35. Tang, B.; Li, R.; Yu, B.; An, R.; Wei, Y.M. How to peak carbon emissions in China’s power sector: A regional perspective. *Energy Policy* **2018**, *120*, 365–381. [CrossRef]

36. van Ruijven, B.J.; van Vuuren, D.P.; Boskaljon, W.; Neelis, M.L.; Saygin, D.; Patel, M.K. Long-term model-based projections of energy use and CO2 emissions from the global steel and cement industries. *Resour. Conserv. Recycl.* **2016**, *112*, 15–36. [CrossRef]

37. Tao, Y.; Wen, Z.; Xu, L.; Zhang, X.; Tan, Q.; Li, H.; Evans, S. Technology options: Can Chinese power industry reach the CO2 emission peak before 2030? *Resour. Conserv. Recycl.* **2019**, *147*, 85–94. [CrossRef]

38. Meng, M.; Jing, K.; Mander, S. Scenario analysis of CO2 emissions from China’s electric power industry. *J. Clean. Prod.* **2017**, *142*, 3101–3108. [CrossRef]

39. Li, Z.; Dai, H.; Song, J.; Sun, L.; Ge, Y.; Lu, K.; Hanaoka, T. Assessment of the carbon emissions reduction potential of China’s iron and steel industry based on a simulation analysis. *Energy* **2019**, *183*, 279–290. [CrossRef]

40. Zhao, Y.; Cui, Z.; Wu, L.; Gao, W. The green behavioral effect of clean coal technology on China’s power generation industry. *Sci. Total Environ.* **2019**, *675*, 286–294. [CrossRef]

41. Quader, M.A.; Ahmed, S.; Ghazilla, R.A.R.; Ahmed, S.; Dahari, M. A comprehensive review on energy efficient CO2 breakthrough technologies for sustainable green iron and steel manufacturing. *Renew. Sustain. Energy Rev.* **2015**, *50*, 594–614. [CrossRef]

42. Xuan, D.; Ma, X.; Shang, Y. Can China’s policy of carbon emission trading promote carbon emission reduction? *J. Clean. Prod.* **2020**, *270*, 122383. [CrossRef]

43. Kim, P.; Bae, H. Do firms respond differently to the carbon pricing by industrial sector? How and why? A comparison between manufacturing and electricity generation sectors using firm-level panel data in Korea. *Energy Policy* **2022**, *162*, 112773. [CrossRef][PubMed]

44. Gonzalez, P.F.; Landajo, M.; Presno, M. The Divisia real energy intensity indices: Evolution and attribution of percent changes in 20 European countries from 1995 to 2010. *Energy* **2013**, *58*, 340–349. [CrossRef]

45. Zhang, X.; Su, B.; Yang, J.; Cong, J. Index decomposition and attribution analysis of aggregate energy intensity in Shanxi Province (2000–2015). *J. Clean. Prod.* **2019**, *238*, 117897. [CrossRef]

46. Liu, N.; Ma, Z.; Kang, J. Changes in carbon intensity in China’s industrial sector: Decomposition and attribution analysis. *Energy Policy* **2015**, *87*, 28–38. [CrossRef]

47. Wang, Q.; Hang, Y.; Zhou, P.; Wang, Y. Decoupling and attribution analysis of industrial carbon emissions in Taiwan. *Energy* **2016**, *113*, 728–738. [CrossRef]

48. Xing, Z.; Wang, J.; Feng, K.; Hubacek, K. Decline of net SO2 emission intensity in China’s thermal power generation: Decomposition and attribution analysis. *Sci. Total Environ.* **2020**, *719*, 137367. [CrossRef]

49. Liu, N.; Ma, Z.; Kang, J. A regional analysis of carbon intensities of electricity generation in China. *Energy Econ.* **2017**, *67*, 268–277. [CrossRef]

50. Ang, B.W. LMDI decomposition approach: A guide for implementation. *Energy Policy* **2015**, *86*, 233–238. [CrossRef]

51. Ang, B.W. Decomposition analysis for policymaking in energy. *Energy Policy* **2004**, *32*, 1131–1139. [CrossRef]

52. Choi, K.-H.; Ang, B.W. Attribution of changes in Divisia real energy intensity index—An extension to index decomposition analysis. *Energy Econ.* **2012**, *34*, 171–176. [CrossRef]

53. Kaya, Y. Impact of Carbon Dioxide Emission Control on GNP Growth: Interpretation of Proposed Scenarios. IPCC Energy and Industry Subgroup, Response Strategies Working Group: Paris, France, 1989.

54. Leal, P.A.; Marques, A.C.; Fuinhas, J.A. Decoupling economic growth from GHG emissions: Decomposition analysis by sectoral factors for Australia. *Econ. Anal. Policy* **2019**, *62*, 12–26. [CrossRef]

55. Roinioti, A.; Koroneos, C. The decomposition of CO2 emissions from energy use in Greece before and during the economic crisis and their decoupling from economic growth. *Renew. Sustain. Energy Rev.* **2017**, *76*, 448–459. [CrossRef]

56. Raza, M.Y.; Wu, R.; Lin, B. A decoupling process of Pakistan’s agriculture sector: Insights from energy and economic perspectives. *Energy* **2022**, *263*, 125658. [CrossRef]

57. Tapio, P. Towards a theory of decoupling: Degrees of decoupling in the EU and the case of road traffic in Finland between 1970 and 2001. *Transp. Policy* **2005**, *12*, 137–151. [CrossRef]

58. Guan, Y.; Shan, Y.; Huang, Q.; Chen, H.; Wang, D.; Hubacek, K. Assessment to China’s recent emission pattern shifts. *Earth Future* **2021**, *9*, e2021EF002241. [CrossRef]
60. Shan, Y.; Guan, D.; Zheng, H.; Ou, J.; Li, Y.; Meng, J.; Mi, Z.; Liu, Z.; Zhang, Q. China CO2 emission accounts 1997–2015. Sci. Data 2018, 5, 170201. [CrossRef]

61. Shan, Y.L.; Huang, Q.; Guan, D.B.; Hubacek, K. China CO2 emission accounts 2016–2017. Sci. Data 2020, 7, 54. [CrossRef]

62. National Bureau of Statistics of China. China Statistical Yearbook; China Statistics Press: Beijing, China, 2010.

63. Wen, H.; Chen, Z.; Yang, Q.; Liu, J.; Nie, P. Driving forces and mitigating strategies of CO2 emissions in China: A decomposition analysis based on 38 industrial sub-sectors. Energy 2022, 245, 123262. [CrossRef]

64. Jiang, M.H.; An, H.Z.; Gao, X.Y.; Liu, S.Y.; Xi, X. Factors driving global carbon emissions: A complex network perspective. Resour. Conserv. Recycl. 2019, 146, 431–440. [CrossRef]

65. Faridzad, A.; Banouei, A.A.; Banouei, J.; Golestan, Z. Identifying energy-intensive key sectors in Iran: Evidence from decomposed input-output multipliers. J. Clean. Prod. 2020, 243, 0118653. [CrossRef]