Analyzing the features of energy consumption and carbon emissions in the Upper Yangtze River Economic Zone

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Abstract: As a vital resource endowment area and ecological barrier area in China, low-carbon development in the upper reaches of the Yangtze River is of great significance. This paper compiled the emission inventory in the Upper Yangtze River Economic Zone in the IPCC regional emission accounting method framework and used the Environmental Kuznets Curve (EKC) model to evaluate economic development and carbon emissions. Finally, this paper used the time series method to predict carbon emissions to 2030. We find that carbon dioxide (CO$_2$) emissions increased rapidly from 2004 to 2012. The average annual growth rate reached 9.16%. After 2012, carbon emissions in the region no longer grow steadily but fluctuate or even decline. The secondary industry contributed 79.77%, the tertiary industry contributed 17.78%, and the primary industry only 2.45% from 2000 to 2015. From the industrial sector and energy consumption, thermoelectricity production and supply division and nonmetallic mineral products industry are the sectors with the most CO$_2$ emissions, accounting for 35.54% and 13.34%, respectively. Raw coal and coke are the main factors causing emissions. Nearly 61.32% of the carbon dioxide produced by raw coal comes from the electricity production sector. However, from 2011 to 2015, the CO$_2$ emissions of raw coal decreased year by year, down by 23.32%. The impact of economic growth on carbon dioxide emissions supports the EKC hypothesis. The CO$_2$ emissions in the Upper Yangtze River Economic Zone will decline after 2020, but Chongqing has shown an upward trend. With the above results, provinces and cities can optimize the regional industrial structure based on sectoral carbon emissions. The study area needs to develop clean energy to optimize the coal-led energy consumption structure. Provinces and cities in the district can learn from each other’s advanced emission reduction experience. © 2021 The Authors. Greenhouse Gases: Science and Technology published by Society of Chemical Industry and John Wiley & Sons Ltd.

Keywords: Upper Yangtze River Economic Zone; Energy consumption; CO$_2$ emission; Emission reduction policy
Introduction

Global climate change caused by human activities emitting carbon dioxide (CO\textsubscript{2})-based greenhouse gases is a huge challenge for human society development.\textsuperscript{1} Human use fossil fuels for power generation, transportation, and industrial production activities, thereby furthering the development of society. But these activities have a significant impact on the environment and human health.\textsuperscript{2–4} Human activities may have caused the global average temperature to rise, with a possibility of as high as 95%.\textsuperscript{5} The burning of fossil fuels and industrial production have contributed 78% to the growth of greenhouse gas emissions.\textsuperscript{5} From 2007 to 2009, China became the world’s largest fossil energy consumer and CO\textsubscript{2} emitter.\textsuperscript{6–8} CO\textsubscript{2} emissions continue to multiply, reaching a peak in 2012 (7.9 Gt).\textsuperscript{9} CO\textsubscript{2} emissions in China account for about 25% of the global total.\textsuperscript{10}

From coastal areas to inland areas, energy consumption and CO\textsubscript{2} emissions are uneven in all China regions. Affected by the Paris Agreement, the Chinese government has set emission reduction targets. These targets are that China’s carbon emission intensity in 2030 will drop by 60–65% from 2005. And China’s carbon emissions will reach a peak. China is a vast country with huge differences between regions.\textsuperscript{11–13} As climate change becomes more serious, China must set different emission targets for each province. To effectively understand the features of China’s CO\textsubscript{2} emissions (including the current status and trends of carbon dioxide emissions, emission intensity, energy types, and industrial sectors, regional differences, etc.), we need to consider regional differences fully. The CO\textsubscript{2} emissions in this article do not include methane (CH\textsubscript{4}), nitrous oxide (N\textsubscript{2}O), and other minor greenhouse gases (CO\textsubscript{2} equivalent).

In recent years, the issue of carbon emissions has received extensive attention from many international research institutions and scholars. Many organizations such as the US Department of Energy’s Carbon Dioxide Information Analysis Center and International Energy Agency (IEA) have done a lot of basic work on global carbon emissions. Many developed countries have formulated climate-related policies at the end of the last century and the beginning of this century, such as the United States, Germany, and Japan.\textsuperscript{14} Developing countries have also responded actively in the past decade.\textsuperscript{15} Currently, the well-known accounting method is the fossil energy consumption model of Intergovernmental Panel on Climate Change (IPCC).\textsuperscript{16} China’s comprehensive energy consumption data in national and provincial energy balance sheets (EBTs) is readily available.\textsuperscript{17} These data can estimate the carbon emissions associated with energy consumption in some regions. Globally, some researchers find a correlation between energy consumption and economic growth in developed and developing countries.\textsuperscript{18} Therefore, some studies have used national and provincial carbon emission characteristics to explain the carbon emissions in various regions of China, such as Guangdong and the southeast coastal areas.\textsuperscript{19–23} Some studies have combined the IPCC and (LMDI) methods to analyze the factors affecting the temporal and spatial changes of carbon emissions in Hunan.\textsuperscript{24} Some researchers have investigated and predicted the seven impact factors of carbon emissions in Hebei, providing a theoretical basis for policy formulation.\textsuperscript{25} Others have studied the interrelationship between economic development and carbon emissions from industrial energy consumption in China’s north–south coastal areas.\textsuperscript{26} Some people have also studied the effects of low-carbon emissions reduction in China’s Beijing—Tianjin–Hebei region and the Greater Bay Area.\textsuperscript{27,28} China has paid more attention to green and low-carbon development. China’s regional economic development and energy consumption structure vary greatly. Regional carbon emission reduction levels vary. Research on carbon emissions is concentrated in coastal areas and centrally developed areas.

An increase in the level of economic development will generate greater energy consumption.\textsuperscript{29} The Environmental Kuznets Curve (EKC) describes how environmental pressures increase as per capita income increases. The EKC model assumes an environmental protection mechanism.\textsuperscript{30} After the economy develops to a certain level, the ecological pressure gradually subsides.\textsuperscript{31} Economic activity is the primary driver of CO\textsubscript{2} emissions.\textsuperscript{32} The improvement of environmental quality can create a better environment for economic development.\textsuperscript{33} Researchers use this method to understand the relationship between carbon emissions and the development of human society.\textsuperscript{34} The area of the Yangtze River Economic Zone is 21% of China’s land area. Both the population and the economic aggregate in the region exceed 40% of the country. There are differences between upstream, midstream, and downstream of the Yangtze River Economic Zone. Downstream is the Yangtze River Delta Economic Zone headed by Shanghai. The
midstream is headed by Wuhan. The Yangtze River’s upstream includes several provinces such as Qinghai, Tibet, Sichuan, Yunnan, Chongqing, Guizhou, and Hubei. The upstream area is relatively backward and has a unique ecological environment. The Upper Yangtze River Economic Zone, dominated by the Chengdu-Chongqing Economic Circle, is China’s future key economic development center. Considering the closeness of political, economic, and cultural exchanges, the Upper Yangtze River Economic Zone in this article refers to the three provinces and one city of Yunnan, Guizhou, Sichuan, and Chongqing. Figure 1 shows the specific location of the Yangtze River in China marked on the left. The entire Yangtze River basin is enlarged on the right, and the red area is the study area (the Upper Yangtze River Economic Zone). In 2019, the total GDP of provinces and cities in the study area (10996.27 billion yuan) accounted for 53.66% of GDP in western China (20490.83 billion yuan). The Upper Yangtze River Economic Zone is a relatively densely populated area. The region’s total population is about 198 million, accounting for 52.9% of the entire western region (about 374 million). The region contains vast hydropower resources. The theoretical reserves of Hydropower are 143 million kilowatts, and the developable technology capacity is 103 million kilowatts, accounting for more than a quarter of the country. The Upper Yangtze River Economic Zone has a large amount of cultural heritage protected by the United Nations. Therefore, the cultural tourism industry is relatively developed. The region has the strongest industrial correlation and abundant natural resources. CO₂ emissions performance in the region may affect carbon emissions in China’s entire western region and hidden energy consumption in infrastructure construction. Therefore, in a climate of growing global climate problems, the energy consumption and corresponding emissions of the upstream economic Zone should get close attention.

Few studies focus on the features of CO₂ emissions in the upper reaches of the Yangtze River in China. The upstream has been facing the problem of compressing and compounding resources. Policymakers need large amounts of data to support the ecological environment’s promotion and safe use of energy in the upper Yangtze River. Simultaneously, the government can better formulate a low-carbon development strategy for underdeveloped provinces and cities in the western region. This paper uses the IPCC regional emission accounting method to compile the emission inventory of the three provinces and one city in the study area. Then we perform quantitative analysis on the calculation results. And we use the EKC model based on SPSS software to evaluate the economic development and carbon emissions of the Upper Yangtze River Economic Zone. By studying the emission reduction targets in the region, we used the time-series method based on the EViews software to make corresponding predictions of the emission volume in the study region from 2016 to 2030. It provides a valuable reference for low-carbon green development in the Upper Yangtze River Economic Zone and even in western China. The government can also promote China’s emission reduction from a more comprehensive perspective. The research boundary of this paper is the upper reaches of the Yangtze River Economic Zone as the research object, and the consumption of 47 industries, 17 types of fossil fuels, and seven types of industrial processes are considered in the research scope (See Supporting Information Appendix Table S1–S3).

Materials and methods

CO₂ emissions

In this paper, we calculated the CO₂ emissions based on the method of the IPCC. Researchers generally use
primary energy inputs to calculate carbon dioxide emissions from the power generation industry, such as fuel oil, raw coal, and diesel. This paper does not consider emissions outside the study boundary to avoid duplication of calculations (e.g., energy, electricity input). We have also eliminated losses due to transportation and other reasons in total energy consumption. The main objects discussed in this article are CO\textsubscript{2} emissions from energy consumption and industrial production processes, excluding methane (CH\textsubscript{4}), nitrous oxide (N\textsubscript{2}O), and other minor greenhouse gases (CO\textsubscript{2} equivalent).

Energy consumption
Research methods show that energy activities in the socioeconomic sectors multiplied by emission factors can calculate fossil fuel-related emissions (see Eqn (1)).

\[
CE_{\text{energy}} = \sum_{i=1}^{17} \sum_{j=1}^{47} CE_{ij}
\]

\[
= \sum_{i=1}^{17} \sum_{j=1}^{47} AD_{ij} \times NCV_j \times O_{ij} \times CC_j \tag{1}
\]

In the formula, \(i\) refers to the type of energy. \(j\) is the social and economic sectors. \(CE_{ij}\) is the CO\textsubscript{2} emissions of the \(i\) type energy and socioeconomic sector \(j\). \(AD_{ij}\) is the consumption of fossil fuels. \(NCV_j\), \(O_{ij}\), and \(CC_j\) are the net calorific value, oxidation efficiency, and carbon content, respectively. These three values are emission factors. Regarding China’s energy consumption, these three values are more accurate. Seventeen fossil fuels were involved in this study, divided into coal, oil, and natural gas by type. We have selected 47 industries as the main industries in the Upper Yangtze River Economic Zone. The national accounting system classifies the industrial sector. Overall, five sectors are mainly related to energy production. The heavy industry sector is mainly metal smelting and processing of nonmetallic mineral products. The light industry is the manufacture of final products such as food and furniture. The last category consists of five high-tech industries.

Industrial process
In China, 95% of the CO\textsubscript{2} emissions from industrial processes are related to industrial processes such as lime, iron, iron-chromium alloys, ammonia, cement, etc.\textsuperscript{11–12,38} The energy used is not taken into account when calculating emissions from industrial processes. This process only calculates the emissions from chemical reactions in seven production processes (See Supporting information Appendix Table S3). The specific calculation process is shown in Eqn (2).

\[
CE_{\text{process}} = \sum_{t=1}^{7} CE_t = \sum_{t=1}^{7} AD_t EF_t \tag{2}
\]

In the above formula, the industrial process is represented by \(t\), \(CE_t\) and \(EF_t\) are the carbon dioxide emissions related to the process and emission factors, respectively, and \(AD_t\) denotes industrial product. Most of the emission factors involved in industrial processes come from IPCC, except for cement, which refers to previous research.\textsuperscript{17}

Data source
Table 1 shows the social and economic indicators of the four provinces in the Upper Yangtze River Economic Zone in 2015. Local statistical yearbooks include population, GDP per capita, and annual gross national product. From the method described above, the total carbon emissions of each province can be obtained. Emissions per unit of GDP are emission intensity. Carbon emissions per capita are the carbon emissions divided by the population. The statistical yearbook also contains energy consumption data, energy balance sheets for various industries, and industrial product output.

Uncertainty analysis
Carbon emissions calculations are affected by the uncertainty of the input and parametric models.\textsuperscript{39} Uncertainty includes economic fluctuations, incomplete data, social environment impacts, data quality, subjective judgments, energy activities, and emission factors.\textsuperscript{40,41} This paper uses the Monte Carlo method commonly used by IPCC to estimate the uncertainty of carbon emissions. The center estimate has a confidence interval (CI), and its upper and lower limits are defined as uncertainty. The Monte Carlo framework contains data activities, input parameters, and emission factors (normal distribution). Emissions estimates for each sector require 20 000 simulations to facilitate analysis of their uncertainty. This paper assumes that the emission factors and activity data are normally distributed and obtains the coefficient of variation (CV standard deviation divided by the...
Table 1. Emission–socio–economic indicators of Upper Yangtze River Economic Zone, 2015.

| Province   | Population ($10^4$) | GDP (RMB ¥$10^8$) | Per capita GDP (RMB ¥) | Total emission (million tons) | Emission intensity (tons/RMB ¥$10^4$) | Per capita carbon emission (tons/person) |
|------------|---------------------|-------------------|------------------------|-----------------------------|---------------------------------------|----------------------------------------|
| Yunnan     | 4741.8              | 13 619.17         | 28 721.52              | 175.9                       | 1.14                                  | 37.10                                  |
| Guizhou    | 3 529.5             | 10 539.62         | 29 861.51              | 233.6                       | 1.07                                  | 66.19                                  |
| Sichuan    | 9102                | 30 053.10         | 33 018.13              | 322.8                       | 2.22                                  | 35.46                                  |
| Chongqing  | 3 371.84            | 15 872.23         | 45 293.46              | 179.3                       | 1.29                                  | 53.17                                  |

Table 2. Changes in parameter values and curve shape.

| Regression equation | Parameter value | Dependent variable change (Y) | Curve shape |
|---------------------|-----------------|-------------------------------|-------------|
| $Y = a_0 + a_1x$    | $a_1 > 0$       | Increases monotonically with the increase of $X$ | Straight line |
|                     | $a_1 < 0$       | Decreases monotonically with the increase of $X$ | Straight line |
| $Y = a_0 + a_1x + a_2x^2$ | $a_1 > 0, a_2 < 0$ | Increase—decrease | Inverted U shape |
|                     | $a_1 < 0, a_2 > 0$ | Decrease—increase | U shape |
| $Y = a_0 + a_1x + a_2x^2 + a_3x^3$ | $a_1 > 0, a_2 < 0, a_3 > 0$ | Increase—decrease—increase | N shape |
|                     | $a_1 < 0, a_2 > 0, a_3 < 0$ | Decrease—increase—decrease | Reverse N shape |

average) from previous studies: The CV of activity data is affected by the industry in the range of approximately 5–30%,42–44 the CV of the emission factor is coal (3%), natural gas (2%) and oil (1%).

Evaluation model

In the 20th century, Simon Kuznets proposed the Environmental Kuznets Curve (EKC) based on empirical data.45 The model points out that there is an inverted U-shaped relationship between economic development and environmental pollution. When the level of economic growth is low, the degree of environmental pollution is light. As per capita income increases, environmental pollution will go from low to high. The degree of environmental degradation increases with economic growth. When economic development reaches a certain level, environmental pollution will reach a critical point. With the further increase in per capita income, environmental pollution will go from high to low. Environmental quality will be improved.46 With the expansion of the research scope of the model, the EKC has produced many new types of curves. In addition to the quadratic equation with an inverted U-shaped curve, the relationship between economic growth and environmental pollution indicators also shows a first-order equation and an N-type cubic equation relationship. The curve relationship presents an inverted U shape, straight line, U shape, N shape, and reverse N shape.47 Regression analysis is a commonly used statistical method to study the non-deterministic relationship between variables and construct empirical formulas between variables. The EKC model creates a functional relationship between variables through regression analysis. We can determine the relationship between variables based on the function and the changing trend of the dependent variable. Table 2 shows the parameter value changes in the model and the curve judgment criteria.

Time series forecasting

This article uses EViews software based on the ARIMA model to predict the carbon dioxide emissions of the Upper Yangtze River Economic Zone from 2016 to 2030. It can provide a basis for low-carbon development in the region. The forecast did not consider the influence of external factors and only analyzed the historical data of the emission time series. The least-square method is used to estimate the
Table 3. Total CO2 emissions in four provinces and cities, 2000–2015 (Unit: million tons).

| Province     | Yunnan | Guizhou | Sichuan | Chongqing |
|--------------|--------|---------|---------|-----------|
| 2000         | 53     | 81.2    | 105     | 71.3      |
| 2001         | 61.4   | 82.9    | 108.8   | 65.2      |
| 2002         | 72.3   | 86.3    | 124     | 70        |
| 2003         | 88.8   | 110.1   | 157.2   | 68.4      |
| 2004         | 58.7   | 128.6   | 175     | 68.3      |
| 2005         | 133.1  | 145.6   | 170.1   | 81.6      |
| 2006         | 150.2  | 189.6   | 189.8   | 90        |
| 2007         | 161.2  | 172     | 208.5   | 99.2      |
| 2008         | 163.8  | 163.4   | 230.1   | 126.3     |
| 2009         | 187.2  | 184.7   | 263.1   | 133.1     |
| 2010         | 194.2  | 191.5   | 303.8   | 141.5     |
| 2011         | 205.4  | 211     | 303.4   | 160.3     |
| 2012         | 211.7  | 230.1   | 330.7   | 164.8     |
| 2013         | 206.2  | 233.2   | 343.1   | 140.3     |
| 2014         | 194.6  | 231     | 341.3   | 156.2     |
| 2015         | 175.9  | 233.6   | 322.8   | 179.3     |

parameters of the model. The static prediction method is used to predict the data 15 times. We take the forecasting steps of Chongqing in 2030 as an example to give the specific forecasting steps and the parameters involved (See Supporting Information Appendix Table S4–S5, Figure A1–A3).

The ARIMA model regards the sequence formed over time as a random time sequence. We use multiple different operations to convert non-stationary data into a stationary series. This model is identifiable. So, we can use current or past data in the time series to predict future data. The ARIMA model only considers the historical data of the time series in the forecasting process. The ARIMA (p, q, d) model expression in Eq. (3).

\[
(1 - \Theta_1 B - \Theta_2 B - \cdots - \Theta_p B^p) (1 - B)^d y_t = (1 + \theta_1 B + \theta_2 B + \cdots + \theta_q B^q) \varepsilon
\]

Where \( y \) is time-series data, \( p \) is the coefficient of the autoregressive term, \( d \) is the order of difference operation, \( q \) is the coefficient of the moving average term. \( \varepsilon \) is a white noise sequence with a mean value of 0 and a variance of \( \sigma^2 \). \( B \) is the lag operator, defined as \( B^k y_t = y_{t-k}, \theta_1 \ldots \theta_p \), and \( \theta_1 \ldots \theta_q \) are coefficients.

Results and discussion

CO2 emissions in the Upper Yangtze River Economic Zone

The upstream leading industries include manufacturing, processing, and extractive industries. These sectors generate large amounts of energy consumption and severe carbon emissions, which affect the upstream ecological environment. This article calculates the carbon emissions of these four major provinces from 2000 to 2015. The emission list is shown in Table 3. At the beginning of this century, China began to implement strategic tasks such as developing the western region and promoting coordinated regional development. This policy has enabled the rapid growth of the social economy in west China. But the phenomenon has also caused corresponding environmental pollution. From 2004 to 2012, carbon dioxide emissions have entered a period of rapid growth. Its average annual growth rate during this period was 9.16%. Compared with 2004, emissions in 2012 increased by 54.1%. The CO2 emissions of the four major provinces and cities during the 16 years are basically on the rise. There has been a slight decline after 2012. The Upper Yangtze River Economic Zone reached a peak of 937.3 megatons in 2012. After 2012, the Upper Yangtze River Economic Zone also paid
Figure 2. The CO₂ emissions features of the three provinces and one city in the Upper Yangtze River Economic Zone.

more attention to environmental issues based on economic development. The overall trend becomes flat. This phenomenon can be traced back to implementing strict environmental protection policies in the region in 2011. Industrial sectors need to pay carbon taxes, energy taxes, etc. These rectification measures have increased the cost of the industrial sector, thus contributing to the endogenous motivation for energy conservation and emission reduction of enterprises. Sichuan is a pioneer in the upper reaches of the Yangtze River. Since 2000, Sichuan has focused on large-scale urban and three-dimensional transportation construction. The province vigorously promotes the establishment of Sino-foreign cooperative industrial parks. These actions require a large amount of energy and industrial product input. During the time covered by this study, Sichuan Province has the most considerable contribution to CO₂ emissions, with an average annual share of 35.06%. Guizhou and Yunnan are the provinces with relatively backward economic Zones in the Upper Yangtze River Economic Zone. As these two provinces have large-scale population outflows, their energy consumption needs are reduced. This phenomenon resulted in lower CO₂ emissions in these two provinces, with a smaller increase.

This article also describes the carbon emission characteristics of the four major provinces in the Upper Yangtze River Economic Zone from the perspective of emission intensity and per capita emissions (Fig. 2). In the 16 years, the carbon intensity of the region was at a slight decline at the beginning of this century. With the promotion of the western development policy and the development of the economy, the carbon intensity has been relatively stable for several years after 2002. In 2007, the Upper Yangtze River Economic Zone actively cooperated with the relevant requirements of the State Council. The region has taken initiatives to address the environmental issues of sustainable development. Carbon intensity has been declining in subsequent years. The carbon intensity of the economic zone has dropped from a maximum of 2.22–1.07 tons/Y10⁴. The carbon intensity of Guizhou Province has always been higher than that of the other three provinces and cities. The carbon intensity of Guizhou province and Yunnan province has also been higher than that of the Upper Yangtze River Economic Zone. Guizhou has been accelerating the industrial process due to industrial adjustment, increasing carbon dioxide emissions. The carbon intensity per capita is also greater than in other regions. Due to population density and industrial structure transfer, Sichuan’s per capita carbon emissions are relatively low. In 2013, the per capita carbon emissions were 44.62 tons/person, reaching the peak.

The comparison of CO₂ concentration and CO₂ emission intensity in the study area in 2015 provided decision support for the spatial management and optimization of regional carbon emissions. It can be
seen from Fig. 3(a) that the 2015 high concentration of carbon dioxide is in Sichuan and Chongqing. Sichuan and Chongqing are the most economically developed regions in the study area, and their carbon dioxide concentrations are higher than in other regions.

The economic strength of Yunnan province and Guizhou province is relatively weak, mainly based on tourism, and the economic development rate is slow, so the carbon dioxide concentration is low during the period. Comparing the carbon dioxide emission intensity can be seen in Fig. 3(b), which is consistent with the measured dioxide emission.

According to the above total CO₂ emissions, three provinces and one city in the Upper Yangtze River Economic Zone can learn from each other’s low-carbon development experience. Sichuan is a pioneer in low-carbon emission reduction and green development. It can provide a reference for other provinces and cities in the upstream economic zone. Provinces and cities such as Sichuan and Chongqing with sound economics and large population density can transfer industries with higher economies of scale to Yunnan and Guizhou. This measure will drive population movements and control the differences in carbon emissions.

**Carbon emissions of the Upper Yangtze River Economic Zone in various sectors and energy types**

Key energy types and major sectors have a decisive impact on per capita Gross Domestic Product and per capita CO₂ emissions. Emissions performance with energy-consuming industries as the leading industry and raw coal as a vital fuel component is often poor. Different types of energy are also used differently. Therefore, studying the main energy use in the three provinces and one city can understand the source of carbon emissions. In the research economic zone, the main types of energy consumption are coal and related products, such as primary coal, coal washing, and coke, followed by petroleum products such as diesel and gasoline.

Coal-related products and petroleum-related products have the most massive total carbon dioxide emissions. Its emissions accounted for 75.02% of the Upper Yangtze River emissions in 2015. The emissions of raw coal, coke, and diesel are among the top three. In the past 16 years, total coal emissions from the Upper Yangtze river Economic Zone peaked at 60.97% (468.3 million tons) in 2009. As of 2015, it fell to 38.33% (349.5 million tons). 61.32% of the CO₂ emitted by raw coal comes from the electricity production sector. Sichuan and Yunnan have many small hydropower stations. However, hydropower is affected by seasonal factors. Thermal power has the features of utilization hours. Less utilization will incur higher costs. After weighing various angles, even to reduce the cost of thermal power, hydropower is not accepted during nonflood periods. Therefore, how to balance the distribution of different electric power in the upper reaches of the Yangtze river economic zone will have a significant impact on the carbon emissions generated by coal input. Coke emissions have been rising volatility, and the situation of growing in 2012 has slowed down, and even a slight decline. The emissions of petroleum products are almost in a steady upward trend. The construction of the western transportation hub was gradually advanced at the beginning of this century. Sichuan is a vital node radiating surrounding provinces.
and cities. The transportation industry of the four major provinces and cities in the Upper Yangtze River Economic Zone has begun to take shape and gradually grow. In this general environment, investment in petroleum products will be further increased. The CO₂ emissions from this type of energy rise steadily.

Carbon dioxide emissions can also indicate which industries are under tremendous pressure to reduce emission or see which industry can serve as a model for other industries or the same industry in other regions. Thermoelectricity production and supply division produced the highest total emissions (3719.7 million tons), accounting for 35.54% of the total emissions in the Upper Yangtze River Economic Zone. The two industries with relatively high CO₂ emissions were ferrous metal smelting industry and nonmetallic mineral industry, accounting for 12.94% and 13.34%, respectively (Fig. 4). CO₂ emissions in the secondary industry were the largest, accounting for 79.77%, followed by the tertiary industry, accounting for 17.78% in the entire Zone. Transportation, storage, post, and telecommunication services are relatively large contributions in the tertiary industry, accounting for 38.04%. The results show that the petroleum and transportation industries are indeed the main contributors to CO₂ emissions. The above figure indicates that multiple values are 0%. Excluding other minerals mining and dressing, logging and transport of wood and bamboo have the actual value of zero. The others display as 0% means that the value of the department accounts for a very small proportion of the total (See Supporting Information Appendix Table S6).

Figure 5 shows the cycle diagram of energy and CO₂ emissions in the economic zone in 2015. The three industries are divided into 47 socioeconomic sectors. Each sector has different amounts of input for 17 energy types. There is a correlation between energy, sector, and emissions. The left figure shows energy consumption in three industries. The middle section shows CO₂ emissions by sector across the three industries. Finally, the carbon emissions of each sector are summarized into three industries. The figure shows that the raw coal input is the largest, and most of the raw coal is invested in the secondary industry. The proportion of energy input for heat and electricity is also relatively high. In 2015, the three sectors of Raw Chemical Materials and chemical products, smelting and pressing of ferrous metals and electric power, steam and hot water production and supply were the largest in terms of energy input, accounting for 17.45, 15.43, and 9.47%. The power sector of the secondary industry and the transportation sector of the tertiary industry also account for a relatively large proportion of carbon dioxide emissions.
Over the years, changes in GDP show that the region's secondary and tertiary industries account for a large proportion. In the past 16 years, the average share of the two industries has reached 84%. And the ratio of the three industries changes little each year. The above figure shows that both the energy input and the amount of carbon dioxide produced by the secondary industry are massive. However, the industry's GDP performance has not been satisfactory. Sectors in the secondary industry, such as mining, metal smelting, electricity production, and chemical production, require significant energy inputs. The tertiary industry is entirely the opposite of the secondary industry. In the study area, the energy input of the tertiary industry is about one-third of that of the secondary industry. CO₂ emissions are also optimistic. In this case, GDP is almost the same as that of the secondary industry. In the tertiary industry, the transportation sector has extensive energy input and high emissions. We need to focus on using measures such as public transport planning or new energy vehicles in the region. It is necessary to improve the industrial structure of the secondary industry and control the input of energy to achieve better economic development.

Based on CO₂ emission produced by energy input and industrial sectors, we can establish a reasonable energy utilization system and carbon trading market to promote energy conservation and emission reduction in the region. The low energy efficiency of the secondary industry in the Upper Yangtze River Economic Zone is the main factor in promoting the sustainable growth of carbon emissions in the region. It can promote the technological innovation of energy conservation and emission reduction of enterprises in the region and improve energy utilization efficiency through the reasonable energy utilization system and carbon trading market. Government departments can vigorously develop clean energy such as nuclear energy and hydropower to replace the existing coal-based energy consumption structure. The upper reaches of the Yangtze River are rich in water resources. The secondary industry production in the Upper Yangtze River Economic Zone should increase the proportion of clean and low-emission energy use. The region needs to reduce its dependence on fossil energy gradually.

All in all, the calculation of the CO₂ emission inventory provides a reference for the initial emission...
allocation. Carbon emissions from sectors and energy types can help set caps. Therefore, the government can formulate a reasonable carbon emission trading plan to control the CO₂ emissions generated by the industrial sector and achieve regional low-carbon development.

**Uncertainty analysis results**

The coefficient of variations from different sectors for activity data is between 5 and 30%. The CVs for coal, natural gas-related, and oil emission factors were 3, 2, and 1%, respectively. The experimental results clarify that the 96.9% uncertainty in the area covered by this study (the center estimate is a confidence interval ± 47.5%) is reduced to the range of −6.2–7.2%.

**Economic development and carbon emission change assessment**

The paper uses GDP per capita in the Upper Yangtze River Economic Zone to reflect economic growth. Carbon emissions reflect the environmental quality status. Before the relationship simulation, we need to observe the changes in the index value (See Supporting Information Appendix Table S7). GDP per capita in the Upper Yangtze River Economic Zone has grown exponentially. The changing trend of carbon emissions is roughly the same as that of GDP per capita. However, the rising trend of carbon emissions and economic development is different. This paper uses SPSS to fit the first-order, second-order, and third-order polynomial models of carbon dioxide emissions and per capita GDP in the Upper Yangtze River Economic Zone from 2000 to 2015 (Fig. 6).

Table 4 lists the complex correlation coefficient $R$, the determination coefficient $R^2$, adjusted $R^2$, and the standard error of the three models. Compare the adjusted $R^2$ and significance to judge the model (See Supporting Information Appendix Table S8–S10). Table 4 shows the fit of the three models. The linear model has the smallest $R^2$, which is 0.773. The quadratic model $R^2$ is 0.978. The model fit is higher than the linear model. The $R^2$ of the cubic model is 0.99. The model has the highest degree of fit. Table 5 shows that the regression equations are $Y = 348.601 + 0.019X$ and $Y = 97.454 + 0.053X - 8.09E^{-7}X^2$, respectively. The cubic coefficient of the cubic model is not significant, so the model cannot be established well.

According to the EKC model theory, when $a_1 > 0$ and $a_2 < 0$, there is an inverted U-shaped relationship between economic development and carbon emissions in the Upper Yangtze River Economic Zone. The region’s economic growth and carbon emissions were
Initially at a stage of high development and high carbon emissions. As the Upper Yangtze River Economic belt is located in western China, its economic development is relatively late. With the advancement of policies for the protection of ecological civilization in the Yangtze river basin in recent years, the economic carbon emission model transition point was reached in 2014. Figure 6 shows that the fit of the cubic model is the highest. There is an N-shaped relationship between economic development and carbon emissions in the Upper Yangtze River Economic Zone. Therefore, the region faces the risk of transforming into a model of high development and high carbon emissions. Economic development and carbon emissions have not fully reached the stage of coordinated development.

The social development of the Upper Yangtze River Economic Zone is in a state of rapid development. This region has obvious characteristics of high consumption and high environmental cost. The industrial sectors need to improve the quality of industrial production factors and increase energy efficiency. In this way, regional development can maintain a state of high yield and low carbon. Government departments should promote the establishment of a reasonable energy system. Major provinces and cities need to focus on regional integration and improve the efficiency of resource allocation.

### Trend analysis of carbon emissions (2016–2030)

The features of energy consumption and carbon dioxide emissions are different at different periods. There are some differences in the path planning for realizing energy saving and emission reduction potential at different stages. This paper predicts the carbon dioxide emissions in the Upper Yangtze River Economic Zone based on the time-series method of EViews software (See Table 6). The GDP growth target mentioned in the 13th five-year plan is 6.5–7.0%. We estimate the emission reduction targets of the Upper Yangtze River Economic Zone and its three provinces and one city. Through forecasting, decision-making departments can understand whether the current reduction rate can achieve the reduction target and whether the reduction rate needs to be changed. It can be seen from Table 7 that almost all the three provinces and one city in the region have reached the emission reduction targets, except for Chongqing, which did not get a peak in 2030.

The forecast results show that the CO₂ emissions in the Upstream will peak in 2012 and will decline sharply after 2020. The emission intensity of western China did not reach the emission reduction target in 2030 and the difference reached 22.5%. The Upper Yantze River Economic Zone, which is more developed in the west, has far exceeded the 65% emission reduction target.

It can be seen from Figure 7 that the proportions of the three provinces and one city at the beginning of this century are roughly the same. After reaching its peak, CO₂ emissions in Sichuan province fell sharply. Laptops and automobiles are the pillar industries of

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**Table 4. Model determination coefficient.**

| Model          | $R$  | $R^2$ | Adjusted $R^2$ | Std. error of the estimate | $R$  | $R^2$ | Adjusted $R^2$ | Std. error of the estimate |
|---------------|------|-------|----------------|---------------------------|------|-------|----------------|---------------------------|
| Linear model  | 0.879| 0.773 | 0.756          | 119.331                   | 0.989| 0.978 | 0.974          | 38.772                    |
| Quadratic model| 0.989|        |                 |                          | 0.995|        |                 |                          |
| Cubic model   | 0.995| 0.99  | 0.987          | 27.584                    |      |       |                 |                          |

**Table 5. Simulation results of the economic growth and carbon emission level measurement model in the Upper Yangtze River Economic Zone.**

| Model          | Constant | $X$   | $X^2$ | $X^3$ | $R^2$ |
|---------------|----------|-------|-------|-------|-------|
| Linear model  | 348.601  | 0.019 |       |       | 0.773 |
| Quadratic model| 97.454  | 0.053 | $-8.09E^{-7}$ | 0.978 |
| Cubic model   | $-29.358$ | 0.080 | $-2.21E^{-6}$ | $1.97E^{-11}$ | 0.995 |
Table 6. 2016–2030 Carbon dioxide emissions forecast (Unit: million tons).

| Province       | Yunnan  | Guizhou | Sichuan | Chongqing |
|----------------|---------|---------|---------|-----------|
| 2016           | 170.2   | 235.3   | 314.4   | 167.4     |
| 2017           | 162.7   | 234.9   | 304.1   | 171.3     |
| 2018           | 153.6   | 235.0   | 288.1   | 195.9     |
| 2019           | 142.7   | 235.0   | 272.5   | 197.0     |
| 2020           | 130.0   | 234.1   | 255.8   | 196.2     |
| 2021           | 129.0   | 232.9   | 236.4   | 217.3     |
| 2022           | 128.1   | 231.4   | 215.7   | 228.6     |
| 2023           | 127.2   | 229.4   | 193.6   | 229.1     |
| 2024           | 126.4   | 227.0   | 169.6   | 245.4     |
| 2025           | 125.7   | 223.6   | 144.0   | 262.9     |
| 2026           | 125.0   | 219.4   | 116.8   | 267.9     |
| 2027           | 124.4   | 214.4   | 88.0    | 280.7     |
| 2028           | 123.8   | 213.6   | 72.9    | 300.9     |
| 2029           | 123.2   | 212.8   | 45.1    | 311.7     |
| 2030           | 122.7   | 212.1   | 18.3    | 323.2     |

Table 7. Forecast of the carbon emission reduction (CER) (Unit: tons/10⁴ CNY).

| Tons/CNY10⁴ | 2005 | 2010 | 2015 | 2020 | 2025 | 2030 | Forecasting CER | Target CER |
|-------------|------|------|------|------|------|------|-----------------|------------|
| Western China | 3.66 | 2.61 | 1.89 | 1.93 | 2.05 | 2.29 | 37.43% | 60–65%   |
| The Upper Yangtze River Economic Zone | 3.25 | 2.25 | 1.30 | 0.93 | 0.62 | 0.38 | 88.31% | 60–65%   |
| Yunnan | 3.84 | 2.70 | 1.3 | 0.71 | 0.52 | 0.38 | 90.10% | 60–65%   |
| Guizhou | 7.26 | 4.16 | 2.22 | 1.67 | 1.19 | 0.84 | 88.43% | 60–65%   |
| Sichuan | 2.30 | 1.77 | 1.07 | 0.64 | 0.27 | 0.02 | 99.13% | 60–65%   |
| Chongqing | 2.35 | 1.78 | 1.14 | 0.93 | 0.93 | 0.86 | 63.4% | 60–65%   |

Chongqing. Chongqing is the last gateway to the ecological barrier in the Yangtze river basin. Its ecological status is very important. But Chongqing has gradually risen over time. Chongqing is expected to become a vital contribution area of CO₂ emissions in the Upper Yangtze River Economic Zone in 2030. The calculation results show that the intensity of carbon dioxide emissions in Chongqing has always been at the top of the three provinces and one city. It is predicted that future emissions will gradually increase. To ensure that Chongqing plays a demonstration role in the green development of the Upper Yangtze River Economic Zone, government departments need to take defensive measures in advance. The trends in Yunnan and Guizhou are generally consistent, and they are almost in a relatively stable state. By 2020, the region’s main core area is production. While vigorously developing production, we must also pay attention to areas where energy consumption is growing too fast. From 2020 to 2030, the production and consumption sectors will become equally important. The focus of work in this area will gradually shift to consumer areas such as construction and transportation.

By predicting regional carbon emissions in the next few years, we can roughly understand that the region needs to optimize the regional industrial structure and
vigorously develop tourism in the future, electronic information, and other industries. Replace the leading industrial pattern of rough resource processing, which is dominated by resource mining, beneficiation, and metallurgy. China’s development is the top priority, so the Upper Yangtze River Economic Zone cannot reduce carbon emissions at the expense of slowing economic growth.

**Conclusions**

The emission features of the four provinces can support the formulation of sustainable development policy in the Upper Yangtze River Economic Zone. It also provides a reference for other regions in the country to formulate and implement low-carbon development strategies. The research is conducive to promoting China’s sustainable economic development. CO₂ emissions in the upstream economic zone peaked rapidly at a growth rate of 9.16% before 2012. From 2000 to 2015, the carbon emissions from energy consumption in the upstream economic zone showed an upward trend. The carbon emissions generated by the secondary industry are significantly higher than the other two industrial sectors. Sichuan and Chongqing have relatively high carbon emissions and a massive increase. The carbon emissions in Guizhou and Yunnan are relatively low, and the growth rate is low. The major changes in carbon emissions in the provinces are also mainly due to the secondary industry. During this period, the high carbon dioxide concentration region coincides with the carbon emission intensity. The high-value area is stable in the relatively developed economy of Sichuan province and Chongqing city. Yunnan and Guizhou provinces mainly focus on tourism, with a slower economic development rate, lower carbon dioxide concentration, and lower emission intensity. From the perspective of energy varieties and industry sectors, coal-related products, and petroleum-related products have produced 75.02% of the total carbon dioxide emissions. The emissions of raw coal, coke, and diesel are among the top three. The total Thermoelectricity Production and Supply Division in the secondary industry accounted for the highest total emissions of 35.54%. Transportation Services account for 38.04% of the contribution of the tertiary industry. The Upper Yangtze River Economic Zone verified the EKC hypothesis, which means that economic carbon emissions have exceeded the threshold level in recent years. Environmental quality has been improved. However, there is still the risk of the model change. Economic development and carbon emissions have not formed a completely coordinated situation.
Government departments must pay attention to the ecological consequences of economic development. We can promote the sustainable development of the Upper Yangtze River Economic Zone by controlling energy consumption in industrial sectors. The forecast results show that as the economy advances, Chongqing’s CO₂ emissions increase year by year. Further research on Chongqing’s industrial structure is needed to ensure that emission reduction targets can be reached by 2030. Due to forecast errors caused by data limitations, CO₂ emissions in Sichuan should be in a downward trend. Whether it can reduce emissions by 99.13% in 2030 compared to 2005 is still somewhat controversial. Yunnan and Guizhou are relatively developed areas of tourism, and the province’s carbon dioxide emissions will be flat after peaking before 2020.

AUTHOR CONTRIBUTIONS STATEMENT

All authors have read and agree to the published version of the manuscript. Xin Li: Conceptualization, Lu Chen: writing-original draft preparation and methodology, Yunqi Yang: formal analysis and investigation, Minxi Wang: data curation, writing-review, and editing.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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