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# Multilevel Index Decomposition of Energy-Related Carbon Emissions and Their Decoupling from Economic Growth in Northwest China

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**Abstract:** Rapid economic growth in Northwest China has been accompanied by a dramatic increase in carbon emissions. Based on the two-level Logarithmic Mean Divisia Index (LMDI) method, this study decomposes changes in energy-related carbon emissions in Northwest China during 1995–2012 from the regional and provincial perspectives. Further, by constructing an expanded decomposition model of the decoupling index, this paper quantitatively analyzes delinking indicators of economic activity and environmental pressure in Northwest China. The results indicate that: (1) at both regional and provincial levels, economic activity effects play a crucial role in increasing carbon emissions, whereas improvements of energy efficiency appear as the main factor in curbing carbon missions; (2) the significance of influencing factors of $CO_2$ emissions varies across provinces. The role of economic activity in Shannxi is more pronounced compared to that of the other four provinces, as well as the role of population in Xinjiang; (3) when the decoupling relationship is considered, "relative decoupling" and "no decoupling" are the main characteristics under investigation during the examined period. Whereas "strong decoupling" was only identified in 2007 and 2009; (4) the current extensive pattern of economic growth in Northwest China poses a serious threat to the decoupling process. Furthermore, the coal-based energy structure also hinders the decoupling process. According to these results, some policy recommendations are proposed.

**Keywords:** $CO_2$ emissions; multilevel LMDI analysis; decoupling index; Northwest China

## 1. Introduction

In recent years, climate change issues, mainly caused by the emission of greenhouse gases (GHGs), have attracted significant attention from both governments and the international community [1–6]. Since 2007, China became the world's largest emitter of $CO_2$ [7] and in 2012, China's $CO_2$ emissions reached 9.21 billion tons, accounting for 26.7% of total global emissions [8]. In 2015, China promised to reduce 40%–45% of carbon emissions by 2020 compared to the level in 2005. To achieve this ambitious target, it is important to find effective measures to control $CO_2$ emissions, reduce their intensity, and decouple $CO_2$ emissions from economic growth [9–11].

As shown in Figure 1, Northwest China, studied in this paper, includes three provinces, Shaanxi, Gansu, and Qinghai and two autonomous regions, Ningxia Hui Autonomous Region and Xinjiang Uygur. This area constitutes approximately one-third of China, and 7.2% of the total population lives there. Since the implementation of the Western Development Strategy, it became one of the most economically vibrant regions in China. In recent years, with its rapid economic growth, this area has witnessed fast growth of greenhouse gas emissions, particularly emissions of $CO_2$. In 2012, the growth rate of $CO_2$ emissions in Northwest China was 12.0, about three times China's average level. At the same time, Northwest China's contribution to $CO_2$ emissions increased from 7.8% in 2000 to 12.0% in 2012, with an average annual growth rate of 3.7%. Moreover, along with the "One Belt, One Road" initiative, the role of this area in the future economic development of China became prominent. Furthermore, economic growth in backward regions may tend to consume more energy, while producing more carbon emissions. Therefore, research on factors that influence $CO_2$ emissions and the relationship between carbon emissions and economic development in Northwest China can center on the identification of technological means to reduce emissions and help achieve emission control goals nationwide. In addition, such results can provide some reference to underdeveloped areas worldwide.


**Figure 1.** Northwest China.

To the best of our knowledge, most previous research tends to focus on $CO_2$ emissions from a regional or national perspective [12–18], and economic sectors with high energy consumption [19–23], but is deficient in underdeveloped areas [24]. Ozturk and Acaravci [13] examined causal relationships between economic growth and carbon emissions in Turkey by using conintegration analysis, and found that controlling carbon dioxide emissions are likely to have no adverse effect on the real output growth of Turkey. Al-Mulali et al. [16] explored the relationships among urbanization, energy consumption, and $CO_2$ emission in the MENA countries. The results showed that slowing down the urbanization level can help reduce the level of pollutions and energy consumption. Zhang and Da [18] utilized the logarithmic mean Divisia index (LMDI) method to decompose changes in China's carbon emissions, and discovered that the economic growth and share of secondary industries are the principal sources of carbon emissions. Karmellos et al. [19] and González et al. [20] studied driving forces of $CO_2$ emissions from the sector perspective, EU power sector and Spanish electricity sector. Regarding methodologies, there are primarily two approaches to research: econometric analysis [25–29], and decomposition methods [18,30–35]. Two broad categories of decomposition technique are often used in analyzing energy consumption and carbon emissions-index decomposition analysis (IDA) and structural decomposition analysis (SDA) [31,32,36,37]. Xu and Ang [38] conducted a comprehensive literature survey on IDA which was applied to energy and emissions. The IDA method can be divided into two groups: the Laspeyres index and the Divisia index [39]. The Laspeyres index measures the percentage change in some aspect of a group of items over time, using weights based on values in some base year, whereas the Divisia index is a weighted sum of logarithmic growth rates, where the weights are the components' shares in total value, given in the form of a line integral [40]. The Divisia index method has been used by Ang et al. [41] and has been extended to the LMDI. In addition, many studies have used the LMDI method to study residential carbon emissions and energy consumption [4,10,15,34,35]. Unlike IDA analysis, the SDA method is based on the input-output analysis [39,41]. Su and Ang [42] compared the IDA and SDA and found the gap between SDA and IDA with regard to the decomposition method used has not widened but instead narrowed. By using IDA, Sheinbaum-Pardo [43] decomposed $CO_2$ emissions from demand services to material production in Mexico. Cansino probed the main drivers of changes in $CO_2$ emissions in the Spanish economy by applying SDA [44].

Based on previous studies, this paper decomposes changes of final energy-related $CO_2$ emissions in Northwest China during 1995–2014 by applying the multilevel LMDI method and decoupling index analysis. This period was chosen because it witnessed the highest economic growth in Northwest China, so the empirical results can be used to formulate realistic and scientific carbon abatement policies. As for Northwest China, it is a typical underdeveloped region in China, and its influencing factors of $CO_2$ emissions and the decoupling relationship between carbon emission and economic growth may differ from those of China, and/or other more developed regions in China. Though there are already papers published analyzing the changes of $CO_2$ emissions in China from a regional perspective [26,35], unfortunately, they all fail to pay adequate attention to underdeveloped areas. Moreover, regarding methodologies, a multilevel decomposition approach was used in this paper. We adopted different decomposition methods, namely additive and multiplicative decompositions to analyze the changes of $CO_2$ emissions on a regional level (Northwest China) and provincial level (Shannxi, Gansu, Qinghai, Ningxia and Xinjiang), respectively. Furthermore, except for the multilevel decomposition analysis, this paper also builds a new decoupling model based on the LMDI to calculate decoupling trends in Northwest China. Combined these two techniques have two advantages. First, according to the results obtained using the LMDI, annual decoupling states were identified with applying the decoupling analysis. Second, the decoupling model can be built using the theory of the LMDI; hence, driving or inhibiting factors of decoupling were clarified. Previous research on the decoupling relationship focused mainly on carbon emission factor resolution, and then assessed the status of decoupling or recoupling, which lacked an in-depth analysis of the contribution of each factor [45–47].

In brief, there are three primary objectives of this study: (1) to identify, quantify, and explain the factors influencing changes in energy-related $CO_2$ emissions in Northwest China at the regional and provincial levels; (2) to explore the relationship between economic growth and carbon emissions in an underdeveloped region from the perspective of the decoupling index; and (3) to ascertain factors for possible decoupling of energy usage and emissions from the point of view of policy making.

## 2. Methodology and Date

### *2.1. Methodology*

#### 2.1.1. Energy-Related $CO_2$ Emissions Estimation Approach

The methods proposed by the Intergovernmental Panel on Climate Change (IPCC) guidelines [48] were applied to estimate $CO_2$ emissions related to end-use energy consumption. The total energy-related $CO_2$ emissions in Northwest China can be calculated based on energy consumption, the fraction of oxidized carbon by fuel, and emission factors, as shown in the following equation:

$$C^t = \sum_{i,j} C^t_{ij} = \sum_{i,j} E^t_{ij} \times O_j \times EF_j \quad (1)$$

where $C^t$ denotes the total $CO_2$ emissions in year $t$ ($10^4$ tons); $C_{ij}^t$ means $CO_2$ emissions based on fuel type j in sub-region $i$ in year $t$; $i$ = 1, 2, 3, 4, 5 denotes the five province-level regions; $j$ indicates the main eight types of energy sources; $E_{ij}^t$ represents the consumption of fuel type $j$ in sub-region $i$ in year $t$ (GJ); $O_j$ denotes the fraction of the carbon oxidized by fuel type $j$; and $EF_j$ denotes the $CO_2$ emission coefficient of fuel type $j$. The potential carbon content, oxidation rate, and $CO_2$ emission factors are listed in Table 1. In order to avoid the double counting of $CO_2$ emissions from the power generation industry, electricity consumption is regarded as clean [49].

**Table 1.** $CO_2$ emission factors of various energy sources.

| Fuel Type | LCV [a] (KJ/kg or KJ/m$^3$) | Oxidation Rate [b] | Potential Carbon Content [c] (kgC/GJ) | $CO_2$ EF [d] (t$CO_2$/ton or $10^3$ m$^3$) |
|---|---|---|---|---|
| Raw coal | 20,908 | 0.918 | 26.37 | 1.981 |
| Coke | 28,435 | 0.928 | 29.5 | 2.860 |
| Crude oil | 41,816 | 0.979 | 20.1 | 3.020 |
| Gasoline | 43,070 | 0.986 | 18.9 | 2.925 |
| Kerosene | 43,070 | 0.980 | 19.6 | 3.033 |
| Diesel oil | 42,652 | 0.982 | 20.2 | 3.096 |
| Fuel oil | 41,816 | 0.985 | 21.1 | 3.170 |
| Natural gas | 38,931 | 0.990 | 15.3 | 2.162 |

[a,b] Source: Chinese Energy Statistic Yearbook [50]; LCV: low calorific value; [c,d] Source: Song et al. [51]; [d] EF: emission factor.

### 2.1.2. Multilevel Index Decomposition Analysis

Among various index decomposition methods, Ang [52] recommended the LMDI due to its theoretical foundations, adaptability, ease of use, results interpretation, and other desirable properties. Based on the expanded Kaya identity [53,54] and Ang [55,56], this study applies both additive LMDI and multiplicative LMDI to probe influencing factors of $CO_2$ emissions at the regional and provincial levels. Specially speaking, the addictive decomposition was utilized on regional level for further decoupling analysis. At the same time, we chose multiplicative decomposition for provincial analyses mainly due to the result presentation of this method is in indexes, which was more convenient to conduct dynamic comparison among different provinces. Due to the constraints of the Kaya identity, different factors were considered for specific regions. In Northwest China, the rapid growth of population and coal based energy mix are two dominant characteristics. Accordingly, considering these regional features and based on the extended Kaya identity, changes in energy-related $CO_2$ emissions in Northwest China may be studied by quantifying contributions from changes in five different factors: the regional population (population effect), overall economic activity (activity effect), energy intensity (intensity effect), energy structure (structure effect), and $CO_2$ emission factors (emission-factor effect). The aggregate $CO_2$ emissions from each province and Northwest China can be evaluated as follows:

$$C = \sum_j C_j = \sum_j P \times \frac{Q}{P} \times \frac{E}{Q} \times \frac{E_j}{E} \times \frac{C_j}{E_j} = \sum_j P \times G \times I \times S_j \times F_j \quad (2)$$

where $C$ refers to the total energy-related $CO_2$ emissions in Northwest China ($10^4$ tons); $P$ denotes the regional population ($10^4$ people); $Q$ is the total economic activity level, where we chose the GDP as its indicator ($10^4$ Yuan, 1995 constant prices); $E$ and $Ej$ are the total end-use energy consumption and energy consumption by fuel type $j$ ($10^4$ tce), respectively; $C_j$ is $CO_2$ emissions by fuel type $j$ ($10^4$ tons); $G$ and $I$ denote the per capita GDP and energy intensity, respectively; $S_j$ denotes the energy share of fuel type $j$; and $F_j$ denotes the emission factor of fuel type $j$.

According to the LMDI method [57,58], the $CO_2$ emissions from year 0 to year $t$ can be expressed in additive and multiplicative forms as follows:

$$\Delta C_{tot} = C^T - C^0 = \Delta C_{pop}^T + \Delta C_{act}^T + \Delta C_{\text{int}}^T + \Delta C_{str}^T + \Delta C_{fac}^T \quad (3)$$

$$D_{tot} = C^T/C^0 = D_{pop}D_{act}D_{\text{int}}D_{str}D_{fac} \quad (4)$$

A structural formula for each factor is shown in Table 2. Here, $\Delta C_{tot}$ means the $CO_2$ emission changes from $C^0$ to $C^T$; $\Delta C_{pop}$, $\Delta C_{act}$ and $\Delta C_{int}$ are the changes in $CO_2$ emissions from the population, economic activity, and energy intensity, respectively; $\Delta C_{str}$ and $\Delta C_{fac}$ are the changes in $CO_2$ emissions caused by the energy structure and emission factor; $D_{pop}$ and $D_{act}$ are the growth rates of $CO_2$ emissions corresponding to the population and activity effect; $D_{int}$, $D_{str}$ and $D_{fac}$ are the growth rates of $CO_2$ emissions corresponding to the intensity, energy-structure and emission-factor effects; The terms $w$ and $w'$ are the estimated weights of the additive and multiplicative LMDI.

**Table 2.** LMDI formulas for decomposition changes in energy-related $CO_2$ emissions.

| **IDA Identity** | $C = \sum_j C_j = \sum_j P \times \frac{Q}{P} \times \frac{E}{Q} \times \frac{E_j}{E} \times \frac{C_j}{E_j} = \sum_j P \times G \times I \times S_j \times F_j$ | |
|---|---|---|
| **Total Effect** | Additive decomposition<br>$\Delta C_{tot} = C^T - C^0 = \Delta C^T_{pop} + \Delta C^T_{act} + \Delta C^T_{\text{int}} + \Delta C^T_{str} + \Delta C^T_{fac}$ | Multiplicative decomposition<br>$D_{tot} = C^T/C^0 = D_{pop}D_{act}D_{\text{int}}D_{str}D_{fac}$ |
| **Effect by Factor** | $\Delta C^T_{pop} = \sum_j w\ln\frac{P^T}{P^0}$ | $D_{pop} = \exp(\sum_j w'\ln\frac{P^T}{P^0})$ |
| | $\Delta C^T_{act} = \sum_j w\ln\frac{G^T}{G^0}$ | $D_{act} = \exp(\sum_j w'\ln\frac{G^T}{G^0})$ |
| | $\Delta C^T_{\text{int}} = \sum_j w\ln\frac{I^T}{I^0}$ | $D_{\text{int}} = \exp(\sum_j w'\ln\frac{I^T}{I^0})$ |
| | $\Delta C^T_{str} = \sum_j w\ln\frac{S^T}{S^0}$ | $D_{str} = \exp(\sum_j w'\ln\frac{S^T}{S^0})$ |
| | $\Delta C^T_{fac} = \sum_j w\ln\frac{F^T}{F^0}$ | $D_{fac} = \exp(\sum_j w'\ln\frac{F^T}{F^0})$ |
| | $w = \frac{C_j^T - C_j^0}{\ln C_j^T - \ln C_j^0}$ | $w' = \frac{(C_j^T - C_j^0)/(\ln C_j^T - \ln C_j^0)}{(C^T - C^0)/(\ln C^T - \ln C^0)}$ |

To overcome the problem of zero values, Ang [59,60] proposed to substitute zeros for δ values between $10^{-10}$ and $10^{-20}$. Ang [60] also showed that this strategy is robust when an appropriate value is used, and that it provides satisfactory results even in highly extreme cases.

### 2.1.3. Decoupling Measurement of $CO_2$ Emissions and Economic Growth

In general, the decoupling index defined by Tapio [61] can be measured as the ratio of the percentage change in carbon emissions to the percentage change in the GDP in a given time period:

$$\varepsilon = \frac{\Delta C/C}{\Delta G/G} \quad (5)$$

However, in this paper, based on the additive decomposition results for energy-related $CO_2$ emission changes, we apply a novel decoupling index which was advanced by Diakoulaki [62] and Vehmas [63] to study the relationship between $CO_2$ emissions and economic growth in Northwest China. The advantage of this approach is that it indicates everything about the real effort needed to achieve the target of decoupling, rather than providing only rough and superficial measurements of the relationship between the GDP and $CO_2$ emissions. Specifically, by combining additive decomposition results and this novel decoupling index, we can identify which factors and to what extent enhance or curtail carbon emissions.

During the study period (1996–2014), the economy of Northwest China witnessed rapid growth, which eventually contributed to an increase in $CO_2$ emissions. Conversely, improving energy efficiency, fuel switching, and controlling population can directly or indirectly induce a decrease in energy-related $CO_2$ emissions. Therefore, we use $\Delta E_t$ to represent the total inhibiting effect on $CO_2$ emissions as follows:

$$\Delta E_t = \Delta C^t_{tot} - \Delta C^t_{act} = \Delta C^t_{pop} + \Delta C^t_{\text{int}} + \Delta C^t_{str} \quad (6)$$

Then, the decoupling index is defined as follows:

$$\delta_t = -\frac{\Delta E_t}{\Delta C_{act}^t} = -\frac{\Delta C_{pop}^t}{\Delta C_{act}^t} - \frac{\Delta C_{\text{int}}^t}{\Delta C_{act}^t} - \frac{\Delta C_{str}^t}{\Delta C_{act}^t} = \delta_{pop}^t + \delta_{\text{int}}^t + \delta_{str}^t \quad (7)$$

where $\delta_t$ indicates the total decoupling index; $\delta_{pop}^t$, $\delta_{int}^t$ and $\delta_{str}^t$ are the effects of the population, energy intensity and energy structure on the decoupling of $CO_2$ emissions and economic growth respectively.

If $\delta_t \geq 1$, there is a strong decoupling effect. In other words, the total $CO_2$ emissions reduction effect is greater than the driving effect of economic growth. If $0 < \delta_t < 1$, there is a relative decoupling effect; in other words, the $CO_2$ emissions reduction effect is weaker than the driving effect. If $\delta_t \leq 0$, there is no decoupling effect, and we can say that the possible inhibiting factors do not reduce $CO_2$ emissions efficiently but rather increase them. The results can help us to disentangle relative contributions of factors to the overall decoupling progress.

### 2.2. Data

This study covers the period from 1995 to 2014, and data used was primarily derived from the China Statistical Yearbook [64], China Energy Statistical Yearbook [50], China Compendium of Statistical [65], and China Population Statistics Yearbook [66]. The whole economy in Northwest China is divided into three aggregated industries, namely the primary, secondary, and tertiary industry. Agriculture and its related activities: farming, forestry, husbandry, secondary production and fishing are the primary industry. The secondary industry sector includes mining, manufacturing, water supply, electricity generation and supply, steam, the hot-water and gas sectors, and construction. The tertiary industry sector is the rest (transportation sector and commerce sector). Regarding energy data, we used the final consumption of raw coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, and natural gas, in ten thousand tons of coal equivalent, obtained from China Energy Statistical Yearbook [50]. The total end-use energy consumption data in each province was taken from the table of energy consumption by regions, China Energy Statistical Yearbook [50]. The GDP and population data was extracted from China Statistical Yearbook [64] and China Population Statistics Yearbook [66]. To eliminate inflation, the GDP was converted to 1995 prices.

## 3. Results and Discussion

### 3.1. Trajectory of $CO_2$ Emissions

#### 3.1.1. Features of $CO_2$ Emissions in Northwest China

Figure 2 shows the change rates of $CO_2$ emissions, per capita $CO_2$ emissions, and $CO_2$ emission intensity during 1996–2014 in Northwest China. It can be analyzed in three periods: 1996–2002, 2003–2009 and 2010–2014. In the first period, both $CO_2$ emissions and per capita $CO_2$ emissions show no significant changes, having average annual growth rates of 2.7% and 1.7%, respectively. On the contrary, the average annual growth rate of $CO_2$ emission intensity was −6% in this period. In the second period, both $CO_2$ emissions and per capita $CO_2$ emissions increased sharply, having the average annual growth rates of 10.1% and 9.5%, respectively. Contrary to expectations, the $CO_2$ emission intensity did not decline but rather increased with an annual growth rate of 1.0%. In the last period, $CO_2$ emissions and per capita $CO_2$ emissions grew faster than in the other periods, with average annual growth rates of 10.6% and 10.0%. However, the $CO_2$ emission intensity barely changed in this period. Overall, the total $CO_2$ emissions and per capita $CO_2$ emissions in 2014 increased 4.60 and 4.04 times in 1996, respectively. However, the $CO_2$ emission intensity in 2014 was only reduced to 69.5% of the 1996 level. It shows that economic growth in Northwest China is characterized by high energy consumption and high $CO_2$ emissions. Compared to China as a whole and other more developed regions, such as Beijing-Tianjin-Hebei (BTH) and Yangtze River Delta (YRD) economic bands, the growth rates of $CO_2$

emissions and per capita $CO_2$ emissions in Northwest China are greater significantly. Furthermore, the reduced rate of the $CO_2$ emission intensity in Northwest China is lower [2,10,18,35].

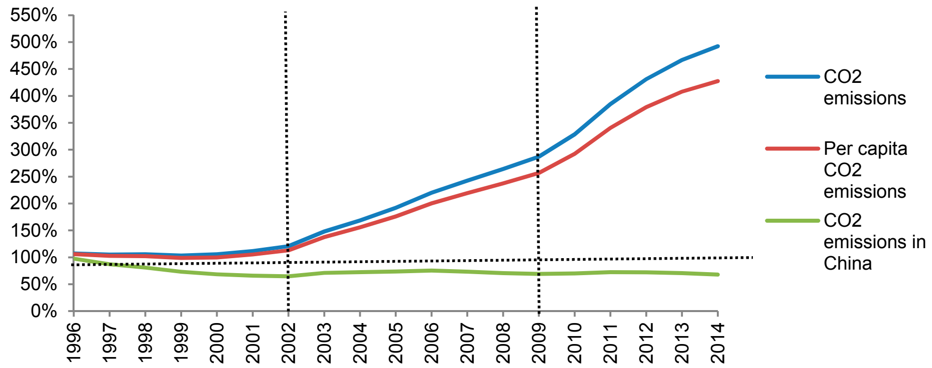



**Figure 2.** Change rates of $CO_2$ emissions, per capita $CO_2$ emissions, and $CO_2$ emission intensity in Northwest China during 1996–2014 (1996 as the baseline year).

### 3.1.2. Features of $CO_2$ Emissions in Each Province

Due to the rapid economic growth, the total energy consumption in Northwest China increased significantly from 11.77 Mtce in 1995 to 58.26 Mtce in 2014. However, the growth in energy consumption varies among the five provinces. With increase in energy consumption, $CO_2$ emissions increased as well. Figures 3 and 4 present the total $CO_2$ emissions and per capita $CO_2$ emissions in five provinces of Northwest China.

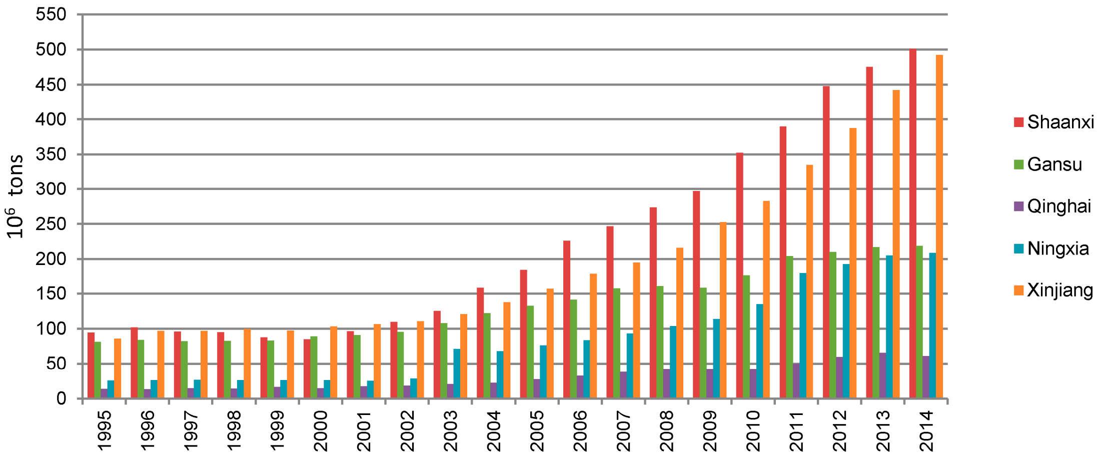



**Figure 3.** Changes in $CO_2$ emissions in five provinces.

As shown in Figure 3, $CO_2$ emissions in the five provinces show a rising trend. The overall changes can be divided into two periods, 1995–2002 and 2002–2014. In the first period, there were subtle fluctuations in $CO_2$ emissions despite the overall trend being relatively stable. We notice that in 1997, the total amount of $CO_2$ emissions in these five provinces declined to different degrees. This may be due to the Asian financial crisis. After 2002, $CO_2$ emissions increased sharply, especially in the Ningxia Hui Autonomous Region and Shaanxi Province. During 2002–2014, the average annual growth rates in these two provinces were 10.5% and 13.5%, respectively. This indicates that the economic development in these two provinces was characterized by high carbon emissions.

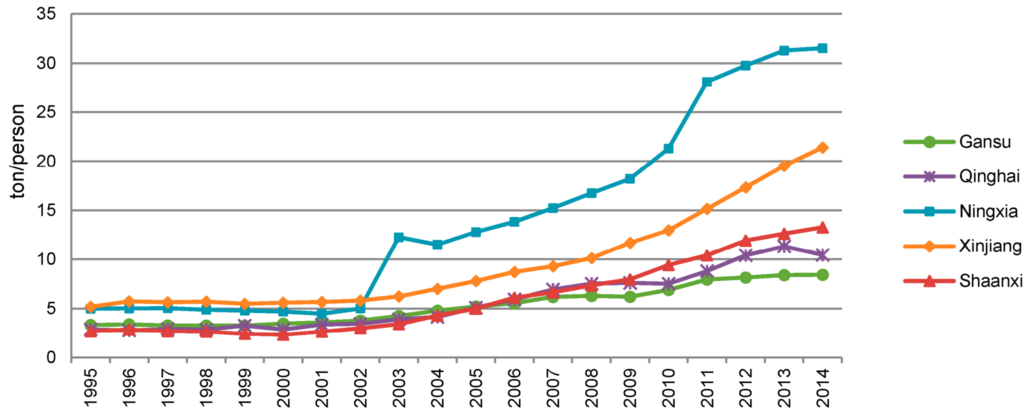


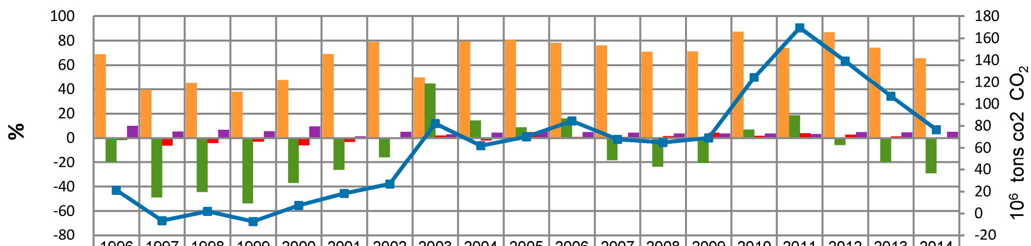

**Figure 4.** Variation in per capita $CO_2$ emissions in five provinces.

As shown in Figure 4, the changes in per capita $CO_2$ emissions in the five provinces of Northwest China showed a growing trend during the study period. However, there exist significant differences among the five provinces in terms of the rates of changes. According to the change rate of per capita carbon emissions, we considered 3 periods: 1995–2002, 2003–2005 and 2006–2014, and sorted these five provinces in descending order in each period. In the first period: Xinjiang, Ningxia, Gansu, Qinghai and Shaanxi; in the second period: Ningxia, Xinjiang, Gansu, Qinghai and Shaanxi; in the third period: Ningxia, Xinjiang, Shaanxi, Qinghai and Gansu. The results show that per capita carbon emissions in Xinjiang and, especially, in Ningxia, are much higher than those in the other three provinces. Taking Ningxia as an example, during 2002–2014, the average annual growth rate of its GDP was 11.6%, while the average annual proportion of the secondary industry output value was 47.6%. Furthermore, since the beginning of 2003, the construction of the Ningdong energy and heavy chemical industry directly led to a rapid increase in energy consumption, with a significant increase in per capita $CO_2$ emissions.

## *3.2. Decomposition Results of $CO_2$ Emissions*

### 3.2.1. Additive Decomposition Results of $CO_2$ Emission Changes at Regional Level

Decomposition results of final energy-related $CO_2$ emission changes in Northwest China from 1996 to 2014 are shown in Figure 5. In the upper section of the figure, the contribution of the various factors appears in a bar graph, while total $CO_2$ emissions appear as a line. At the bottom of the figure, $CO_2$ emission variations appear as a percentage for each factor, where the sum of these variations is an absolute value used to interpret the total change. Several findings are identified as follows.




| | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| act | 68.88 | 39.65 | 45.09 | 37.94 | 47.87 | 69.25 | 78.82 | 50.12 | 79.35 | 80.32 | 78.19 | 76.04 | 70.99 | 71.21 | 87.21 | 74.07 | 86.73 | 74.30 | 65.56 |
| int | -19.6 | -48.8 | -44.2 | -53.7 | -36.8 | -26.2 | -15.6 | 44.70 | 14.43 | 8.86 | 16.03 | -18.4 | -23.6 | -20.5 | 7.04 | 18.60 | -5.65 | -19.6 | -28.9 |
| str | -1.40 | -6.08 | -3.88 | -2.81 | -5.84 | -3.00 | -0.34 | 2.08 | -1.84 | 4.82 | 0.93 | 1.05 | 1.56 | 4.45 | 1.90 | 4.04 | 2.82 | 1.42 | -0.32 |
| pop | 10.08 | 5.43 | 6.80 | 5.52 | 9.48 | 1.48 | 5.19 | 3.10 | 4.38 | 6.00 | 4.85 | 4.51 | 3.78 | 3.78 | 3.85 | 3.29 | 4.81 | 4.66 | 5.22 |
| CO2 | 21.23 | -6.48 | 1.89 | -7.20 | 7.39 | 18.26 | 26.83 | 82.27 | 62.11 | 70.16 | 84.52 | 67.84 | 65.03 | 69.16 | 124.3 | 169.4 | 139.4 | 107.1 | 76.70 |

**Figure 5.** Decomposition of changes of $CO_2$ emissions in Northwest China.

First, changes of $CO_2$ emissions increased during 1995–2014 except for 1997 and 1999. Specifically, $CO_2$ emissions increased by 1180.12 million tons with the annual growth rates of 8.8%. There were two high speed phases: 2003–2007 and 2010–2014. In these two phases, the average annual growth rate of $CO_2$ was above 10.2%. In particular, the annual growth rates reached 22.7%, 14.6%, and 17.1% in 2003, 2006, and 2011, respectively.

Second, the weight of the economic activity contributes strongly to the increase in $CO_2$ emissions, which is consistent with the results of existing literature [18,35,58,67–69]. According to the decomposition results, the $CO_2$ emission changes from economic activity increased by 95.7 million tons during 1995–2014. Based on the annual average contribution rate, economic activity accounts for 67.5% of the total $CO_2$ emission change in absolute terms. Since the implementation of the Western Development Strategy in 2000, the economic development of Northwest China accelerated, and the average annual growth rate of GDP was 11.7% during 2000–2014. At the same time, $CO_2$ emissions also continued to rise, with the average annual growth rate of 11.6%. This shows that along with high-speed economic development, $CO_2$ emissions increased rapidly.

Third, the intensity effect was a major inhibiting factor of $CO_2$ emissions during 1995–2014. During this period, the energy intensity in Northwest China declined from 4.28 tce/$10^4$ Yuan to 2.92 tce/$10^4$ Yuan, with the average annual decline rate of 2.0%. Based on the annual average contribution rate, the energy intensity accounts for $-13.3\%$ of the total $CO_2$ emission change in absolute terms. However, in six of the nineteen years studied, the energy intensity increased with $CO_2$ emissions. This can be explained by sudden booms in production capacity after the entrance to the World Trade Organization (WTO) and implementation of the Western Development Strategy, where not enough attention was given to energy efficiency. To improve energy efficiency, a wide range of policies were implemented, such as "Ten-key Projects" [70] and "Top 1000 Priorities" [71]. These policies halted the rise in energy intensity efficiently. So, the intensity effect decreased $CO_2$ emissions clearly during 2007–2009.

Fourth, the weight of the energy-structure factor as a determinant of $CO_2$ emission variations failed to show a consistent pattern. From 1995 to 2002, the energy structural effect inhibited $CO_2$ emissions by $-12.39$ million tons. But after 2002, the effect increased $CO_2$ emissions with exception of 2004 and 2014. This anomaly may have been caused by the implementation of the Western Development Strategy, which spurred the transfer of heavy industries to Northwest China. Overall, in Northwest China, the accumulated energy-structure effect is an increase in $CO_2$ emissions by 16.12 million tons during the study period.

Finally, the demographic growth contributed to increase in $CO_2$ emissions in Northwest China during the period under consideration. The accumulated effect of population is an increase in $CO_2$ emissions by 84.60 million tons, with the annual average contribution rate of 5.08%. As Figure 5 shows, the population effect is the second most significant factor after economic activity. These results are in line with those found in other countries and regions [72,73].

### 3.2.2. Multiplicative Decomposition Results of $CO_2$ Emission Changes at Provincial Level

According to the results of Section 3.2.1, on the regional level, the economic activity and energy intensity are the crucial factors influencing $CO_2$ emissions, whereas the population and energy structure play a marginal role in changes in $CO_2$ emissions. Is this conclusion applicable at the provincial level? Are there significant differences in the factors affecting $CO_2$ emissions of provinces? In this section, we further explore the influencing factors of $CO_2$ emissions at the provincial level.

Unlike the additive LMDI decomposition which was applied in Section 3.2.1, the multiplicative LMDI decomposition method is used to analyze influencing factors of each province's $CO_2$ emissions. Note that we choose different approaches to investigate influencing factors of carbon emissions at the regional and provincial levels. The underlying reason is that the results of the multiplicative decomposition were much smaller than the results of the additive decomposition, thus more convenient to conduct horizontal comparison of provinces [55]. In addition, the results of the multiplicative decomposition are given in indexes while those of additive decomposition are given as physical units [56]. Therefore, the multiplicative decomposition can be used to analyze dynamic trends appropriately. In order to display results clearly and concisely, the multiplicative decomposition results for the 9th (1996–2000), 10th (2001–2005), and 11th (2006–2010) periods as well as 2011–2014 are presented in the Table 3. It is worth noting that the values in the last column of Table 3 are the accumulative decomposition of changes in $CO_2$ emissions in different provinces.

**Table 3.** Multiplicative LMDI decomposition of $CO_2$ emissions in different provinces.

| Effect | Province | 1996–2000 | 2001–2005 | 2006–2010 | 2011–2014 | 1996–2014 |
|---|---|---|---|---|---|---|
| **Population** | Shannxi | 1.0372 | 1.0126 | 1.0122 | 1.0107 | 1.0745 |
| | Gansu | 1.0509 | 0.9934 | 1.0058 | 1.0121 | 1.0627 |
| | Qinghai | 1.0732 | 1.0515 | 1.0373 | 1.0346 | 1.2111 |
| | Ningxia | 1.0818 | 1.0753 | 1.0615 | 1.0458 | 1.2913 |
| | Xinjiang | 1.1132 | 1.0870 | 1.0851 | 1.0536 | 1.3833 |
| **Economic Activity** | Shannxi | 1.5329 | 1.7316 | 1.9207 | 1.5484 | 7.8943 |
| | Gansu | 1.4796 | 1.6697 | 1.6898 | 1.5096 | 6.3020 |
| | Qinghai | 1.4169 | 1.6795 | 1.7395 | 1.4896 | 6.1661 |
| | Ningxia | 1.5207 | 1.5657 | 1.7029 | 1.4159 | 5.7405 |
| | Xinjiang | 1.3190 | 1.4774 | 1.5228 | 1.4529 | 4.3114 |
| **Energy Intensity** | Shannxi | 0.6042 | 1.2412 | 0.9780 | 0.8901 | 0.6528 |
| | Gansu | 0.7152 | 0.8917 | 0.7754 | 0.8109 | 0.4010 |
| | Qinghai | 0.7102 | 1.0667 | 0.8596 | 0.9399 | 0.6120 |
| | Ningxia | 0.6295 | 0.9308 | 0.9700 | 1.0426 | 0.5926 |
| | Xinjiang | 0.8366 | 0.9570 | 1.0516 | 1.1180 | 0.9413 |
| **Energy Structure** | Shannxi | 0.9368 | 0.9973 | 1.0045 | 1.0217 | 0.9588 |
| | Gansu | 0.9831 | 1.0090 | 1.0113 | 0.9990 | 1.0021 |
| | Qinghai | 0.9881 | 0.9933 | 0.9845 | 0.9945 | 0.9609 |
| | Ningxia | 0.9894 | 1.0140 | 1.0070 | 1.0031 | 1.0134 |
| | Xinjiang | 0.9786 | 0.9866 | 1.0390 | 1.0168 | 1.0200 |
| **Total Effect** | Shannxi | 0.8999 | 2.1706 | 1.9098 | 1.4231 | 5.3092 |
| | Gansu | 1.0932 | 1.4923 | 1.3328 | 1.2378 | 2.6062 |
| | Qinghai | 1.0670 | 1.8713 | 1.5269 | 1.4406 | 4.3920 |
| | Ningxia | 1.0247 | 1.5891 | 1.7657 | 1.5485 | 4.4522 |
| | Xinjiang | 1.2020 | 1.5162 | 1.8054 | 1.7402 | 5.7257 |

As Table 3 shows, taking these five provinces as a whole, both economy activity and population contributed to the increase in aggregate $CO_2$ emissions, whereas the energy intensity had a negative influence on the aggregate value as a consequence of energy efficiency improvement. In addition, the structural effect has different signs depending on the province. Specifically, the structural effect inhibited the $CO_2$ emissions in Qinghai and Shannxi, conversely, it increased the $CO_2$ emissions in the other three provinces. In general, the decrease was nowhere near enough to overcome the increase. Consequently, the total effect in every province was a sharp increase. For example, the total effects in Shannxi and Xinjiang were 430.9% and 472.6% overall increase, respectively. Not surprisingly, the contribution of each effect was different among provinces. This reflects differences in economic perspectives, market and owner structures, local energy and environmental policies.

Focusing on specific factors, a positive population effect is observed for all provinces. However, each province was affected differently. Among these provinces, the impact of population on carbon emissions in Ningxia and Xinjiang was more significant than in the other three provinces. Take Xinjiang for example, the increase due to population reached up to 38.3%. It is much higher than 6.3% in Gansu. The underlying cause for this disparity is different family planning policies implemented in Han and ethnic minorities. Pro-natalist policies promoted population growth in ethnic autonomous regions, such as Ningxia and Xinjiang. In 2012, the natural growth rate of population in Xinjiang and Ningxia was 10.6‰and 9.0‰, while it was only 3.7‰in Shaanxi. Therefore, the contribution of population growth to carbon emissions in Ningxia and Xinjiang was significantly higher than that in the other provinces.

Regarding the activity effect, there is a common pattern in every province. Specifically, the economic growth plays a determining role in increase in $CO_2$ emissions. In these five provinces, the contribution of economic growth to carbon emissions was more remarkable in Shannxi and Gansu. In 2014, the cumulative effect of activity was 7.9 times that of 1995 in Shannxi. This can be explained by different economic growths. For instance, the annual growth rate of economy in Shannxi is 11.9% which is higher than 9.9% in Xinjiang.

As Table 3 shows, the intensity effects were negative in all provinces. Taking the accumulated effect during 2006–2014 as an example, it was weak in Xinjiang, whereas it is very strong in Gansu. A number of factors, including more efficient industrial processes and transport systems, tougher standards and better labelling on appliances, energy conservation accountability, improving energy performance of buildings, and, more generally, adaptation of more efficient technologies, tend to reduce energy consumption. In the 11th Five-Year Plan period, a more stringent energy conservation policy was implemented in Gansu. However, the energy intensity played a positive and promotional role in increasing $CO_2$ emissions in Ningxia and Xinjiang during 2011–2014. Specifically, in Xinjiang, the intensity effect was also positive in 2006–2010. This indicates that in these three provinces, energy efficiency and conservation were not obtained or improved.

The structural effect exhibits a great deal of variability depending on the province, ranging from −4.2% in Shannxi to 2.0% in Xinjiang. In Gansu, Ningxia and Xinjiang, changes in the energy structure contributed to increase in aggregate $CO_2$ emissions. This was especially remarkable in Xinjiang. On the contrary, both in Shannxi and Qinghai, the structural effect contributed to decrease in $CO_2$ emissions. This was mainly due to transformation processes by which the importance of raw coal and diesel oil in energy consumption decreased, and increased for natural gas and cleaned coal.

### *3.3. Decoupling State in Northwest China*

Based on the decoupling index, the relation between $CO_2$ emissions and economic growth in Northwest China from 1995 to 2014 was explored. The decoupling indices were obtained according to Equation (7). The results are shown in Table 4, and some insightful conclusions were acquired.

**Table 4.** Decoupling of $CO_2$ emissions and economic growth.

| Time Period | $\delta$ | $\delta_{pop}$ | $\Delta_{int}$ | $\Delta_{str}$ | Decoupling State |
|---|---|---|---|---|---|
| 1995–1996 | 0.1591 | −0.1464 | 0.2851 | 0.0204 | Relative decoupling |
| 1996–1997 | 1.2483 | −0.1369 | 1.2318 | 0.1534 | Strong decoupling |
| 1997–1998 | 0.9162 | −0.1509 | 0.9810 | 0.0861 | Relative decoupling |
| 1998–1999 | 1.3446 | −0.1455 | 1.4160 | 0.0741 | Strong decoupling |
| 1999–2000 | 0.6929 | −0.1981 | 0.7690 | 0.1220 | Relative decoupling |
| 2000–2001 | 0.4011 | −0.0214 | 0.3792 | 0.0433 | Relative decoupling |
| 2001–2002 | 0.1370 | −0.0659 | 0.1986 | 0.0043 | Relative decoupling |
| 2002–2003 | −0.9952 | −0.0619 | −0.8919 | −0.0414 | No decoupling |
| 2003–2004 | −0.2138 | −0.0553 | −0.1818 | 0.0232 | No decoupling |
| 2004–2005 | −0.2451 | −0.0747 | −0.1104 | −0.0600 | No decoupling |
| 2005–2006 | −0.2789 | −0.0620 | −0.2051 | −0.0119 | No decoupling |
| 2006–2007 | 0.1689 | −0.0593 | 0.2420 | −0.0138 | Relative decoupling |
| 2007–2008 | 0.2585 | −0.0532 | 0.3336 | −0.0219 | Relative decoupling |
| 2008–2009 | 0.1731 | −0.0530 | 0.2887 | −0.0625 | Relative decoupling |
| 2009–2010 | −0.1467 | −0.0441 | −0.0807 | −0.0218 | No decoupling |
| 2010–2011 | −0.3501 | −0.0445 | −0.2511 | −0.0546 | No decoupling |
| 2011–2012 | −0.0228 | −0.0555 | 0.0651 | −0.0325 | No decoupling |
| 2012–2013 | 0.1822 | −0.0628 | 0.2640 | −0.0191 | No decoupling |
| 2013–2014 | 0.3659 | −0.0796 | 0.4408 | 0.0048 | Relative decoupling |

According to the method presented in Section 2.1.3, the decoupling effort indices ($\delta$) were divided into three states: strong decoupling, no decoupling, and relative decoupling. The decoupling indices 1.248 for 1997 and 1.345 for 1999 are both greater than 1. This indicates a strong decoupling effect, and implies that the reduction effect of inhibiting factors, such as the energy intensity and energy structure has larger impact compared to the driving effect of economic growth. However, the decoupling indices were negative during 2003–2006 and 2010–2013. This means there was no decoupling of $CO_2$ emissions and economic growth. In other words, in these years, rapid economic growth was characterized by high energy consumption and high $CO_2$ emissions. Relative decoupling is observed in the other study period. This conclusion is different from previous results regarding other more developed regions [10,35]. Put precisely, more "no decoupling" was observed in Northwest China than in more developed regions [18,37,54,74,75]. This means that underdeveloped areas clearly lag behind developed areas in the process of decoupling. It is necessary to clarify the decoupling state by deeper analysis of each influencing factor. Each factor is analyzed separately below.

The population effect ($\delta_{pop}$) generally results in a constant increase in $CO_2$ emissions over the study period, which does not contribute to decoupling. This indicates that the ongoing population growth hinders decoupling. Although over decades China has implemented strict family planning policies, the natural population growth rate is still high in Northwest China [76]. Taking Xinjiang for instance, the average growth is 11.6‰ over the examined period, which is about two times the average value in the whole country.

Regarding the energy intensity effect ($\delta_{int}$), it plays a critical role in dissociating the relation between $CO_2$ emissions and economic growth, except during 2003–2006 and 2010–2011. Generally, owing to extensive use of energy saving technologies and advancements in energy management, the energy intensity should decline gradually [77–79]. However, two exceptions occur during 2003–2006 and 2010–2011. There are two main reasons: China's accession to the WTO, and the Western Development Strategy. Specifically, in these two periods, $CO_2$ emissions caused by rapid economic growth overwhelmed reduction, which was mainly due to improved energy efficiency.

As for the energy structure effect ($\delta_{str}$), it decreased $CO_2$ emissions during 1996–2002. From 2005 to 2013, the energy structure effect played a negative role in the decoupling progress. In other words, this indicates that with continuous economic growth, the structure of energy use was not optimized, but degraded constantly. Take Ningxia as an example, where coal accounts for 80% of total energy consumption. This hinders the healthy development of the sustainable energy consumption [80–82]. Again, in the case of Xinjiang, the proportion of coal declined from 50.0% in 1996 to 43.4% in 2002, and then increased from 44.3% in 2003 to 58.0% in 2014. This fully shows that adjustment of the energy mix is an important obstacle to decoupling process.

## 4. Conclusions and Policy Implications

### *4.1. Conclusions*

In this paper, we compared and analyzed historical trajectories of $CO_2$ emissions in Northwest China from the regional and provincial perspectives. We decomposed changes in final energy-related $CO_2$ emissions in Northwest China and five provinces during 1995–2014 to identify main influencing factors by utilizing the LMDI method. At the same time, we built a new decoupling model to analyze the decoupling relation between $CO_2$ emissions and economic growth in Northwest China. Moreover, to investigate factors affecting the decoupling progress, changes in decoupling indicators were divided into four factors based on the LMDI approach. Several conclusions can be obtained as follows:

- In Northwest China, total $CO_2$ emissions and per capita $CO_2$ emissions increased rapidly during 1996–2014. In 2014, these two indicators were 4.9 times and 4.3 times their 1995 levels. At the same time, the trend of the $CO_2$ emission intensity is more complicated. From 1996 to 2002, it decreased slowly. Then, it increased with the average annual rate of 1.0% during 2002–2009. After 2009, it almost unchanged. Specifically at the provincial level, although the trends of the total $CO_2$ emissions, per capita $CO_2$ emissions, and $CO_2$ emission intensity were similar in the provinces, variations of these indicators were different among provinces.
- The results derived from the additive decomposition of $CO_2$ emissions at the regional level show the following. The economic activity proves to be an overwhelming contributor to $CO_2$

emissions increase, which accounts for 67.5% of the total emissions during the study period. At the same time, the population also contributes to $CO_2$ emissions with the contribution rate of 5.1%. Conversely, the energy intensity partially offsets emission growth, with the contribution rate of −13.3%. Moreover, the energy structure has a marginal effect with the rate of only about −0.02%.

- Comparative analysis of the multiplicative decomposition results for the five provinces indicates that the population effect in Ningxia and Xinjiang is more significant than that in the other provinces. At the same time, the contributions of the economic growth to carbon emissions are more remarkable in Shannxi and Gansu. Moreover, the intensity effect was weak in Xinjiang, whereas it was very strong in Gansu. In addition, the structural effect varies significantly among provinces, ranging from −4.2% in Shannxi to 2.0% in Xinjiang.
- According to the decoupling index, the "relative decoupling effort" and "no decoupling effort" are the main characteristics during the examined period. Specifically, in 1996, 1998, 2000–2002 and 2007–2009, the decoupling state is characterized as "relative decoupling", while during 2003–2006, 2010–2013, the decoupling state is characterized as "no decoupling". Also, there was "strong decoupling" in 1997 and 1999.

### 4.2. Policy Implications

Based on the empirical conclusions above, to achieve reduction in the carbon emission intensity by 40%–50% by 2020 compared to the level of 2005, some policy recommendations proposed as follows.

- More attention should be paid to the environmental impact of the Western Development Strategy. To achieve low-carbon development in Northwest China, the government should continually change economic growth patterns. In particular, the government should increase its investments in energy-related technologies, while restricting transfers of backward production capacities to Northwest China. For other underdeveloped regions, it is equally important to change the mode of economic growth. Underdeveloped areas should obtain more technology spillovers from advanced areas, but not as pollution havens, aimed to boost the economy without considering the environment and only relying on a large number of resources consumption.
- Readjusting the energy use structure is urgently required. From the national point of view, the energy use structure significantly inhibited $CO_2$ emissions in recent years [10,18]. On the contrary, it increased $CO_2$ emissions since 2005 in Northwest China. This indicates that optimization of the energy use structure in Northwest China, where the proportion of coal consumption continued to be at around 60.0%, clearly lags behind the rest of the country. The government must strictly control coal consumption caps, and continuously reduce the proportion of coal in the total primary energy consumption mix. Furthermore, policy makers should seize the opportunities of the "One Road, One Belt" initiative, strengthen energy cooperation with Central Asia, and increase the proportion of clean and renewable energy. In addition, there are many efficacious energy innovation policy tools and energy innovation organizations, such as energy development plan, preferential taxes, subsidies, and public procurement which can be used to invite investment in clean and renewable energy technology.
- Energy efficiency should be persistently improved. Northwest China is a major energy and chemical industry base. Since 2000, the central government began to implement the Western Development Strategy. Financial support and preferential policies were provided to promote growth of economy, especially industries. However, the progress in developing energy utilization technologies in Northwest China lags far behind the national average. Accordingly, the government should focus more on research and development of advanced energy technologies, eliminating backward production capacities to improve energy efficiency. Moreover, given that technology inequity exists between developed and undeveloped regions, the central government has to make significant efforts to balance the development of carbon emission reduction technology through removing technology barrier between regions.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| LMDI | Logarithmic Mean Divisia Index |
| BTH | Beijing-Tianjin-Hebei |
| YRD | Yangtze River Delta |

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