Postprint: Influencing Factors of Sectoral Carbon Emissions and Decoupling Efforts in Gansu Province

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Abstract

Utilizing the LMDI model, this study decomposed the factors influencing carbon emissions and their effects across 13 sub-sectors in Gansu Province from 2010 to 2019. The Tapio decoupling model was employed to analyze the decoupling relationship between economic growth and carbon emissions, and based on this, the degree of effort exerted by each factor toward decoupling was examined. The results indicate that: (1) From 2010 to 2019, total carbon emissions from sub-sectors in Gansu Province increased by 3843.13$×$104 t, primarily concentrated in high-energy-consuming industries such as petroleum manufacturing, chemical manufacturing, steel manufacturing, and the power industry; the energy consumption structure exhibited prominent high-carbon characteristics, while energy consumption intensity demonstrated a declining trend. Improving the energy consumption structure of high-energy-consuming industries and promoting their transformation and upgrading constitute the key priorities for future carbon emission reduction in Gansu Province. (2) Economic growth and population size generated incremental effects on carbon emissions, whereas energy intensity and energy structure produced emission reduction effects; industrial structure yielded emission reduction effects in certain sectors. (3) The decoupling status between carbon emissions and economic growth across industries tended to improve; except for the power industry, which remained weakly decoupled, other industries transitioned from negative decoupling or weak decoupling during 2010–2016 to strong decoupling or recessive decoupling during 2016–2019. (4) The energy intensity effect exhibited the highest decoupling effort, while the decoupling efforts of energy structure and industrial structure effects, though relatively modest, gradually strengthened; the decoupling effort of population size effect was not significant.

Full Text

Influencing Factors and Decoupling Efforts of Industry-Related Carbon Emissions in Gansu Province

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Abstract: Accurate identification of specific focus points for industry carbon reduction is crucial to realizing China' s goal of "carbon peak by 2030 and carbon neutrality by 2060." This study uses the Logarithmic Mean Divisia Index (LMDI) method to decompose the influencing factors and their effects on carbon emissions from 13 subsectors in Gansu Province from 2010 to 2019. The Tapio decoupling model analyzes the relationship between carbon emissions and economic growth. Accordingly, a decoupling effort model of influencing factors (excluding economic factors) is constructed to analyze the efforts made by other factors toward decoupling. The following results are obtained: (1) From 2010 to 2019, carbon emissions from subsectors in Gansu Province increased by 3843.13$×10^{4}$ t, mainly concentrated in petroleum manufacturing, chemical manufacturing, steel manufacturing, and power generation—industries with high energy consumption. Specifically, Gansu Province' s energy consumption structure is characterized by high carbon emissions, with coal consumption accounting for 64.89% of total fossil energy consumption in 2019. Energy consumption intensity shows a decreasing trend, while energy efficiency continues to improve. (2) Economic growth and population scale exhibit incremental effects on carbon emissions, with the economic growth effect being the primary driver. Energy intensity and structure demonstrate significant reduction effects, with energy intensity showing a more pronounced effect. However, the influence direction of the industrial structure effect fluctuates considerably across different time periods and industries. The industrial structure effect on chemical and construction industries shows relatively significant reduction, whereas that on steel and power industries increases carbon emissions. (3) The decoupling of carbon emissions from economic growth across the 13 subsectors shows improvement. From 2010 to 2013, all industries exhibited weak decoupling, except for mining and light manufacturing, which showed negative decoupling and expansion connection. From 2013 to 2016, some industries such as agriculture, chemical, and steel manufacturing achieved strong decoupling. From 2016 to 2019, all sectors transitioned to strong or recessionary decoupling, except for the power sector, which remained weakly decoupled. (4) The energy intensity effect plays the most important role in decoupling. The decoupling effects of energy structure and industrial structure are small but gradually increasing, whereas that of population scale is not evident. Evidently, reducing energy consumption intensity and improving energy use efficiency are crucial for accelerating carbon emission reduction and effectively enhancing the decoupling level in Gansu Province. Based on these findings, the following should be proposed: First, governments and enterprises should actively introduce low-carbon

production technologies and high-efficiency energy-saving equipment, encourage innovation, and focus on developing and optimizing energy-saving and environmental protection technologies. Second, governments should comprehensively consider local industrial structure characteristics, carbon emission levels, and emission reduction potentials of subsectors to formulate differentiated quota schemes for industrial carbon emissions for high- and low-energy industries.

Keywords: carbon emission; LMDI model; decoupling; industry segmentation; Gansu Province

Introduction

Climate warming has attracted widespread attention due to its severe ecological damage and urgent threat to human survival and development. Global collective action against climate change has become an essential part of the community with a shared future for mankind. According to the International Energy Agency (IEA), China ranked first globally in carbon emissions with 98.09$\times 10^{8}$ t in 2019. In response to this severe situation, China has made a solemn commitment to the international community to achieve carbon peak by 2030 and carbon neutrality by 2060, incorporating the "dual carbon" goals into the overall layout of ecological civilization construction in its 14th Five-Year Plan.

Gansu Province is not only a major energy and resource supply base in China but also an important ecological security barrier region. In recent years, the Belt and Road Initiative has placed higher demands on local industrial energy efficiency. However, the development path characterized by "energy and resource-intensive" industries has led to an economic operation model featuring "high consumption, high input, and low output," making the resulting energy consumption and carbon emission increases an urgent problem to solve. Conducting influencing factor analysis and decoupling analysis on carbon emissions from Gansu' s subsectors is of great practical significance for planning and implementing carbon reduction targets and promoting green, low-carbon industrial transformation and development.

Different industries exhibit significantly different carbon emission characteristics, making industry-level research crucial for accurately identifying specific focus points for regional carbon reduction. Studies show that industry carbon emissions are jointly determined by multiple factors including population, economy, technological progress, and industrial structure. The Logarithmic Mean Divisia Index (LMDI) decomposition method and regression analysis methods represented by the STIRPAT model have become two mainstream approaches for studying carbon emission influencing factors. The LMDI method is favored by scholars for its ability to accommodate zero values and produce no residual after decomposition, and has been widely applied in studies on carbon emission influencing factors in agriculture, transportation, and other sectors. For instance, Wang et al. studied influencing factors of carbon emissions from China' s manufacturing industry and found that economic growth has a significant incremental effect on carbon emissions, while energy intensity shows bidirectional effects depending on the region. Lai et al. decomposed influencing factors of carbon emissions from key industries in Fujian Province and concluded that developing low-carbon technologies and adjusting industrial and energy structures are important focus points for achieving carbon reduction and environmental protection in the region.

Numerous studies indicate that economic growth is the main driver of increased carbon emissions. How to better balance economy and environment, development and emission reduction is a major issue in achieving China' s "dual carbon" goals. Research on this relationship mostly proceeds from two perspectives: the long-term correlation based on the Environmental Kuznets Curve (EKC) hypothesis and short-term effects. At the sectoral level, Li et al. conducted decoupling analysis of power, steel, and cement industries in Chinese provinces; Wang et al. studied the decoupling status between economic growth and carbon emissions in China' s industrial subsectors; Liu et al. measured regional industrial carbon emission decoupling indices and constructed a decoupling effort model to explore the internal drivers of decoupling.

In summary, existing literature has greatly enriched research on industry carbon reduction, but few studies have addressed carbon emission issues in subsectors at the provincial level in less-developed regions. This study takes 13 subsectors in Gansu Province as research objects, uses the LMDI method to decompose influencing factors of industry carbon emissions, and employs the Tapio decoupling model to analyze the decoupling relationship between economic growth and carbon emissions. Furthermore, it examines the decoupling efforts made by various influencing factors to provide a basis for formulating and implementing industry carbon reduction strategies in Gansu Province.

Methodology

Data Sources and Processing

Data on energy consumption, year-end permanent population, and Gross Domestic Product (GDP) are all obtained from the *Gansu Development Yearbook (2011-2020).* Since industrial GDP for subsectors cannot be obtained, following the approach of He et al., we calculate it using (industrial output value/industrial total output value) × industrial GDP. To eliminate price factor influences, all GDP values are converted to constant 2010 prices.

IPCC Method

We use the IPCC method to calculate carbon emissions from subsectors in Gansu Province, with the formula:

$$C = \sum_i \sum_j E_{ij} \times k_j \times m_j$$

where:
- C is carbon emissions;
- i represents 13 subsectors;
- j represents 9 fossil fuels including raw coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, liquefied petroleum gas, and natural gas;
- k_j and m_j are the carbon emission coefficient and standard coal conversion coefficient for fossil fuel j, respectively;
- E_{ij} is the consumption of fossil fuel j by industry i;
- k_j is calculated based on the relative molecular (atomic) mass of j.

LMDI Model

Following Ang et al., we decompose influencing factors of subsector carbon emissions using the formula:

$$C_{ij} = \sum_i \sum_j \frac{C_{ij}}{E_{ij}} \times \frac{E_{ij}}{E_i} \times \frac{E_i}{G_i} \times \frac{G_i}{G} \times \frac{G}{P} \times P = \sum_i \sum_j CI \times ES \times EI \times SI \times GP \times P$$

The change in carbon emissions is decomposed as:

$$\Delta C = \Delta C_P + \Delta C_{GP} + \Delta C_{SI} + \Delta C_{EI} + \Delta C_{ES} + \Delta C_{CI}$$

where:
- C_{ij} is carbon emissions from fossil fuel j in industry i;
- E_{ij} is consumption of fossil fuel j in industry i;
- E_i is total energy consumption of industry i;
- G_i is GDP of industry i;
- G is total GDP;
- P is year-end population;
- CI, ES, EI, SI, GP, and P represent carbon emission coefficient, energy structure, energy intensity, industrial structure, economic growth, and population scale, respectively;
- ΔC_x is the effect of influencing factor x;
- C_t and C_0 are carbon emissions in target year and base year, respectively.

The specific calculation formula for each influencing factor' s effect is:

$$\Delta C_x = \sum_i \sum_j L(C_{ij}^t, C_{ij}^0) \ln\left(\frac{x_t}{x_0}\right)$$

where:
- x represents each influencing factor mentioned above;
- ΔC_x is the carbon emission effect of factor x;
- $L(C_{ij}^t, C_{ij}^0)$ is the weight;

- C_{ij}^t and C_{ij}^0 are carbon emissions from fossil fuel j in industry i in target year and base year, respectively;
- x_t and x_0 are factor values in target year and base year, respectively.

The weight formula is:

$$L(C_{ij}^t, C_{ij}^0) = \frac{C_{ij}^t - C_{ij}^0}{\ln C_{ij}^t - \ln C_{ij}^0} \quad \text{or} \quad L(C_{ij}^t, C_{ij}^0) = C_{ij}^0 \quad \text{when} \quad C_{ij}^t = C_{ij}^0$$

For easier comparison, following Lai et al., we use relative contribution to describe the influence degree of each effect on carbon emissions:

$$\delta = \frac{\Delta C_x}{\Delta C} \times 100\%$$

where:
- δ is relative contribution.
- If $\delta > 0$, the factor promotes carbon emissions, and larger values indicate stronger promotion.
- If $\delta < 0$, the factor inhibits carbon emissions, and larger absolute values indicate stronger inhibition.

Decoupling Analysis

We use the Tapio decoupling model to study the decoupling relationship between economic growth and carbon emissions:

$$\varepsilon = \frac{\Delta C/C}{\Delta G/G}$$

where:
- ε is the decoupling index;
- ΔC and ΔG are growth rates of carbon emissions and GDP, respectively;
- C and G are carbon emissions and GDP in base year, respectively.

Specific decoupling state definitions are shown in [Figure 1: see original paper].

Decoupling Effort Model To further analyze the efforts made by various factors toward decoupling economic growth from carbon emissions, we construct the following model:

$$D_x = \frac{\Delta C_x/C}{\Delta G/G}$$

where:
- D_x is the decoupling effort indicator of influencing factor x (excluding economic growth effect);
- ΔC_x is the carbon emission change caused by factor x.
- When $0 < D_x < \varepsilon$, it indicates weak decoupling effort;
- When $D_x < 0$, it indicates strong decoupling effort;
- When $D_x > \varepsilon$, it indicates no decoupling effort.

Results

Energy Consumption Status in Gansu Province

From the overall perspective of industrial energy consumption in Gansu Province ([Figure 2: see original paper]), total energy consumption in 2019 was 7919.59$×10^{4}$ t standard coal. Coal and oil consumption accounted for 64.89% and 34.67% of total fossil energy consumption, respectively, indicating that coal remains the primary form of energy consumption. The energy consumption pattern shows prominent high-carbon characteristics, leaving considerable room for optimization of the energy consumption structure. By sector, power generation, steel manufacturing, and chemical manufacturing accounted for 34.82%, 15.13%, and 7.56% of energy consumption, respectively, representing the main coal-consuming industries. Petroleum manufacturing and transportation accounted for 29.98% and 4.93% of energy consumption, respectively, representing the main oil-consuming industries.

Using the mean energy consumption intensity of 0.11 $\text{t} \cdot (10^4 \text{ yuan})^{-1}$ as the threshold, industries are divided into high-energy and low-energy categories for analysis ([Figure 3: see original paper]). Overall, energy consumption intensity of subsectors in Gansu Province showed a decreasing trend from 2010 to 2019, indicating significant improvement in energy-saving technology and a gradual shift in industrial development mode from high-energy, extensive patterns to low-energy, intensive patterns. By sector, high-energy industries represented by power generation and petroleum manufacturing showed significant declines in energy consumption intensity, but remained at relatively high levels compared to other industries. Mechanical manufacturing, trade and catering, and other services maintained low energy consumption intensity levels throughout the years, with mean values of 0.07 $\text{t} \cdot (10^4 \text{ yuan})^{-1}$, 0.05 $\text{t} \cdot (10^4 \text{ yuan})^{-1}$, and 0.05 $\text{t} \cdot (10^4 \text{ yuan})^{-1}$, respectively, demonstrating high energy utilization efficiency.

Carbon Emission Status in Gansu Province

From an overall perspective, carbon emissions from subsectors in Gansu Province increased from 16520.90$×10^{4}$ t to 20364.03$×10^{4}$ t from 2010 to 2019, an increase of 3843.13$×10^{4}$ t ([Figure 4: see original paper]). The power industry contributed the most, accounting for 53.85% of the total increase in subsector carbon emissions. Carbon emissions from mining, petroleum manufacturing, chemical manufacturing, steel manufacturing, transportation, trade and catering, and other services also showed positive growth. In contrast, carbon emissions from agriculture, light manufacturing, textile manufacturing, mechanical manufacturing, and construction decreased to varying degrees, with reductions ranging from 20.49×10^{4} t to 119.28×10^{4} t.

Combined with carbon emission data for subsectors in Gansu Province (), it is evident that carbon emissions are concentrated in high-energy industries such as petroleum manufacturing, chemical manufacturing, steel manufacturing, and power generation, all showing upward trends. Therefore, improving the energy consumption structure of high-energy industries and promoting their transformation and upgrading are top priorities for carbon reduction in Gansu Province.

Factor Decomposition Analysis of Carbon Emissions in Gansu Province

The relative contribution of each influencing factor to subsector carbon emissions is shown in . Considering the Belt and Road Initiative proposed in 2013 and the impact of the 13th Five-Year Plan on carbon emissions in Gansu Province, the study period is divided into three time segments: 2010–2013, 2013–2016, and 2016–2019.

Population Scale Effect (ΔC_P) The population scale effect promoted carbon emission increases during all three periods. Except for light manufacturing, textile manufacturing, and mechanical manufacturing, the population scale effect of the other 10 industries showed an increasing trend. Among them, transportation, construction, and agriculture had relatively high relative contribution values, with mean values of 12.8%, 11.9%, and 10.3%, respectively. The impact of population expansion on transportation pressure, housing demand, and land use changes is increasingly evident for carbon emission growth.

Economic Growth Effect (ΔC_{GP}) The economic growth effect showed significant promotion of carbon emission increases across all periods, but this effect declined over time. From 2010 to 2013, the economic growth effect was particularly significant in petroleum manufacturing, construction, and transportation, with relative contributions of 74.8%, 70.0%, and 60.3%, respectively. From 2013 to 2016, mining showed the most significant effect with a relative contribution of 67.9%. By 2016–2019, the promoting effect of economic growth had significantly weakened, with relative contributions for all industries falling below 60%. Although the promoting effect of economic growth on subsector carbon emissions in Gansu has clearly declined, it remains the primary driver of emission increases. The challenge of achieving carbon reduction while maintaining economic growth still requires urgent solutions.

Industrial Structure Effect (ΔC_{SI}) The industrial structure effect consistently promoted carbon emissions in the power industry and other services throughout all periods. In contrast, mechanical manufacturing and construction showed inhibitory effects that gradually strengthened. The industrial structure effect on other industries fluctuated significantly in direction. The number of industries where the structure effect showed inhibition was 5 in 2010–2013, increased to 8 in 2013–2016 (with mining, textile manufacturing, and steel manufacturing shifting from promotion to inhibition), and decreased to 6 in 2016–2019. This indicates that the Belt and Road Initiative proposed in 2013 enhanced industrial upgrading in Gansu, with significant achievements in industrial structure optimization. However, the industrial structure effect of high-energy industries such as petroleum manufacturing and power generation still mostly shows promotional effects, indicating that green and low-carbon development of high-energy industries remains a future priority.

Energy Intensity Effect (ΔC_{EI}) Energy intensity showed significant reduction effects on carbon emissions across all periods, with strengthening trends, indicating gradually improving energy utilization efficiency in Gansu' s subsectors and growing emphasis on energy-saving technology innovation that has received positive feedback. Industries with relatively large energy intensity effect contributions include mechanical manufacturing (-61.7%), steel manufacturing (-48.1%), textile manufacturing (-42.3%), and power generation (-41.2%).

Energy Structure Effect (ΔC_{ES}) Over time, the number of industries where energy structure showed inhibitory effects on carbon emissions gradually increased, and the inhibition gradually strengthened. From 2010 to 2013, 5 industries showed inhibitory effects. By 2013–2016, agriculture, textile manufacturing, and steel manufacturing shifted from promotion to inhibition, bringing the total to 8 industries. From 2016–2019, 9 industries showed inhibitory effects, with only mining, power generation, petroleum manufacturing, and steel manufacturing showing promotional effects. The *Gansu Province 14th Five-Year Energy Development Plan* notes that during the 13th Five-Year period, Gansu significantly enhanced its non-fossil energy supply capacity by leveraging new energy development advantages in the Hexi region and continuously deepening energy system reforms.

Decoupling Analysis of Carbon Emissions and Economic Growth in Gansu Province

The decoupling status between carbon emissions and economic growth in Gansu' s subsectors is shown in . From 2010 to 2013, all industries showed weak decoupling except for mining and light manufacturing, which showed expansion negative decoupling and expansion connection, respectively. From 2013 to 2016, agriculture, chemical manufacturing, steel manufacturing, and other industries improved their decoupling status, shifting from weak to strong decoupling. However, transportation, trade and catering, and other services showed expansion negative decoupling, indicating that while Gansu' s tertiary industry developed rapidly, its dependence on energy consumption increased. From 2016 to 2019, all industries shifted to strong or recessionary decoupling except for the power industry, which remained weakly decoupled. Some industries such as mining, light manufacturing, chemical manufacturing, and steel manufacturing even showed recessionary decoupling, where the rate of carbon emission reduction exceeded the rate of economic decline, indicating significant industrial structure transformation and economic recession in some sectors during this period.

Decoupling Effort Analysis of Influencing Factors

The decoupling efforts of various influencing factors on subsector carbon emissions in Gansu Province are shown in . Throughout the study period, the decoupling effort values of population scale effects for all 13 industries were less than 0, indicating no effort made.

Regarding industrial structure effects, different industries made differentiated decoupling efforts across the three periods. From 2010 to 2013, agriculture, trade and catering, construction, transportation, petroleum manufacturing, and mechanical manufacturing made weak decoupling efforts. From 2013 to 2016, the decoupling effort values for mining, textile manufacturing, and steel manufacturing turned from negative to positive, while petroleum manufacturing and trade and catering improved from weak to strong decoupling efforts. From 2016 to 2019, the number of industries making decoupling efforts decreased, indicating that Gansu' s industrial structure adjustment still has considerable room for improvement.

Regarding energy intensity effects, this factor made decoupling efforts for most industries during the study period, with efforts becoming stronger over time. Except for light manufacturing, which showed weak decoupling effort, all other industries showed strong decoupling effort.

Regarding energy structure effects, decoupling efforts showed a significant strengthening trend over time. From 2010 to 2013, energy structure effects made decoupling efforts for only 3 industries. By 2013-2016, this increased to 8 industries. From 2016 to 2019, energy structure effects made decoupling efforts for most industries, indicating that Gansu' s industrial energy structure adjustment policies have been effective.

Discussion

Most studies on factor decomposition of carbon emissions in Gansu Province have focused on the macro level. Liu et al. and Dong et al. decomposed influencing factors of carbon emission changes in Gansu, finding that economic growth has a significant incremental effect while energy intensity is a key reduction factor. This study, conducted at the subsector level in Gansu, finds that economic growth and population scale show incremental effects, with economic growth being the primary driver, while energy intensity and structure show reduction effects, and the industrial structure effect varies by industry. Dong et al. added forest carbon sinks and urbanization rates to their evaluation system, finding that urbanization promotes carbon emissions while forest carbon sinks have strong carbon sequestration effects.

This study shows that energy intensity effects not only have obvious carbon reduction effects but also make significant decoupling efforts between carbon emissions and economic growth, consistent with Lai et al.' s research on influencing factors and decoupling efforts of carbon emissions in Fujian Province. Therefore, reducing energy consumption intensity and improving energy efficiency are important focus points for enhancing decoupling levels. Governments and enterprises should actively introduce low-carbon production technologies and high-efficiency energy-saving equipment, increase R&D investment, encourage innovation, and focus on developing and optimizing energy-saving and environmental protection technologies to further leverage the supporting role of technological innovation.

Under China' s "dual carbon" targets, it is crucial for governments to better perform macro-regulation functions and create a favorable policy environment for carbon reduction. Governments should comprehensively consider local industrial structure characteristics, subsector carbon emission levels, and emission reduction potentials to accurately identify specific focus points for carbon reduction in each industry. Differentiated industry carbon emission quota schemes should be formulated for high- and low-energy industries. Meanwhile, a fusion mechanism for carbon emission trading rights and carbon tax should be established to further improve Gansu' s carbon reduction policy system.

Previous studies have predicted peak times and sizes for industrial subsectors at the national level and assessed their reduction potentials. Dong et al. predicted carbon peak for five northwestern provinces and analyzed the impact of environmental regulation on the peak. This study only discusses influencing factors and decoupling effects of industry carbon emissions in Gansu; the carbon peak situation and reduction potential of subsectors require further assessment.

Conclusions

This study draws the following conclusions: (1) From 2010 to 2019, carbon emissions from subsectors in Gansu Province increased by 3843.13×10^{4} t, with high-energy industries such as petroleum manufacturing, chemical manufacturing, steel manufacturing, and power generation being the main sources. Coal consumption accounts for 64.89% of total energy consumption, showing prominent high-carbon characteristics, though energy consumption intensity across subsectors shows a decreasing trend. (2) Economic growth and population scale exhibit incremental effects, while energy intensity and structure show significant reduction effects; industrial structure effects produce reduction effects in some industries. (3) The decoupling of carbon emissions from economic growth across industries is improving, with energy intensity effects making the highest decoupling efforts. The decoupling efforts of energy structure and industrial structure effects, though relatively low, are continuously strengthening, while population scale effects show no evident decoupling effort.

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Note: Figure translations are in progress. See original paper for figures.