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City-Level Features of Energy Footprints and Carbon Dioxide Emissions in Sichuan Province of China

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Abstract: The sustainable development of the western region of China has always been essential to the national development strategy. The Western region has undertaken an industrial transfer from the Eastern and Central regions. Therefore, the CO_2 emission intensity in the western region is higher than those of the Eastern and Central regions of China, and consequently its low-carbon development pathway has an important impact for China as a whole. Sichuan Province is not only the province with the highest CO_2 emissions, but also the most economically developed province in Western China in 2018. In order to promote low carbon development in the western region, it is important to understand the features of emissions in Sichuan Province and to formulate effective energy strategies accordingly. This paper uses the IPCC regional emission accounting method to calculate the carbon emissions of 15 cities in Sichuan province, and to comply with the city-level emission accounts. The results show that the total carbon emissions of Sichuan province over the past 10 years was 3258.32 mt and reached a peak in 2012. The smelting and pressing of ferrous metals, coal mining and dressing were the leading sectors that contributed to the emissions, accounting for 17.86% and 15.82%, respectively. Raw coal, cleaned coal, and coke were the most significant contributors to CO_2 emissions, accounting for 43.73%, 9.55%, and 6.60%, respectively. Following the above results, the Sichuan provincial government can formulate differentiated energy structure policies according to different energy consumption structures and carbon emission levels in the 15 cities. By controlling the level of total emissions and regulating larger industrial emitters in Sichuan province, some useful information could be provided as an essential reference for low-carbon development in Western China, and contribute to the promotion of emissions mitigation from a more holistic perspective.

Keywords: energy footprint; Western China; low-carbon development; CO_2 emission

1. Introduction

Climate change is one of the most severe and complex issues in human history [1,2]. According to the International Energy Agency (IEA) report, the latest statistics show the energy consumption and carbon dioxide emissions related to energy in 2018 both had the fastest growth in this decade. The global energy demand grew by 2.3% in 2018, while energy-related CO_2 emissions rose by 1.7%, and reached an all-time high of 33 Gt. The pressure from the interrelationship between vast amounts of energy usage and carbon emission caused by energy have forced policymakers to undertake action in order to mitigate climate change and achieve low-carbon economic development [3–5]. At present, as the world's largest developing country, China has become the largest energy consumer and the largest CO_2 emitter in the world [6–8]. In 2012, China's CO_2 emissions reached a historical peak (7.9 Gt), accounting for a quarter of global emissions [9,10]. With the rapid growth of population and industrialization all over the world, the demand for fossil fuel energy in human activities is increasing, with the use of coal being especially dominant in China. It is the energy consumption characteristics that involve mainly relying on coal that is consequently causing increasingly serious emission problems [11,12].

China is not only geographically divided into three regions, Eastern, Central, and Western regions, but also hosts a significant disparity with respect to economic development and carbon dioxide emissions between the three areas [13]. Although the absolute amount of CO_2 emission in western China does not occupy the largest share in the total domestic emissions (i.e., eastern, central, and western China with shares of 44.21%, 24.34%, and 31.45%, respectively in 2015 [14]), due to the less developed economy and more local industries with high primary energy use, the emission intensity is the highest (1.03 tons/10^4 CNY, 1.44 tons/10^4 CNY and 1.89 tons/10^4 CNY in eastern, central, and western China, respectively). Different economic development levels and industrial structures have led to differences in CO_2 emissions between the three regions, indicating that the emission reduction strategies of Western China will be unique. An analysis of particular CO_2 emission and emission-related energy will contribute to a scientific understanding of energy footprint characteristics, as well as provide essential references for energy transformation and emission reduction strategies.

The Western region covers 12 provinces and municipalities in China, with land area and population accounting for 71.2% and 32.3% of China, respectively. Abundant raw resources in this area have attracted much attention from the government and investors alike. Since 2000, the Chinese government have implemented the "western development" strategy which gives priority, financially and politically, to support for the economic development of the Western region. In nearly two decades, the development of infrastructure construction in the West has achieved tremendous success, providing a more conducive environment for economic development. The Belt and Road Initiative also encourages the development of Central and Western China. Western China can take advantage of its geographical position in order to pursue economic cooperation with Central Asia, South Asia, and Southeast Asia. With the help of this policy support and the participation of private capital, the rapid economic development in the Western region resulted in an average annual GDP growth of 8.8% between 2013–2017. In 2017, the GDP in the Western region was 20.7% of the national total; however, the total emission mitigation failed to perform as well as its GDP. In 2015, the western region accounted for 31.45% of CO_2 emissions [14], with the highest emission intensity implying an imbalance between economic and environment. Adjusting the development trend in the western region is important and urgent for the emission reduction process in China, as well as the world.

Sichuan Province has the best economic development in the Western region, with the largest proportion of GDP in the Western region reaching 21.6% in 2015 [13]. Moreover, the total emissions in Sichuan province occupied the largest share of total emissions in Western China (11.8% in 2015 [14]). In Western China, Sichuan's economic status is promising where mineral resource reserves, population, animal husbandry, fishery production value, industrial added value, the added value of the service industry, investment in fixed assets and the financial industry's total assets have always ranked highest in the country [13]. Therefore, the economic development of Sichuan is not only influential for the Western region but also powerful for whole of China. As for the CO_2 emissions in this province, it is better to analyze the emission sources in order to figure out how, and where we need to take actions to reduce the carbon dioxide emissions.

Cities consume two-thirds of the world's energy and contribute more than 70% of the world's CO_2 emissions [15]. When considering the terminal consumption of power, cities consume 71–76% of total CO_2 emissions [16]. With rapid population growth and the acceleration of urbanization, cities are experiencing continuous increases in both energy demand and per capita CO_2 emissions [17–19]. China's urban carbon dioxide emissions contribute 85% of total emissions, higher than the world average, and much higher than developed countries and regions such as Europe (69%) and the United

States (80%). Therefore, in light of the importance of city-level conditions, the decision-makers and implementers of climate change mitigation policies should pay more attention, and we should conduct more in-depth studies on energy utility and CO_2 emissions at the city level [20–23]. Understanding the characteristics of urban energy consumption, establishing an accurate urban carbon dioxide emissions inventory, and investigating the driving factors of CO_2 emissions are the primary conditions for implementing climate change mitigation and corresponding measures [24,25]. Detailed carbon emission data revealing the sources of energy can provide technical support and management methods for building low-carbon cities and research into low-carbon development strategies [26]. At present, emission inventories and carbon emission drivers of some national and provincial regions in China have been studied and discussed, such as Liaoning province, Hunan province, southeast coastal areas and northern coastal areas [27–32]. Studies on China's urban-level emission inventory and energy consumption are mostly concentrated in provincial capitals and megacities such as Beijing, Shanghai, Guangzhou, Hong Kong, Tianjin, Nanchang, Chongqing, Shenzhen and the Greater Bay area [24,30,33–40]. At present, few studies have focused on carbon dioxide emissions in western China. This study focuses on Sichuan Province, regarded as the most important province in the Western area, that can provide references for other provinces in the same region in order to understand their energy selection among many industries and sectoral carbon emission, formulate low-carbon development strategies in the economically underdeveloped areas and further help China to make overall national decisions.

In this paper, in order to clarify the features of the energy footprint and related carbon dioxide emissions in Sichuan Province, the carbon emission inventory related to the energy consumption of 15 key cities in Sichuan Province from 2006 to 2015 are quantified based on the Intergovernmental Panel on Climate Change regional emission calculation method [41]. Moreover, the achievement of emission reduction goals in these regions before has also been examined. Such quantification can provide a useful reference for the low-carbon development of Western China, as well as contribute to the promotion of emission mitigation from a more holistic perspective in China.

2. Methodology

This study employs the Intergovernmental Panel on Climate Change method (IPCC) regional emission calculation method in order to calculate the CO_2 emissions of 15 cities in Sichuan Province from the production side, and with a sectoral approach. The IPCC method assumes that the CO_2 emissions inventory is based on two sources: energy consumption and industrial processes. By adopting this method, the carbon dioxide emissions from 47 socioeconomic sectors, 17 fossil fuels, and seven primary industry processes are considered (see Tables S1–S3 in the Supplementary Materials) within the urban boundaries of 15 Chinese cities [5]. Using the same IPCC method, this study analyzes energy consumption more comprehensively. In the investigation, the emissions from the electricity generation industry are calculated only through conventional energy inputs (e.g., raw coal, petrol, and diesel oil). However, the emissions generated from energy and electricity across the city boundaries to other regions are not calculated. In order to avoid the problem of double counting, energy used for chemical materials and that lost during transport are removed from the total energy consumption [42,43].

2.1. Quantification of Energy Consumption and CO_2 Emissions

Based on the IPCC method, the total carbon emission from one society includes the emissions from different fossil fuels and sectors. Precisely, each sector's emission from one kind of energy is calculated by multiplying the energy activities (energy consumption) and emission factors of the respective socio-economic sector as follows:

$$CE_{energy} = \sum_{i=1}^{17}\sum_{j=1}^{47} CE_{ij} = \sum_{i=1}^{17}\sum_{j=1}^{47} AD_{ij} \cdot NCV_j \cdot CC_j \cdot O_{ij} \quad (1)$$

where i is the type of energy and j is the socio-economic sector (see Table S1). CE_{ij} represents CO_2 emissions of energy type i in the socio-economic sector j. AD_{ij} represents the activity data, using fossil fuel consumption of energy i in sector j as a proxy. NCV_j, CC_j and O_{ij} are referred to as emission factors, representing the net calorific value, carbon content, and oxidation efficiency from j department or i energy type, respectively. Liu, Guan et al. (2015) deeply investigate the energy consumption in China by employing these three emission factors.

In this study, the main kinds of fossil fuel, i.e., coal, oil, and natural gas, are divided into 17 types. We select 47 sectors as the main development direction in Sichuan Province, based on the industrial sectors classification of the National Economic Accounting System [44]. These 47 divisions can be assorted into four categories. Specifically, there are five energy production-related sectors which generate energy covering the primary and secondary types. Sixteen heavy industry sectors, producing intermediate products, which include ferrous metal ore dressing, non-metallic mineral products and so on. The light industry category covers the food processing sector, furniture manufacturing sector and another 11 sectors producing end products. The last category constitutes the five industries focusing on high and new technologies [18].

2.2. Industrial Process

Different industrial processes have different impact levels of carbon emission. In this study, we focus on seven emission-intensive industrial processes, accounting for more than 95% of China's total process-related emissions [42,45,46]; namely silicon metal, iron, iron-chromium alloys, ammonia, soda ash, cement, and lime processes. It is worth mentioning that CO_2 emissions from these industrial processes represent emissions only from chemical reactions; however, they do not consider the energy-specific use in these industries. We can use the following equation to indicate the process-related CO_2 emissions calculation:

$$CE_{process} = \sum_{t=1}^{7} CE_t = \sum_{t=1}^{7} AD_t \cdot EF_t \quad (2)$$

where t denotes industrial process, CE_t represents the process-related CO_2 emissions in process t. AD_t denotes activity data by proxying production of industrial process t; EF_t is the emission factor in process t provided mainly by the IPCC, while the cement production factor is derived from [47].

2.3. Uncertainty Analysis

Uncertainties associated with input and parametric modeling can have potentially significant impacts on the accuracy of carbon dioxide emission estimations [48]. Uncertainties may derive from incomplete data, economic fluctuations, environmental factors, and many implications related to subjective judgments and data quality issues [49,50]. Further, uncertainties from emission factors and energy activities also could affect the estimation. Following the recommendation of the IPCC, this study employs the Monte Carlo simulation in order to alleviate the uncertainty. In the Monte Carlo framework, all input parameters regarding activity data and emission factors are assumed as having a normal distribution. In total, 20,000 simulations were conducted to analyze the uncertainty of emissions estimation by socio-economic sector. The coefficients of variations (CV, standard deviation divided by the mean) are adopted from previous research [41,51,52].

2.4. Examination of the Achievement of Emission Reduction Goal

Based on the average growth rate of GDP and CO_2 emissions in the past 10 years, the emission intensity in Eastern, Central, Western China, as well as Chengdu, Mianyang, and Panzhihua is estimated. The emission intensity in the nth year, CI_n, can be formulated as:

$$CI_n = CE_0(1+\alpha)^n / X_0(1+\beta)^n \quad (3)$$

where CE_0 represents the total emissions of the target region in the benchmark year; X_0 represents the GDP of the target region in the benchmark year; α represents the annual growth rate of total emissions in the target region, and β represents the annual growth rate of GDP in the target region. In this paper, both the benchmark year of emission and GDP are set as 2015; at the same time, both α and β are obtained by the moving average value from 2005 to 2015.

Since the emission reduction goal is set in the form of emission intensity, whether the region in question may achieve the emission reduction goal can be roughly examined.

2.5. Data Source

This study selects 15 cities of the 21 urban districts in Sichuan Province because the energy consumption data of these 15 cities are available in the study interval (2006–2015). The GDP of these 15 cities accounts for 85.83% of the total GDP of Sichuan Province. Moreover, the carbon dioxide emissions from these cities account for even more than 90% of total emissions in this province. Therefore, it is enough to use these 15 cities to represent the carbon emission of this province. Table 1 provides the socio-economic indicators of 15 key cities in Sichuan Province in 2015.

The annual GDP, population, and GDP per capita data are obtained from the statistical yearbooks of each city. The total carbon dioxide emissions are calculated according to the methods in Section 2.1. It is concluded that the emission intensity is the carbon dioxide emissions per unit of GDP, and the carbon dioxide emissions per capita is the ratio of the total carbon dioxide emissions to the population of the city.

The energy balance sheet, the energy consumption data of industrial sub-sectors, and the output of industrial products are all from the statistical yearbooks of these 15 key cities. The energy consumption data of Ganzi (2006–2007) and Yaan (2006) are not reported in the statistical yearbook, thus some of the carbon dioxide emissions inventories cannot be estimated (Sichuan statistical yearbook, 2006–2016).

Table 1. Emission and socio-economic indicators of 15 cities in Sichuan Province, 2015.

City	Population (10^4)	GDP (10^8 CNY)	GDP Per Capita (CNY)	Total Emission (Million Tons)	Emission Intensity (Tons/10^4 CNY)	Carbon Emission Per Capita (Tons/Person)
Chengdu	1228.05	10,801.16	87,953.75	47.46	0.44	3.86
Mianyang	473.94	1700.33	35,876.48	12.22	0.72	2.58
Panzhihua	123.20	925.18	75,095.78	84.39	9.12	68.50
Deyang	351.09	1605.06	45,716.48	7.53	0.47	2.14
Guangyuan	305.31	605.43	19,830.01	17.55	2.90	5.75
Yibin	552.08	1525.90	27,639.11	22.65	1.48	4.10
Luzhou	505.68	1353.41	26,764.16	16.39	1.21	3.24
Zigong	327.46	1143.11	34,908.39	5.90	0.52	1.80
Leshan	353.79	1301.23	36,779.73	39.36	3.02	11.13
Suining	378.75	915.81	24,179.80	13.83	1.51	3.65
Ganzi	116.49	213.04	18,288.27	1.06	0.50	0.91
Meishan	349.20	1029.86	29,491.98	21.11	2.05	6.05
Neijiang	420.43	1198.58	28,508.43	36.18	3.02	8.61
Yaan	111.42	502.58	45,106.80	3.30	0.66	2.96
Ziyang	354.72	1270.40	35,814.16	5.56	0.44	1.57

3. Results and Discussion

3.1. CO_2 Emissions in 15 Key Cities

The city-level emission accounts for the 2006–2015 period are shown in Table 2 which includes the total carbon dioxide emissions of 15 cities in Sichuan Province. The trends of total emissions in 15 cities indicate they have experienced their peaks and have entered a slow decline phase. It can be seen that province-level emission peaked at 406.23 million tons in 2012 and then fell to 334.49 million tons in 2015. The rapid increase phase of Sichuan Province is between 2007–2012 with total carbon dioxide emissions demonstrating an average annual growth rate of 12.31%. In this decade, the carbon dioxide emissions of three cities, Panzhihua, Chengdu, and Leshan, are almost equivalent to one-half of the total emissions in this province. Notably, 2015 contributed the most to the province's carbon dioxide emissions among all 15 cities, accounting for 25.23%, 14.19%, and 11.77%, respectively.

Table 2. Total carbon dioxide emissions in 15 key cities in Sichuan Province, 2006–2015 (million tons).

City	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Chengdu	21.75	33.33	31.01	34.69	40.38	42.97	42.15	41.21	48.32	47.46
Mianyang	17.09	15.83	10.23	12.09	14.54	14.62	14.89	15.05	14.40	12.22
Panzhihua	68.89	105.16	94.22	109.75	115.27	120.91	104.28	86.72	87.32	84.39
Deyang	6.71	8.14	7.49	8.87	10.56	10.18	10.69	9.85	9.23	7.53
Guangyuan	6.98	9.23	7.83	8.92	10.78	16.58	18.28	13.40	13.11	17.55
Yibin	15.85	14.37	16.00	17.06	18.61	25.38	30.30	31.60	27.38	22.65
Luzhou	15.30	16.79	17.27	21.14	23.95	32.41	23.40	16.28	17.21	16.39
Zigong	8.00	8.18	8.05	8.85	10.59	12.14	10.72	8.18	7.31	5.90
Leshan	11.95	15.67	18.30	21.75	28.26	35.12	41.06	39.69	32.73	39.36
Suining	8.10	9.96	11.81	12.18	12.02	12.85	15.01	10.18	11.60	13.83
Ganzi	-	-	0.81	0.89	1.07	1.06	1.31	0.95	0.97	1.06
Meishan	11.52	13.32	15.91	17.48	19.65	21.79	24.02	23.83	22.64	21.11
Neijiang	12.79	17.86	21.36	27.08	35.11	46.28	58.01	52.28	41.50	36.18
Yaan	-	1.03	1.27	2.55	3.85	5.10	5.05	3.41	3.36	3.30
Ziyang	3.46	4.85	6.04	6.42	7.17	7.27	7.06	6.11	5.88	5.56
Total	208.39	273.72	267.6	309.72	351.81	404.66	406.23	358.74	342.96	334.49

In order to analyze the features of emissions in 15 cities from multiple angles, this paper also analyzes carbon emission intensity and carbon dioxide emissions per capita. According to Figure 1, in 2015, the range of the carbon emission intensity between 15 cities was from 0.44 tons/10^4 CNY (Chengdu) to 9.12 tons/10^4 CNY (Panzhihua). The overall carbon intensity reached a peak of 66.47 tons/10^4 CNY in 2007. And then the carbon intensity was declining, dropping to 28.05 tons/10^4 CNY in 2015. This peak happened earlier than the carbon dioxide emissions maximum, indicating the economic development decreased the intensity while increasing the amount of emissions. In Sichuan, the economic structures of Ganzi and Chengdu are dominated by services and high value-added industries. Therefore, they have the lowest carbon emission intensity, compared with high-intensity industrial cities, such as Panzhihua, Neijiang, and Leshan. The trend of emissions per capita is similar with the total amount increasing rapidly at an average annual growth rate of 10.79% between 2007 and 2012, reaching a peak of 173.15 tons/person in 2011, and then starting to slow down with an annual average growth rate of 6.51%.

To further explore the CO_2 emissions of cities in Sichuan Province, and to confirm which emission level this province belongs to, a comparison with the average emissions in China will display the difference between this area and the average country level. In 2015, China's total carbon dioxide emissions were 9.78 billion tons [14], with a total GDP of 68,905 billion CNY and a total population of 1.37 billion [13]. It is easy to find that the average emission intensity (1.87 tons/10^4 CNY) of the 15 cities in 2015 is 31.69% higher than that of China's urban average (1.42 tons/10^4 CNY). Further, the most significant gap is observed with Panzhihua City having an emission intensity of 9.12 tons/10^4 CNY which is more than five times of China average (Figure 1). As for the emissions per capita, it also indicates a similar situation to that of the Sichuan province average of 8.84 tons/person, which is 1.24 times the amount of the national average of 7.11 tons/person. Even though two indicators both display a higher level of carbon emission in Sichuan, in fact, these 15 cities have made significant efforts to promote low-carbon development with the help of technological advancement, industrial transformation and the implementation of incentive policies. From 2006 to 2015, the carbon emission intensity decreased from 4.03 tons/10^4 CNY to 1.87 tons/10^4 CNY, while the national average decreased from 2.78 tons/10^4

CNY to 1.42 tons/10[4] CNY [14]. With the increase of economic growth and decrease in carbon emission, Sichuan's intensity would be close to the national average emission intensity at this rate.

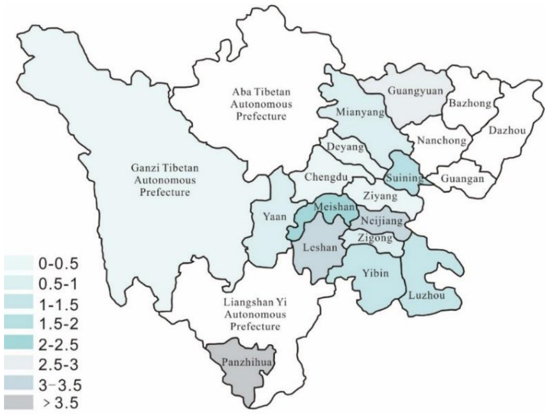

Figure 1. CO_2 emission intensities of 15 key cities in Sichuan, 2015 (Unit: tons/10^4 CNY).

3.2. CO_2 Emissions in 15 Key Cities in Terms of Energy Type and Industrial Sectors

Different types of energy have various uses, and emission amounts also vary by type. Therefore, more detailed information about the energy used in each city could reveal real carbon emitters and would be helpful to inform targeted strategies in order to reduce emissions. Among the target cities, coal and coal-related products (raw coal, washed coal, other coal washing, briquette, and coke) are the main types of energy consumed, followed by petroleum products (crude oil, gasoline, kerosene, diesel and fuel oil).

In 2015, coal-related and oil-related products produced 71.88% of the total CO_2 emissions in Sichuan, of which the emissions from raw coal, clean coal and coke were the top three. During the past ten years, the total emissions from raw coal in these 15 major cities reached a peak of 49.18% (199.78 Mt) in 2012 and fell to 36.17% (120.99 Mt) in 2015. The fluctuation of coke emissions is small, and these emissions account for an average of 6.68% per year. In 2015, emissions decreased to 5.37%. The contribution rates of gasoline and diesel are quite low but in an increasing trend that is increasing from 0.96% and 1.62% to 3.70% and 3.49% in these ten years, respectively. Natural gas has a stable share of around 6.70%.

Separating the emissions according to different industrial sectors can also indicate some trends with respect to which industries need more pressure to reduce their carbon dioxide emissions, or which industries have been an excellent example for other industries, or the same industry in other regions. In Sichuan Province, the smelting and pressing of ferrous metals division has had the highest total emissions, with 581.94 Mt of carbon emissions over the past decade, accounting for 21.6% of the 15 cities. Unlike the gross province trend, this industry still demonstrates a growing trend and reached a peak of 65.56 Mt in 2015. The following sectors with the highest carbon dioxide emissions were nonmetal mineral products, electric power, steam, and hot water production and supply, with contribution ratios of 19.0%, 15.7%, respectively (Figure 2). Finally, in Sichuan Province, the secondary industry contributed a maximum of 88.73%, and the tertiary industry shared 10.52%, of which the transportation sector dominated, accounting for 3.57% of the 15 cities.

Figure 3 displays the circulation map of energy and carbon dioxide emissions in Sichuan Province in 2015. These 17 energy types are invested in primary, secondary and tertiary industries, which are divided into 47 socio-economic sectors, and energy consumption in various sectors produces different amounts of carbon dioxide emission. There are three linkages between the factors worthy of focus. The left one shows how the different types of energy are consumed in three industries; the middle one shows how energy consumption generates carbon dioxide emissions with a more detailed decomposition within the sub-sectors of three departments, and the last relationship, on the right hand side, once again summarizes the carbon emissions into three departments.

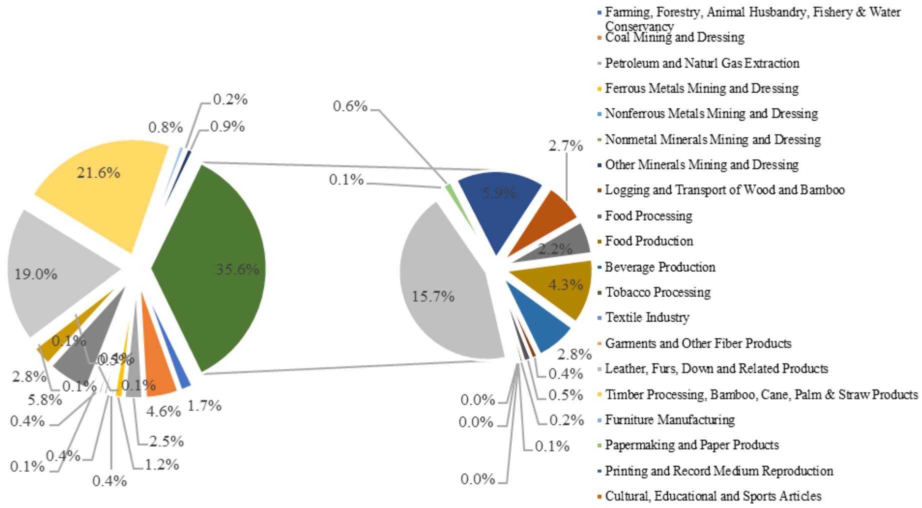

Figure 2. The proportion of carbon dioxide emissions in the industrial sector (Smelting and Pressing of Ferrous Metals, Nonmetal Mineral Products, Electric Supply, 21.6%, 19.0%, 15.7%).

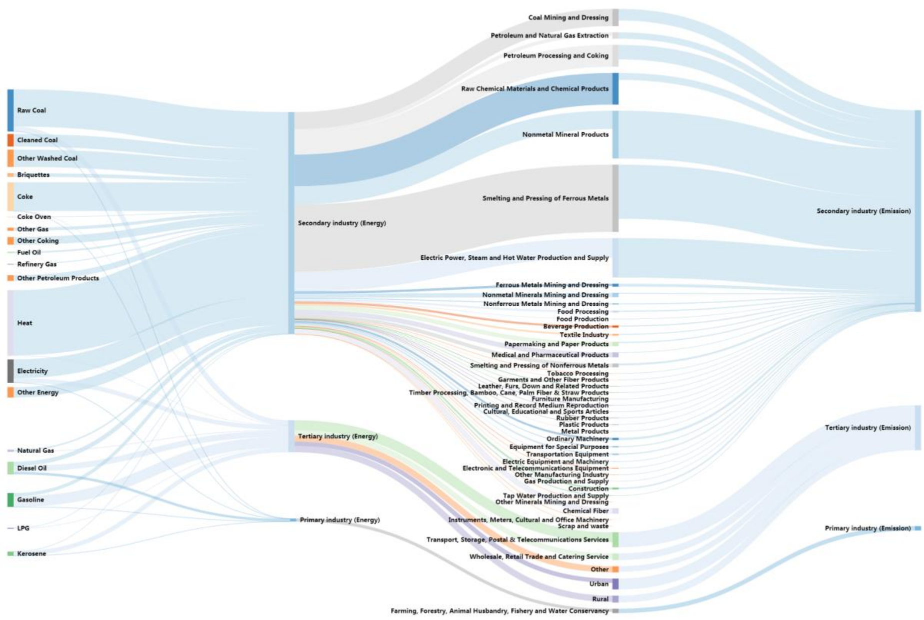

Figure 3. Energy and carbon emission's circulation map of target cities in Sichuan Province, 2015.

As for the sectors, namely the smelting and pressing of nonferrous metals, raw chemical materials, and chemical products, coal mining and dressing, which consume relatively more energy but emit relatively fewer emissions, this is due to a higher dependence on electricity consumption instead of other energy sources such as fossil fuels.

Sichuan Province is a typical region in China with a sufficient capacity of hydropower. The emission intensity of the electricity supply sector in Sichuan has been less than the average level of all regions in China. Therefore, a better understanding of the carbon dioxide emissions contributed by industry, sector and energy type, shown in Table 3, is conducive for the government to develop a low carbon policy. For Sichuan Province, which benefits from an abundant clean electricity supply, it is better to control the energy consumption of the electricity channel and to encourage fossil fuel users to transform their energy selection from higher emission to lower emission electricity (hydropower), by way of innovating their electricity-consuming equipment or machines. The inventory list of the target cities provides data support for the low carbon development plan in Sichuan.

Table 3. Types of energy consume in 15 key cities in Sichuan Province, 2015.

Types of Energy	Raw Coal	Cleaned Coal	Other Washed Coal	Briquettes	Coke	Coke Oven Gas	Other Gas	Other Coking Products	Crude Oil	Gasoline	Kerosene	Diesel Oil	Fuel Oil	LPG	Refinery Gas	Other Petroleum Products	Natural Gas	Heat	Electricity	Other Energy
Unit:	10^4 tce	10^4 tce	10^4 tce	10^4 tce	10^4 tce	10^8 m^3	10^8 m^3	10^4 tce	10^4 tce	104 tce	10^4 tce	10^4 tce	10^4 tce	10^4 tce	10^4 tce	10^4 tce	10^8 m^3	10^{10} Kj	10^8 kWh	10^4 tce
Chengdu	286.2	92.6	0.4	2.7	21.9	1.5	0.0	0.0	214.3	209.5	109.6	197.5	10.4	31.9	0.6	15.4	35.3	1893.2	344.2	3.4
Mianyang	255.9	17.4	0.0	0.0	8.3	0.0	0.0	0.0	0.2	23.9	0.3	14.0	0.0	1.1	0.0	0.3	7.1	13.9	55.7	0.0
Panzhihua	483.6	187.5	59.4	65.6	370.6	14.2	138.8	6.1	0.0	5.3	0.0	11.5	0.1	0.3	0.0	0.8	0.5	1282.2	138.7	0.0
Deyang	192.6	0.0	0.0	0.0	9.7	0.0	0.0	0.0	0.0	16.1	0.0	13.4	0.0	0.8	0.0	0.0	14.8	0.7	88.8	0.0
Guangyuan	145.1	60.2	0.2	40.4	1.0	0.7	0.0	0.0	0.0	11.8	0.0	6.0	0.0	0.6	0.0	0.0	5.9	0.4	41.6	0.1
Yibin	94.6	1.9	3.6	1.9	7.3	0.8	0.7	0.0	0.0	32.2	8.9	29.4	0.6	1.8	0.3	0.4	5.1	207.9	90.9	5.5
Luzhou	108.9	84.9	12.6	0.0	6.2	0.2	0.4	0.0	17.6	32.0	10.9	23.6	0.2	1.9	0.1	0.0	16.0	173.3	51.4	1.5
Zigong	178.5	3.6	1.8	2.5	4.4	0.1	0.0	0.0	0.0	13.9	0.1	7.1	13.9	1.2	0.0	0.3	3.8	102.8	37.5	1.3
Leshan	238.2	119.3	44.9	95.6	142.1	0.2	43.8	0.1	20.7	24.7	7.4	26.3	0.2	1.5	0.1	187.7	7.9	66.8	182.5	2.1
Suining	68.9	18.1	0.5	0.0	4.4	0.1	0.0	0.0	48.1	22.8	3.4	18.7	0.0	1.4	0.0	26.4	11.7	208.1	165.0	0.2
Ganzi	34.8	0.0	1.0	0.0	0.2	0.2	0.0	0.0	0.0	8.5	1.6	6.9	0.2	0.5	0.1	0.1	0.4	0.0	10.0	1.5
Meishan	123.2	35.1	7.9	15.2	13.0	0.1	0.0	0.3	11.4	14.1	4.1	13.5	0.0	0.0	0.0	0.1	6.7	203.7	86.7	20.0
Neijiang	249.9	1.4	0.4	0.0	0.8	0.1	0.0	0.0	−0.8	25.2	8.3	19.2	0.1	1.4	0.0	40.0	28.6	0.8	8.4	0.6
Yaan	53.5	9.3	5.5	0.0	17.6	1.2	0.0	0.0	0.0	9.1	3.6	9.5	1.0	0.5	0.5	4.6	0.0	0.8	77.6	8.2
Ziyang	142.0	0.0	0.8	0.0	0.3	0.1	0.0	0.0	0.0	26.0	7.5	30.5	0.0	2.3	0.0	0.1	4.3	0.0	23.2	0.3
Total	2655.7	631.3	138.9	223.8	607.6	19.5	183.7	6.5	311.5	475.1	165.8	427.1	26.8	47.2	1.8	276.1	148.2	4154.9	1402.3	44.9

3.3. Uncertainty Analysis Results

For the activity data, CVs from different sectors are between 5% to 30%, while CVs for the emission factors related coal, oil, and natural gas are 3%, 1% and 2%, respectively. The simulation results show that 97.5% of the uncertainty in 15 cities (central estimated value of ±47.5% confidence interval) decreased to a range of −5.6–7.8%.

3.4. Examination of the Achievement of Emission Reduction Goal in Regions and Cities

In the "Paris Agreement", China proposed an emission reduction goal to reduce 60–65% of their emission intensity by 2030 compared to the level in 2005 [53]. Based on the assumption of a moving average in regional CO_2 emission amounts and GDP growth, the emission reduction in Eastern, Central, And Western China (including several key cities in Sichuan) in 2025 and 2030 are estimated. This analysis will explain if the reduction goal can be achieved with the current speed, and if the reduction speed needs to be raised for achieving this goal. The results are shown in Table 4.

Table 4. Forecast of the carbon emission intensity.

Tons/CNY 10^4	2005	2010	2015	2020	2025	2030	Actual Emission Reduction	Target Emission Reduction
Eastern Region	2.25	1.50	1.03	0.92	0.85	0.83	63.15%	60–65%
China Central	3.34	2.21	1.44	1.33	1.29	1.32	60.43%	60–65%
Western Region	3.66	2.61	1.89	1.93	2.05	2.29	37.50%	60–65%
Chengdu	0.88	0.73	0.44	0.49	0.57	0.67	23.86%	60–65%
Mianyang	3.36	1.51	0.72	0.55	0.44	0.38	88.69%	60–65%
Panzhihua	20.52	22.01	9.12	8.85	8.99	9.46	53.90%	60–65%

According to the results, Eastern and Western China will be able to reach the national overall reduction goal by 2030, although this will be more challenging for Western China. The total reduction in emission intensity in Western China will be 37.50% according to this reduction speed, falling far from a goal of at least a 60% reduction. Within Sichuan Province, cities also display different results. Mianyang will be able to reach the goal with a reduction in its emission intensity greater than 88.69%, while Chengdu cannot achieve the goal, partially because it has always had a lower level of intensity which is hard to reduce. The truly confusing cities, such as Panzhihua, suffer a higher level of intensity. However, they have not found nor implemented useful actions to stop failing. Therefore, for achieving the reduction goals in Western China, at first, analyzing the carbon intensity from the absolute value and relative value would provide a fuller picture. Then, paying more attention to the cities which display higher carbon intensities, by investigating the industrial structures, dominant industries and making more city-level reduction policies with targeted or specific purposes. Finally, for maintaining the balance between economic growth and the transformation to a low-carbon society, dynamic control is necessary, especially for city-level governments.

3.5. Discussion

Since energy consumption data at the city-level and sub-sector level are difficult to obtain, data availability makes this study focus on 15 cities in Sichuan Province. By including all critical cities in Sichuan, such as Chengdu, Panzhihua, and Mianyang, we can attain the main characteristics of this province and provide some typical results in order to inform some policies or strategies with respect to economic development and the reduction of CO_2 emissions.

As shown in Sections 3.1 and 3.2, the overall emissions of 15 cities snowballed in 2007–2012 and peaked in 2012. However, the carbon intensity reached a peak of 66.47 tons/10^4 CNY in 2007 and then dropped to 28.05 tons/10^4 CNY. The average emission intensity of 15 cities in 2015 was 1.87 tons/10^4 CNY, demonstrating that the emission intensity in Western China is higher than average city-level in China. Coal and coal-related products (raw coal, clean coal, other coal washing, briquette, and coke) are the most consumed types of energy. They are also the main energy emitting CO_2 in Sichuan. The heavy industries, such as, smelting and pressing of ferrous metals, coal mining and dressing, nonmetal mineral products, production and supply of electric power, steam and hot water are the sectors contributed the most to CO_2 emissions during the study period, accounting for 17.86%, 15.82%, 14.26%, and 14.17%, respectively. It also proves that Sichuan Province is still in the middle stage of industrialization, and the secondary industry dominates its economic structure. Furthermore, the proportion of GDP supports the economic structure of Sichuan where the primary, secondary and tertiary industries constitute 12.24%, 44.08% and 43.68%, respectively, in 2015. Thus, it is unsurprising that the secondary industry's carbon dioxide emissions accounted for the largest share of 88.73%, and that Sichuan needs to mainly focus on how to maintain secondary industry development and lower emissions by exploiting fully the use of the hydropower.

As mentioned in the supporting analyses in Sections 3.2 and 3.3, in Sichuan Province, hydropower generation occupies a large share of the total power supply. In 2015, the generation of hydropower was 276.74 billion kWh, occupying 86.3% of the total electricity supply in Sichuan, and installed capacity is 69.39 million kW, representing 80.01% of the province-level capacity [54]. As we all know, optimizing the structure of energy supply by increasing the share of clean energy is crucial to low-carbon development [55–58]. Sichuan has been in the leading position to develop clean energy. The expansion of hydropower capacity has led to a sharp decrease in the share of CO_2 emissions in the electricity supply sector, from 14.5% in 2003 (a historical peak level) to 4.8% in 2015 and emission amounts also declining from 9.85 mt in 2010 to 3.56 mt in 2015. Such great achievement of CO_2 emission reduction can be important references to the low-carbon development in the regions with the potential of expanding hydropower capacity. More specifically, the Western region of China holds relatively more advantages with respect to natural conditions for the development of clean energy, including hydropower, wind power, solar power, and biomass power generation. For energy policymakers, the re-structuring of the energy supply and the promotion of low-carbon development in the Western region of China does not only benefit local producers and consumers, but with the increasingly frequent electricity transmission between different grids in China, the whole country, and even other countries affected by the supply of electricity from China, could benefit in terms of CO_2 emission mitigation.

4. Conclusions

This study, based on the IPCC regional emission method, is the first research performed on carbon dioxide accounting for 15 key cities in Sichuan Province representing Western China, and is consistent with the national and provincial emission inventories. The CO_2 emissions inventories consisted of 17 fossil fuels, 47 socioeconomic sectors and seven industrial processes to reveal useful information in order to determine the city's major emission contributors and different emission characteristics. Therefore, this study can provide an opportunity to analyze the features of emissions in 15 cities in Sichuan Province, provide key data to support the formulation of low-carbon policies in Sichuan Province, and provide a reference for the development and implementation of low-carbon development strategies in other parts of the Western region. It is useful for the advancement of China's low carbon development process.

The total carbon dioxide emissions in 15 cities increased rapidly from 2007 to 2012, with an average growth rate of 12.31% and peaked in 2012 with 406.23 million tons. From 2006 to 2015, the total emissions of Sichuan Province accounted for 14.92% of the western region, and the emission intensity and emissions per capita were 1.42 and 1.24 times of the national average, respectively. For sector sources, the secondary industry contributed 88.73% in total carbon dioxide emissions and the tertiary industry contributed 10.52%. In the secondary industry, metals and energy-related heavy industry accounts the majority parts. During the study period, raw coal was the highest contributor in all energy categories (43.73%), reaching a peak of 199.78 Mt in 2012. It is worthy to research how to decrease the high emissions from coal by way of more targeted policy control or market incentives.

Sichuan Province is shifting from an industrial economy to a service economy, and carbon dioxide emissions in most cities have peaked in 2011–2013 and moved to a stage of decline.

It is Sichuan Province that is China's leader in economic development in the Western region, especially under the "Western Development" and "One Belt, One Road" initiatives. It also plays an essential role in promoting low carbon and sustainable development in the Western region. Due to the economic structure transitioning from the secondary industry to the tertiary industry, and the advanced development of clean energy power generation, at present, the overall emissions in the main cities have begun to decline. In order to continue to maintain a low-carbon development trend in Sichuan Province, government departments should formulate active and effective development strategies, such as increasing the proportion of clean energy to replace fossil energy, optimizing the industrial structure, and enhancing processing techniques in order to promote regional low-carbon economic development.

Unfortunately, there are still some limitations to this study. The missing data of energy consumption in some cities lead the carbon emission incomplete. In the meantime, we choose 15 cities to make this analysis, also partially due to the data quality issues or relatively low levels of emission. Furthermore, even though we mentioned a large amount of clean energy consumption in Sichuan Province, such as hydropower generation, we believe the continuous development of these clean energy resources will have a positive impact on regional carbon emission reduction. This study does not consider the contribution of hydropower development to the greenhouse effect in Sichuan Province and nearby regions. We will improve the above shortcomings and limitations in future work, and explore the impacts of emission reduction approaches and energy footprints on the emission reduction potential of Western China.

Supplementary Materials: The following are available online at http://www.mdpi.com/1996-1073/12/10/2025/s1.

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