A LMDI decomposition analysis of carbon dioxide emissions from the electric power sector in Northwest China

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Abstract

Taking advantage of the electrification strategy, Northwest China has made full use of its natural resources endowment, to develop renewable energy as the substitution of thermal power. To evaluate carbon dioxide (CO₂) emissions from electric power sector, an extended Kaya identity equation and the Logarithmic mean Divisia index decomposition method are applied to Northwest China from 1998 to 2017. Six explaining factors are analyzed, including carbon intensity, energy mixes, generating efficiency, electrification, economy and population. The results show that driving force of CO₂ emissions from electricity system varied greatly among provinces. Generally, economic growth has mainly contributed to increase CO₂ emission, while the improvement in the power-generating efficiency has crucially decreased CO₂ emission. In 2017, Promoting electrification directly increased CO₂ emissions from electric system, but indirectly reduced CO₂ emissions from the whole region by 5.10% through the estimation of a clean development mechanism method. Therefore, local governments are suggested continuing to promote electrification to guide future emission reduction, while enterprises and...
individuals need to make their own contributions to low-carbon development.

**Recommendations for Resource Managers:**

- Variations of carbon dioxide (CO₂) emissions of all five provinces in Northwest China are analyzed.
- Logarithmic mean Divisia index analysis is used to study the main drivers of CO₂ emission change.
- Improvements in the generating efficiency significantly reduced CO₂ emissions.
- Due to electrification effects, CO₂ emissions from electric power increased, but CO₂ emissions from the region decreased.
- Economy effects were still the biggest drivers affecting CO₂ emission.

**KEYWORDS**

CO₂ emissions, electrification, LMDI analysis, regional development, renewable energy

1 | INTRODUCTION

It is certificated that global warming results from rising carbon dioxide (CO₂) emissions given off by human activities. A series of extreme climate disasters have attacked the earth in retaliation, restricting the sustainable development of the world (Department of Trade & Industry, 2003). Developing low-carbon economy has become a global consensus. In 1997, the Kyoto Protocol was formally established as an international binding agreement to combat global warming (UNFCCC, 2018).

After half a century of rapid development, China has leaped to the largest developing country with the largest energy consumption and CO₂ emissions in the world (Dai et al., 2018). Under the Copenhagen Accord of the United Nations Framework Convention on Climate Change (UNFCCC) in 2010, the Chinese government proposed that by 2020, CO₂ emissions per unit GDP would be reduced by 40%–45% compared to the 2005 levels. And the proportion of nonfossil energy to primary energy consumption would reach about 15% (UNFCCC, 2018). In 2015, China pledged in its Intended National Determined Contribution (INDC) to reduce the intensity of CO₂ emissions by 60%–65% by 2030 from the 2005 levels (UNFCCC, 2018). Once the national targets are set, the next problem would be the allocation of regional emissions. To ensure the more operational targets, the objective of emission reduction has become an important criterion to local governments under the political accountability.

At present, issues with renewable energy utilization in China have been mainly distributed in the northwestern region. For example, in 2018, more than 57% of the total abandoned wind and solar power in China were occurred in two northwestern provinces, Xinjiang and Gansu.
This is because the demand side has not yet formed the large-scale capacity to absorb renewable energy. To solve this problem, Northwest China has been promoting the terminal users to consume electric power instead of fossil fuels, such as coal, oil, natural gas, and so forth. It is also known as electrification (Khanna et al., 2018). It optimizes energy structure and enlarges low-carbon power supplies by accelerating diversified utilization of renewable energy, mainly including wind power, solar power, hydropower. In addition, electrification helps to develop related manufacturing industry and bring new opportunities for economic growth (European Commission, 2014).

As a high energy-consuming and basic industry, the electric system converts primary energy into electric power for terminal usage. It is also a main source of CO₂ emissions. Approximately two-thirds of total greenhouse gas (GHG) emission was released by the electric system (Batel et al., 2013). With the largest decarbonization potential and an advantageous allocation of large-scale energy, the electric system has become a breakthrough for Northwest China to expand the access to renewable energy utilization, thus promoting low-carbon development (Khan, 2019).

To provide suggestions for future emission reduction, the driving forces of CO₂ emissions from electric power industry and their emission reduction potential are explored in this paper from 1998 to 2017. Section 2 summarizes the main results from former studies. Section 3 describes the methods used in this paper, including the inventory analysis, an extended Kaya Identity equation, the Logarithmic mean Divisia index (LMDI) decomposition method and a clean development mechanism (CDM) estimation. Section 4 introduces Northwest China and clarifies the data sources. In Section 5, the characteristics of driving forces and their evolution history are discussed in depth. The emission reduction is evaluated both directly and indirectly. Finally, Section 6 concludes the main results and suggestions of emission reduction.

2 LITERATURE REVIEW

Exiting studies on CO₂ emissions have generally focused on the following aspects: CO₂ emissions estimations (Kennedy et al., 2011), decomposition methods (Sheinbaum-Pardo et al., 2012), simulations of techniques and policies for CO₂ emission reduction (J. F. Li et al., 2012). Among them, the first method is the basis of CO₂ emission research. There are many factors affecting CO₂ emissions, such as population growth, economic development, energy consumption, and technological progress. The Kaya identity equation is one of the most widely used models to determine the above driving forces of CO₂ emissions (Antonio Duro, 2010). And the decomposition method is the foundation to implement the simulation and analysis of emission reduction techniques. As Kopidou et al. (2016) explained, decomposition technology provided a different way for studying the complexity of reality. The relative contribution of each factor over time can be revealed to inform the policies to be taken.

There are two main decomposition methods, structural decomposition analysis (SDA; B. Su & Ang, 2012) and index decomposition analysis (IDA; Ang, 1995). SDA needs input-output (IO) data. For example, Xu et al. (2017) used SDA to analyze factors that affecting China’s air pollutant emissions. However, China updates its IO data once every 5 years, and the latest data is up to 2012. It seems to be not suitable to study recent circumstances. By contrast, IDA can be used on time series variables. To overcome the shortcomings of other IDA methods, Ang et al. (1998) proposed to use LMDI to decompose CO₂ emissions. The additive function of LMDI can reflect the real value of each index’s contribution to pollutant emissions (Ang et al., 2003). It has several merits, including numerous indexes analysis, no residuals production, complete
decomposition and consistent results (Meng et al., 2016). LMDI has been widely used to decompose GHG emissions from many fields. For example, it has been applied to the transport (Kim, 2019), industrial (L. Li et al., 2019), and household sector (Kurniawan et al., 2018).

Because of the huge emission reduction potential of the electric power industry, most of the studies focusing on CO₂ emissions from electric system were at the national level. For example, Karmellos et al. (2016) studied on the driving factors of CO₂ emissions from the power sector in the European Union countries. De Oliveira-De Jesus (2019) analyzed the evolution of carbon accumulation intensity in Latin America and the Caribbean to identify the impact of generating capacity. Mousavi et al. (2017) investigated the impacts of energy consumption and fossil fuels on generating carbon intensity. Ang and Su (2016) evaluated the carbon intensity of electricity production (ACI) globally. They found that the decrease of ACI was mainly due to the improving efficiency of thermal power rather than fuel conversion. Accordingly, they suggested that the share of fossil fuels should be reduced and cleaner fossil fuels should be consumed. And the generation efficiency should be improved to reduce ACI. Based on former studies, Goh et al. (2018) pointed out that the geographical displacement of electricity production offset the positive effect of global generation efficiency improvements. Deepening the penetration of renewable energy and international cooperation would help to reduce ACI in developing countries. Xie et al. (2019) analyzed CO₂ emissions from the process of electric transmission. Gu et al. (2015) predicted the emission reduction under different scenarios, and suggested policies of low carbon development of China’s electric power industry. Some studies on China’s electric power sector focused on the decomposition of electricity consumption. For example, Wang et al. (2018) and Fang et al. (2019) studied electricity consumption from the perspective of geographical distribution.

However, emissions from the regional level, especially multiregional level, received less attention (Liu et al., 2017). Compared with national-level research, regional research makes it more feasible to achieve CO₂ emissions reduction. Compared with microlevel, regional research is more conducive to provide targeted and characteristic strategies. As far as we know, there is no study targeting at Northwest China, especially at the electrification effect. As a key gateway for opening up to the world and an important energy production base, Northwest China is facing an opportunity of strategic development (Yang & Zeng, 2019). However, most industries in the northwestern regions are high energy-consuming. And their energy structure is heavily taken by coal. The task of CO₂ emission reduction is hence arduous. Strictly controlling CO₂ emissions is crucial to the sustainable development in Northwest China.

Therefore, referring to the existing research, this paper first measures CO₂ emissions from the electric industry in Northwest China from 1998 to 2017 by the the inventory analysis. Then the LMDI method and an extended Kaya identity equation are used to fulfill thorough assessment at the regional level. Six selected indexes, respectively are carbon intensity, energy mixes, generating efficiency, electrification, economy, and population effect. Each index is discussed as the basis of environmental and economic policies. The emission reduction is lastly assessed by the CDM method to propose targeted suggestions of energy saving and emission reduction.

3 | METHODOLOGY

3.1 | The inventory analysis

The inventory analysis is based on the approach provided by the energy volume of the Guidelines for National Greenhouse Gas Inventories from the Intergovernmental Panel on
Climate Change (IPCC) in 2006 (United Kingdom Meteorological Office, 2006). Following the framework, CO₂ emissions can be estimated by the amount of fossil fuels combustion and their specific emission factors. It can be calculated as follow:

\[ C_t = \Sigma_i \times \text{LCV}_i \times \text{CF}_i \times O_i \times \frac{44}{12}, \]  

where \( C_t \) represents the total CO₂ emissions in the year of \( t \); \( \Sigma_i \) represents the total consumption of energy \( i \) in the year of \( t \); LCV\(_i\) represents the lower calorific value of energy \( i \); CF\(_i\) represents carbon emission factor of energy \( i \); \( O_i \) represents the oxidation rate of energy \( i \); \( \frac{44}{12} \) represents the conversion coefficient of carbon to CO₂.

### 3.2 the Kaya identity equation and LMDI decomposition method

The Kaya identity equation was first proposed by Japanese professor Yoichi Kaya at an IPCC seminar in 1989 (Kaya, 1989). It is expressed as follows:

\[ C = \frac{C}{E} \times \frac{E}{G} \times \frac{G}{P} \times P \]  

The above equation links CO₂ emissions with energy, economy and population. In this paper, the Kaya identity equation is further extended to six contributing factors as follow:

\[ C = \frac{C}{F} \times \frac{F}{E} \times \frac{E}{S} \times \frac{S}{G} \times \frac{G}{P} \times P \]  

In formula (2) and (3), C, F, E, S, G, and P, respectively, represents the CO₂ emissions, fossil fuels consumption, total energy consumption, generated electrical power, gross domestic product (GDP), and population. Specifically, \( \frac{C}{F} \) is CO₂ emission per unit of fossil energy. It measures the emission intensity of fossil energy. \( \frac{F}{E} \) is the share of fossil energy in total energy. It measures the cleanliness of energy structure. \( \frac{E}{S} \) refers to energy required for per unit of electric power supply. \( \frac{S}{G} \) is electricity generation per GDP value, representing the level of electrification. \( \frac{G}{P} \) is GDP per capita. It is an effective tool to measure macroeconomic operation of a country or region.

The classical Kaya identity equation only considers the impact of total energy consumption on CO₂ emissions. With the diversified structure of energy, it is necessary to study the impact of nonfossil energy consumption on CO₂ emissions. Therefore, the structure of total energy and the fossil energy are respectively discussed in this paper to clarify the contribution of renewable energy. Generated electric power is also taken into account as an index to appraise electrification.

The change of CO₂ emissions is the result of the all six factors above. Each factor has different effect on CO₂ emissions during different periods. The LMDI allows to assess CO₂ emissions by various types of individual indexes in addition or multiplication decomposition.
Based on formula (3), after logarithmic transformation, the additive function of the LMDI method of CO₂ emissions is shown as follow:

\[
\Delta C = C_t - C_0 = \frac{C_t - C_0}{\ln C_t - \ln C_0} \times (\ln C_t - \ln C_0)
= A \times \left( \ln \left( \frac{C_t}{C_0} \right) \times \frac{F_0}{F_t} \right) + \ln \left( \frac{F_t}{E_t} \times \frac{E_t}{F_0} \right) + \ln \left( \frac{S_t}{S_0} \times \frac{G_0}{G_t} \right) + \ln \left( \frac{S_t}{S_0} \times \frac{G_0}{G_t} \right)
+ \ln \left( \frac{G_t}{P_t} \times \frac{P_t}{G_0} \right) + \ln \left( \frac{P_t}{P_0} \right) = \Delta I + \Delta R + \Delta L + \Delta D + \Delta B + \Delta P. 
\] (4)

In formula (4), \( \Delta C \) represents the difference between CO₂ emission \( C_t \) in the year \( t \) and \( C_0 \) in the basis year 0; \( \Delta I \) represents the contribution of \( C/F \) in formula (3) to \( \Delta C \). And it is defined as carbon intensity effect; Accordingly, \( \Delta R \) represents the contribution of \( F/E \) and is defined as energy mixes effect; \( \Delta L \) represents the contribution of \( E/S \) and is defined as generating efficiency effect; \( \Delta D \) represents the contribution of \( S/G \) and is defined as electrification effect; \( \Delta B \) represents the contribution of \( G/P \) and is defined as economic effect; \( \Delta P \) represents the contribution of \( P \) and is defined as population effect. And to simplify the calculation, \( A \) is defined as follows:

\[
A = \frac{C_t - C_0}{\ln C_t - \ln C_0}. 
\] (5)

To evaluate the contribution to the change of CO₂ emissions, six indexes can be calculated during any period as follows:

\[
\Delta I = A \times \left( \ln \frac{C_t}{F_t} - \ln \frac{C_0}{F_0} \right), 
\] (6)

\[
\Delta R = A \times \left( \ln \frac{F_t}{E_t} - \ln \frac{F_0}{E_0} \right), 
\] (7)

\[
\Delta L = A \times \left( \ln \frac{E_t}{S_t} - \ln \frac{E_0}{S_0} \right), 
\] (8)

\[
\Delta D = A \times \left( \ln \frac{S_t}{G_t} - \ln \frac{S_0}{G_0} \right), 
\] (9)

\[
\Delta B = A \times \left( \ln \frac{G_t}{P_t} - \ln \frac{G_0}{P_0} \right), 
\] (10)

\[
\Delta P = A \times (\ln P_t - \ln P_0). 
\] (11)

If the contribution is positive, it means that the index increases the CO₂ emissions. On the contrary, if the contribution value is negative, it means that the index reduces CO₂ emissions.
### 3.3 Renewable energy and CO₂ emission reduction

There are two ways to increase renewable energy usage by electrification strategy. First, promoting electrification increases the consumption of wind power, solar power, hydropower, instead of thermal power. With structural optimization of generation, the usage of renewable energy increases. Second, promoting electricity substitution increases electricity consumption. It directly increases the usage of renewable energy, if electricity is provided by low-carbon sources (Luh et al., 2020). Even with the unchanged energy structure of generation, electricity consumption increases renewable energy usage. Electrification strategy eventually mitigates pollutants emission caused by the burning of fossil fuels (Niu, Song, & Xiao, 2017). Taking electric heating as an example, electric device replaces the coal-fired heating boiler. It reduces coal combustion and increases the usage of renewable energy by using more electricity. Thereby, one of the purposes of electrification strategy is to increase electricity consumption.

To evaluate electrification, some researchers used the ratio of electricity consumption in total energy consumption (Lin & Zhu, 2020). And the energy intensity can be calculated by dividing the total energy consumption by real GDP (Liddle, 2010). In this study, the level of electrification is defined as electric power per GDP to represent electric intensity. The higher electric intensity is, the more electricity is required for production of a given GDP, and the more renewable energy is utilized.

Therefore, this study uses the increasing amount of renewable energy, which is the result of both increasing electricity and optimizing structure, to calculate CO₂ emission reduction.

As renewable energy has been registered under the CDM projects, this paper adopts the CDM methodology to estimate the CO₂ emission reduction associated with electrification. There are nearly 100 accounting methods approved by CDM, of which AMS-I.D. UNFCCC (2014) and ACM0002 (UNFCCC, 2019) are suitable for grid-connected renewable energy generation. But AMS-I.D. is for small-scale projects, with installed capacity (IC) less than 15 MW. And ACM0002 is for large-scale projects, which having IC more than 15 MW. In this paper, all renewable energy generation plants are assumed to be large scale. If all the electric power is produced by the thermal power, the emissions from required thermal power are the initial emissions. After the integration of renewable energy in electric system, it reduces the CO₂ emissions compared to the initial emissions. According to ACM0002, the reduction part is the baseline emission. It can be calculated as follows:

\[
BE_t = EG_t \times EF_t. \tag{12}
\]

In formula (12), \(BE_t\) is baseline emission in year \(t\); \(EG_t\) is the capacity of renewable energy generation integrated into the power grids in year \(t\); \(EF_t\) is the combined margin CO₂ emission factor for grid-connected power generation in year \(t\), calculated using “TOOL07: Tool to calculate the emission factor for an electricity system” (UNFCCC, 2018). \(EF_t\) can be calculated as follows:

\[
EF_t = OM_t \times W_{OM} + BM_t \times W_{BM}. \tag{13}
\]

In formula (13), \(OM_t\) is the operational marginal emission factor in year \(t\); \(BM_t\) is the building marginal emission factor in year \(t\); \(W_{OM}\) and \(W_{BM}\) are the weight of \(OM_t\) and \(BM_t\), respectively. According to TOOL07 (UNFCCC, 2018), for wind and solar power generation...
The CO$_2$ emission reduction of grid-connected renewable energy generation can be calculated as follows:

$$ER_t = BE_t - PE_t - L_t.$$  \hspace{1cm} (14)

In formula (8), $ER_t$ is the CO$_2$ emission reduction; $PE_t$ is the CO$_2$ emission released by renewable energy power generation; $L_t$ is the leakage of CO$_2$ from renewable energy. When calculating CO$_2$ emission reduction in this paper, both $PE_t$ and $L_t$ are neglected as being 0.

Based on the above methodology, the proposed framework of this paper is shown in Figure 1.

4 | CASE STUDY

The five provincial-level divisions located in Northwest China are the autonomous regions of Xinjiang and Ningxia, and the provinces of Shaanxi, Gansu, and Qinghai. They are all called provinces in this paper. As shown in Figure 2, the total land coverage of Northwest China is about one-third of that of China. Most of these northwestern provinces have arid or semiarid
climate and long sunshine duration. And they are generally characterized by less developed economy and abundant resources of wind and solar energy. In addition, Northwest China plays an important role in “Belt and Road” initiative of China. It has brought a crucial opportunity for the northwestern provinces. To seek rapid economic development, these provinces need to strength transportation infrastructure, cultural exchanges and westward opening up.

The data of GDP, population and energy are derived from Statistical Yearbook (NSB of China, 1999-2018) and Energy Statistics Yearbook (NSB of China, 1999-2018) published by National Statistical Bureau (NSB) of China from 1999 to 2018. And to maintain comparability, the prices for GDP have been converted to real GDP based on the year of 1998. The fossil energy sources of the electric power sector are divided into eight main categories: raw coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, and nature gas. And their emission factors, lower calorific value and oxidation rate are collected from China’s Guidelines for National Greenhouse Gas Inventories (MEE of China, 2018), issued by the Department of Climate Change of the Ministry of Ecology and Environment (MEE) of China. To conduct estimation of emission reduction, the relevant calculated coefficients, including BM and OM, are derived from Baseline Emission Factors for Regional Power Grids in China (MEE of China, 2018), issued by the Department of Climate Change of MEE, and Electric Power Yearbook (NEA of China, 2017) issued by the National Energy Administration (NEA) of National Development and Reform Commission (NDRC) of China. Some Supporting Information data were obtained through Annual Report on Development of Northwest China (Yue et al., 2018). All the data used in this article are collated in Supporting Information Materials.

FIGURE 2 The map of Northwest China
5.1 CO₂ emissions

Based on formula (1), the CO₂ emissions from electric power sector in Northwest China can be calculated. Figure 3 shows the results. The CO₂ emission from Northwest China increased from 426.82 million tons in 1998 to 2.68 billion tons in 2017, with an average annual growth rate at 10.41%. In general, the total emissions had been increasing rapidly before 2013. This might be related to the extensive development of economy at the early stage. The emission growth started to slow down from 2014, and even declined once in 2015, by 4.64%. This might be due to the downward pressure on economy and expanding renewable energy consumption. Similarly, CO₂ emissions from five northwestern regions also showed substantial increases at the early stage, but the sluggish growth at the latter stage. But the emission from Xinjiang kept growing significantly after 2011. In 2017, Xinjiang had the largest CO₂ emission with 972.96 million tons. Shaanxi ranked the second with emission of 700.43 million tons. Qinghai had the lowest with 98.07 million tons.

5.2 Contributing indexes

To explain the driving forces of above CO₂ emissions, this section investigates the contribution of carbon intensity (ΔI), energy mixes (ΔR), generating efficiency (ΔL), electrification (ΔD), economy (ΔB), and population (ΔP). Table 1 shows the results, calculated by the LMDI method in formula (6)–(11). Among them, the positive values represent the promoting effect on CO₂ emissions. On the contrary, the negative values represent the inhibiting effect, which is shown in red in Table 1. Since 1998 was set as the base year, the contributing indexes and CO₂ emission change (ΔC) in 1998 were 0.

To make provincial comparisons, Figure 4 shows the cumulative contributing indexes of each province. For example, the CO₂ emission change of electric system in Xinjiang was 883.62 million tons from 1998 to 2017. This change can be decomposed into three positive factors (ΔB, ΔP, and ΔD) and three negative factors (ΔL, ΔR, and ΔI).
TABLE 1  The decomposition of CO₂ emission change (annual) from the electric power sector in Northwest China from 1998 to 2017

| Year  | ΔC   | ΔB   | ΔP   | ΔL   | ΔR   | ΔI   | ΔD   |
|-------|------|------|------|------|------|------|------|
| 1998  | 0    | 0    | 0    | 0    | 0.00 | 0    | 0.00 |
| 1998–1999 | 18.38 | 34.01 | 1.29 | 25.34 | −31.17 | −0.1 | −10.99 |
| 1999–2000 | 36.98 | 32.76 | 4.57 | −17.28 | 22.26 | −0.37 | −5.71 |
| 2000–2001 | 60.9  | 38.26 | 3.14 | −14.26 | −32.49 | −0.48 | 63.23 |
| 2001–2002 | 47.58 | 42.2  | 3.64 | −12.52 | 91.64 | 1.72 | −49.59 |
| 2002–2003 | 111.05 | 54.89 | 3.54 | 8.51  | 8.66  | −2.32 | 21.98 |
| 2003–2004 | 157.12 | 62.94 | 3.64 | 12.59 | 11.47 | −1.21 | 35.42 |
| 2004–2005 | 69.38 | 66.52 | 5.04 | −12.52 | −22.54 | −5.55 | 19.19 |
| 2005–2006 | 108.83 | 71.06 | 4.55 | −20.52 | 5.74  | 6.4  | 8.97  |
| 2006–2007 | 215.61 | 86.51 | 5.34 | 16.23 | 9.28  | −0.30 | 27.83 |
| 2007–2008 | 163.31 | 94.86 | 5.05 | 13    | −12.78 | 5.32 | −4.37 |
| 2008–2009 | 16.73 | 80.54 | 4.47 | −9.92 | −32.77 | −4.79 | −27.79 |
| 2009–2010 | 376.43 | 111.16 | 4.92 | 93.13 | −49.63 | −1.08 | 64.77 |
| 2010–2011 | 216.19 | 118.77 | 5.35 | −151.5 | 43.15 | −0.15 | 100.26 |
| 2011–2012 | 152.86 | 116.56 | 6.63 | −47.59 | −28.65 | −0.07 | 31.32 |
| 2012–2013 | 281.79 | 107.43 | 6.95 | −17.72 | −19.91 | 0.05 | 64.43 |
| 2013–2014 | 85.76 | 94.01 | 8.02 | −89.29 | 11.38 | 0.05 | 16.49 |

(Continues)
In Table 1, the largest positive index was $\Delta B$, accounting for 94.21% of the overall CO$_2$ emission change of the electric system in Northwest China from 1998 to 2017. With the further development of reform and opening up, the economy of China has developed steadily. Behind the rapid economic growth, there are dramatic hidden resource consumption and environmental pollution. As showed in Figure 5a,b from 1998 to 2017, China’s real GDP per capital had steadily increased, with an average annual growth rate at 8.57%. The real GDP per capital of China was bigger than that of each northwestern province. It might be owing to the less developing economy of Northwest China. There were three provinces having higher per capital GDP growth rates than China, respectively Shaanxi (11.12%), Gansu (10.05%), and Qinghai (10.86%). At the same time, they were the provinces with the top three economic effects, with shares of $\Delta B$ bigger than 130% of the provincial emission changes in Figure 4. In contrast, Xinjiang (6.32%) and Ningxia (7.98%) had smaller growth rates. And their economic effects were relatively smaller, with shares of $\Delta B$ not exceeding 60%. It is found that there were

![Image of Table 1](image-url)

**TABLE 1** (Continued)  

| Year       | $\Delta C$ | $\Delta B$ | $\Delta P$ | $\Delta L$ | $\Delta R$ | $\Delta I$ | $\Delta D$ |
|------------|------------|------------|------------|------------|------------|------------|------------|
| 2014–2015  | −118.16    | 77.01      | 6.88       | −93.9      | −15.5      | 0.3        | −29.47     |
|            | (−65.17%)  | (−5.82%)   | 79.47%     | (13.12%)   | (−0.25%)   | (24.94%)   |            |
| 2015–2016  | 84.16      | 65.13      | 14.17      | −15.89     | 1.68       | 1.77       | −26.77     |
|            | (77.38%)   | (16.84%)   | (−18.89%)  | (2.00%)    | (2.11%)    | (−31.81%)  |            |
| 2016–2017  | 169.47     | 63.04      | 11.7       | −11.98     | −32.57     | −0.65      | 50.56      |
|            | (37.20%)   | (6.90%)    | (−7.07%)   | (−19.22%)  | (−0.38%)   | (29.84%)   |            |
| 1998–2017  | 2254.37    | 2123.75    | 157.05     | −467.26    | −31.77     | −4.63      | 477.22     |
|            | (94.21%)   | (6.97%)    | (−20.73%)  | (−1.41%)   | (−0.21%)   | (21.17%)   |            |

Note: The contribution share of each index is shown in its below bracket.

### 5.2.1 Economic effect

In Table 1, the largest positive index was $\Delta B$, accounting for 94.21% of the overall CO$_2$ emission change of the electric system in Northwest China from 1998 to 2017. With the further development of reform and opening up, the economy of China has developed steadily. Behind the rapid economic growth, there are dramatic hidden resource consumption and environmental pollution. As showed in Figure 5a,b from 1998 to 2017, China’s real GDP per capital had steadily increased, with an average annual growth rate at 8.57%. The real GDP per capital of China was bigger than that of each northwestern province. It might be owing to the less developing economy of Northwest China. There were three provinces having higher per capital GDP growth rates than China, respectively Shaanxi (11.12%), Gansu (10.05%), and Qinghai (10.86%). At the same time, they were the provinces with the top three economic effects, with shares of $\Delta B$ bigger than 130% of the provincial emission changes in Figure 4. In contrast, Xinjiang (6.32%) and Ningxia (7.98%) had smaller growth rates. And their economic effects were relatively smaller, with shares of $\Delta B$ not exceeding 60%. It is found that there were

![Image of CO2 Emission Change](image-url)

**FIGURE 4** The decomposition of CO$_2$ emission change (cumulative) from 1998 to 2017 in five northwestern provinces. The histogram represents the contribution of each index. The line represents the CO$_2$ emission change of the electric power sector. The percentage number above each bar is the contributing share of each effect.
differences in economic effects among provinces. Besides, the economic effect on the whole area had been increasing rapidly before 2013 in Table 1. With the declining economic growth after 2014, the economic effect had gradually slowed down. The transformation of economic development models seemed to reduce economic effect on CO2 emissions.

Overall, the economic effect measured the impact of economic development. It was the most important factor to increase CO2 emission, which is consistent with other studies in Section 2. This might be related to that the economic growth is generally accompanied by the rapid process of industrialization and accelerated consumption of energy (Wu et al., 2019). In addition, the resident income has increased with the economic prosperity. And electronic goods, such as air conditioners and refrigerators, have been popularized, resulting in a significant increase in electricity consumption.

In the past, the economic development of Northwest China mainly depended on the governments' investment of public infrastructure. Besides, Northwest China was relatively infirm in national division of labor. Traditional industries, represented by resource-intensive and energy-intensive industries, accelerated their transfers to the northwestern provinces. With extensive development pattern and the unreasonable energy structure, Northwest China is now under greater pressure on curbing excess manufacturing capacity and eliminate backward production capacity. Besides, due to its unique geographic advantages and crucial role in westward opening up, Northwest China has been facing the opportunity of development from the Belt and Road initiative since 2013. The traffic construction, business logistics and cultural communication have been increased dramatically. It would inevitably lead to more constraints
on resources and environment. Therefore, the task of energy saving and emission reduction in Northwest China is more arduous. The northwestern provinces need to promote industrial transformation and upgrading to fulfill the coordinated development among economy, society and environment to reduce CO₂ emissions during the economic development process.

5.2.2 | Population effect

The smallest positive index was ΔP, accounting for 6.97% of the overall CO₂ emissions. The total population of Northwest China was about 101.86 million persons in 2017, accounting for approximately one fourteenth of the total population of China. Most provinces were sparsely populated. As can be seen in Figure 6, Shaanxi had the largest population and Qinghai had the least. The population of Qinghai and Ningxia were close to each other. The population growth of Xinjiang was the most obvious, with an average growth rate at 1.79% annually. In 2017, the population of Xinjiang reached around 24.45 million persons, close to the population of Gansu. Ningxia and Gansu had the second and the third largest growth rate at 1.27% and 0.92%. Population growth in other two provinces were relatively flat, not exceeding 0.35%. At the same time, the province with the highest contributing share of population effect was Xinjiang (14.06%) in Figure 4. The second was Qinghai (11.65%). Gansu (1.36%) had the lowest. From the annual decomposition of whole Northwest China in Table 1, population effect had been slowly increasing with population growth.

Overall, CO₂ emissions were highly correlated with population growth. It reflected electric power consumption from the aspect of residential demand. With the advancement in modernization and the widespread usage of electronic products, residential demand for electricity has increased significantly. Both population growth and improvements of people’s living standards affect the generation scale of electric industry. It is possible that the contribution of population to CO₂ emissions would not decrease much in the short term. Therefore, improving residents’ awareness of energy conservation and recycling can help reduce CO₂ emissions.

5.2.3 | Generating efficiency effect

The largest negative index was ΔL, accounting for −20.73% of the overall change from 1998 to 2017. In Figure 7, the energy consumption intensity of Northwest China generally showed a
downward trend, from 363.79 ton of SEC/kW h in 1998 to 248.56 ton of SEC/kW h in 2017. It reflected the continuous advancement progress of energy-saving technology, especially after 2010. All provinces had the similar trends, except Qinghai. Its energy intensity increased dramatically from 2007 to 2010, which might be due to the excessive development of renewable energy. Energy supplies might exceed absorptive capacity of the generation. And the difficulty in peak-shaving of power grid also could cause a slight increase in energy consumption.

Energy intensity was positively correlated with CO2 emission. When the generating efficiency improved in Figure 7, its effect on in CO2 emission turned negative in Table 1, and vice versa. It showed that the northwestern provinces were gradually changing their extensive development models, and their energy efficiency were constantly improved. From the provincial comparison, $\Delta L$ in Shaanxi contributed the most, taking up $-40.69\%$ of the emission change. At the same time, Shaanxi had the most obvious improvement in generating efficiency. The following were Gansu ($-21.15\%$) and Xinjiang ($-20.22\%$). Only Ningxia had a positive $\Delta L$ share (3.99\%), as it was the only region with increasing energy intensity. Technical progress had a positive impact on the CO2 emissions from the electric system. With continuous advancement in technology and productivity, energy consumption decreased, thus reducing CO2 emissions. Ningxia needs to implement policies to improve energy efficiency, such as upgrading technology of electric generation, to save energy and reduce emissions.

5.2.4 | Energy mixes effect

The second largest negative index was $\Delta R$, accounting for $-1.41\%$ of the total emission change. It was also positively correlated with CO2 emission, similar with $\Delta L$. Under a certain amount of energy consumption, the larger the weight of fossil energy was, the less renewable energy was used, and the higher the CO2 emission was. On the contrary, expanding the share of renewable energy could reduce CO2 emissions. In Figure 4, only Shaanxi had a positive $\Delta L$ share (0.09\%), as its energy structure in 2017 remained the same ratio as in 1998 at 87%. In fact, Shaanxi was the second largest province of coal production in China in 2017. With the coal-based energy structure, the share of renewable energy in Shaanxi was only 12.57\%, which was the smallest among five northwestern provinces.
In general, $\Delta R$ had a limited impact on emission reduction. This might be related to the energy structure dominated by thermal power in Northwest China. As showed in Figure 8, electric power industry had been developing rapidly. The scale of electric generation increased substantially from 86.39 billion kW h in 1998 to 818.15 billion kW h in 2017, with an average annual growth rate at 12.76%. However, the ratio of thermal power to total energy only declined from 74.36% in 1998 to 73.00% in 2017. Because of the shortage of water resources in most provinces in Northwest China, the proportion of hydropower decreased gradually by about 12.04% from 1998 to 2017. The proportion of other renewable energy had expanded from 0.04% in 1998 to 13.44% in 2017. Thermal power generation was absolutely dominant. And the share of renewable energy was still low.

Most of the northwestern provinces have natural endowment of energy and mineral resources. For example, their reserves of coal, oil, and natural gas are abundant, ranking in the forefront of China. They are also rich in wind and solar resources suitable for electric generation. Among them, Ningxia and Gansu are two provinces with the top two abundant solar energy resources in China. Xinjiang has large-scale wind power industry, ranking the second in China. Therefore, the renewable energy industry has become one of the pillar industries in Northwest China, which not only brings new opportunities to economic growth, but also improves the low-carbon development of Northwest China.

However, the energy structure in Northwest China still needs to be optimized. To specifically take the scarcity of traditional fossil energy into consideration, it is needed to increase the consumption of renewable energy to replace fossil fuels. Therefore, expanding the access to renewable energy seems to be an effective way to achieve emission reduction.

5.2.5 | Carbon intensity effect

$\Delta I$ was even weaker, accounting for $-0.21\%$ of the total emission change. It is different from other scholars’ conclusions in Section 2. Because the index set in this paper is the carbon...
intensity of fossil energy, instead of that of all energy sources. It excludes the effect of renewable energy, which is assessed by $\Delta R$ above. Not all types of energy bring CO₂ emissions. Fossil fuels are the major sources. And carbon intensity varies from different fossil fuels combinations, which is in line with the definition of carbon intensity. For example, diesel oil and fuel oil have greater carbon intensity than raw coal, which have even greater carbon intensity than natural gas. On the contrary, the utilization of renewable energy, such as wind and solar power, would not release CO₂. Therefore, emissions from the electric power sector would be different, if the energy sources are different. As shown in Figure 9, the carbon intensity during the selected period decreased by only 0.06 ton/ton of SEC. This is because that coal took up more than 99% of fossil energy. Other types of fossil energy shared less than 1% of the total consumption.

The electric power industry in Northwest China was still heavily dependent on coal. Therefore, the contribution of carbon intensity was the smallest. However, future policies aimed at expanding the proportion of energy with low carbon intensity, such as natural gas, would stimulate the potential of CO₂ emission reduction.

### 5.2.6 Electrification effect

Another positive effect was $\Delta D$, accounting for 21.17% of the total emission change. In Figure 10, the level of electrification in Northwest China had increased from 0.22% kW h/Yuan in 1998 to 0.33% kW h/Yuan. This might be due to the popularized electric facilities. In the past, decentralized coal combustion was the major source of industrial energy supply. To reduce emission, the Chinese government has imposed a series of rigid constraints on emission reduction in electric power sector (Zhu & Zhao, 2017). Some factories have been shut down, if they had not undergone transformation from fossil energy to electric power or natural gas. Backward production capacity has been accelerated to phase out. Using electrical energy as the substitute for decentralized fuels has been encouraged for low-carbon development, including
electric heating and electric boilers (C. Su et al., 2019). Driven by the national policies, the northwestern provinces gradually promote the implementation of the electrification strategy. Xinjiang and Ningxia had the top two largest $\Delta D$ in Figure 4. And their electrification also ranked the first and the second in Northwest China. Especially in Xinjiang, where $\Delta D$ was even bigger than $\Delta B$. This is related to the “Electrified Xinjiang” strategy implemented by Xinjiang to promote electrification (The government of Xinjiang Uygur Autonomous Region of China, 2016). Although the CO2 emissions from the electric system had increased, the CO2 emission from Xinjiang was expected to reduce with the increasing renewable energy consumption. In contrast, the electrification in the other three provinces decreased slightly compared to 1998 and their $\Delta D$ were negative.

$\Delta D$ represents the industrial consumption intensity of electric power. Promoting electrification can increase the scale of electricity production, resulting in higher CO2 emissions from the electric industry. However, increasing electricity consumption indirectly expands the utilization of renewable energy, which helps to reduce the total CO2 emissions from a region. For example, it is encouraged by electrification strategy to use electrical power equipment as the alternative to coal-fired equipment. It has practical significance for consuming excess renewable energy and electricity. In addition, with advanced technology in pollution abatement and control, such as desulfurization and denitrification, electrification helps to avoid industrial emissions (Peng et al., 2018).

5.3 | CO2 emission reduction

The purpose of electrification strategy is to expand electricity market, to make room for the consumption of renewable energy. It can not only defuse the risks of overcapacity in renewable energy in Northwest China, but also optimize the energy mix. It targets an increased share of electricity generated from renewable sources and, by necessity, a diminished share from fossil fuels (Cullen, 2017). The combustion of fossil fuels release a large amount of CO2, which is the negative externality of thermal power plants. As consuming renewable energy replaces the combustion of fossil fuels, it effectively reduces CO2 emissions and improves the overall environmental benefits.

With the increase in electric generation, CO2 emissions from the electric system might increase. But CO2 emissions from the whole region decrease due to the increasing consumption of renewable energy by electrification strategy. In this way, electrification strategy guarantees human beings with
the power needed for social and economic development. At the same time, it avoids further deterioration of the ecological environment, thus realizing the low-carbon development.

To assess this compensation effect, the CO₂ emission reduction brought by renewable energy consumption can be calculated by formula (14). The results are shown in Figure 11. In 1998, the total CO₂ emission reduction in Northwest China was 18.63 million tons, accounting for 4.37% of the total emission. In 2017, the emission reduction was 136.82 million tons with share of 5.10%. In comparison, the contribution of electrifications effect was 477.22 million tons from 1998 to 2017 in Table 1. Therefore, by promoting electrification, CO₂ emissions from the electric power sector increased directly, but CO₂ emissions from the whole region declined indirectly. However, the overall electrification did not change much in Northwest China. Therefore, CO₂ emissions only decreased by 5.10% in 2017. It is expected that the inhibiting effect of electrification on CO₂ emission reductions would become greater with the promotion of electric substitution.

Electrification effects varied greatly among provinces in Figure 4. The shares of ΔD of five provinces range from −20% to 61%. Xinjiang and Ningxia had the largest two ΔD shares, respectively at 61% and 33%. It also can be found in Figure 10 that they had the biggest two rises in electrification level in Figure 10. At the same time, they had the largest two CO₂ emission reduction increases in Figure 11. Their reductions in 2017 were more than approximately 10 times higher than those in 1998. In contrast, emission reductions in the other three provinces in 2017 had only increased by less than four times as much as in 1998. This might be related to their relatively underdeveloped electrification strategies.

6 | CONCLUSIONS

Under the policy background of “electrification strategy,” Northwest China had made progress in promoting renewable energy consumption to replace fossil energy. From 1998–2017, economic growth was the biggest factor affecting the growth of total CO₂ emissions from the electric power industry. By contrast, improving energy efficiency was the biggest factor to restrain emissions. Optimizing energy structure and reducing carbon intensity also had inhibiting effects on emissions. But these effects were limited, as the energy supply was still dominated by thermal power, especially coal combustion. Promoting electrification led to the growth of CO₂ emissions from the electric system, but the decline of CO₂ emissions at the regional level. This is the result of both increasing usage of renewable energy by electrification.
and optimization of energy structure. However, the overall electrification did not change much and the emission decline is not significant. Qinghai and Xinjiang had achieved better results of emission reduction by emphasizing electrification.

To continue to curb carbon pollution, decision making need to rely on the factors with inhibiting effects on emissions. Northwest China needs to change its extensive economic growth mode. Macro-policies, such as electrification strategy, need to ensure the sustainable development. It is necessary to take measures to speed up the pace of energy restructuring and maximize the renewable energy consumption. However, the utilization of renewable energy is a systematic problem, related to power grid and power load. Improving the peak shaving ability of the system is the key to expand renewable energy absorption. Direct ways include encouraging constructions of energy storage stations, transformation to environmental friendly thermal power stations and guidance of self-owned power plants to participate in system peak shaving, and so forth. In addition, taking their geopolitical advantages of the Belt and Road Initiative, the northwestern provinces need to deepen cooperation with Central Asian countries in oil and natural gas and promote a more cooperative global regime for combating climate change. It is necessary to actively promote cross-regional industrial cooperation to reduce the waste of resources caused by repeated construction among provinces. Besides, local governments need to strengthen demand side management through preferential policies, such as taxes and subsidies, to encourage enterprises and residents to achieve energy conservation. They also need to make efforts to foster environmentally friendly industries.

Moreover, as electric products are becoming more and more popular among terminal users, the industry and household sector need to adhere to the perception of green consumption. They need to realize that the risks associated with climate change are devastating. It is necessary to pay more attention to behavioral energy-saving, such as upgrading energy-saving technology, using efficient household appliances and giving priority to the equipment with renewable energy supply, thus providing sufficient market for renewable energy consumption.

This paper intends to examine the influencing factors of CO₂ emissions from the electric power industry in Northwest China to provide corresponding suggestions. The results have practical value of promoting the low-carbon development. However, due to the difficulties in data acquisition and analysis, this paper still has some limitations. Some assumptions made in this paper might cause slight deviations in the results. In addition, this paper only analyses the driving forces of CO₂ emissions from the electric system. Compared with the decentralized coal combustion, electrification strategy also reduces emission of other pollutants. Future studies need to focus on a more comprehensive analysis of the environmental and economic benefits of electric substitution.

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CONFLICT OF INTERESTS
The authors declare that there are no conflict of interests.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.

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