Article

Scenario Analysis of Energy-Related CO₂ Emissions from Current Policies: A Case Study of Guangdong Province

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Abstract: Regional carbon management is essential for China to achieve the carbon reduction target. Studying the emission peak time and volume for Guangdong Province, which is the largest economic province with rapid carbon growth, is important for developing regions to formulate low-carbon policies. In this study, an end-use energy-based emission model integrating the guidelines for provincial CO₂ emission peaking action plans and updated policies was developed to study the regional energy-related peaking time and emission scale. Taking Guangdong as a case, multiple scenarios were designed and analyzed considering factors of economic development, energy intensity, and structure. The results show that the energy-related CO₂ cannot reach its peak by 2030 without control, even under low economic growth scenarios. Specifically, under high economic growth scenarios, the carbon peak can only be addressed by 2030 at around 0.65 Gt in the context of a strong transformation in energy structure as well as improvement in energy efficiency. Under medium and low economic scenarios, energy-related CO₂ emissions will reach a plateau before 2030 between 0.61 and 0.64 Gt by implementing the medium and strengthening optimization of energy structure. Thus, effective measures are necessary for Guangdong’s peak target in both energy efficiency improvement and energy structure optimization. At last, this study puts forward policy recommendations for the low-carbon pathway of Guangdong Province, which can provide an experience for other regions in understanding their carbon emission trajectories and help policymakers enact appropriate actions.

Keywords: CO₂ peak; regional carbon management; scenario analysis; energy-related; policy recommendation

1. Introduction

The IPCC 1.5-Degree C special report [1] highlights that global warming of 2 °C would have a significantly larger risk than 1.5 °C. Rapid and far-reaching low-carbon actions are required to limit warming to 1.5 °C. According to the record from Energy and Climate Intelligence Unit [2], more than 130 countries or regions have proposed carbon neutral goals, of which 17 countries have enshrined the target in law and over 30 countries included their climate target in policy documents. Although achieving the carbon neutral goal is a global challenge, it is also a powerful driver for the energy revolution to achieve sustainable development.

As both the largest developing country and the largest CO₂ emitter in the world, China is playing a critical role in achieving the global climate goal. In this context, China has made great efforts in controlling energy-related CO₂ emissions and moving to a cleaner and more efficient economy [3]. In 2014, China pledged to achieve the peaking of CO₂ emissions around 2030 and to try to peak it earlier in a joint US–China government announcement [4]. The goal was reaffirmed, along with an additional target to reduce CO₂ intensity by 60–65% by 2030, below 2005 levels, as part of the Enhanced Action of Climate Change: China’s Intended Nationally Determined Contributions (INDCs) [5]. Most recently, at the 75th United Nations General Assembly in September 2020, the Chinese government announced...
that China will aim to achieve carbon neutrality before 2060, which is a big shift for curbing emissions and a significant step forward in international cooperation. Indeed, China has achieved remarkable results in combating climate change. According to the recent report on China’s policies and actions for addressing climate change in 2018, China had achieved its 2020 carbon emission target three years ahead of schedule, which was reversing the rapidly rising trend of CO$_2$ emissions [6].

Various models have been developed to understand China’s future energy and emission trend, mainly including the top-down or general equilibrium models, the bottom-up models, and hybrid models [7,8]. Zhou et al. [9] presented a comprehensive review of recent China long-term energy and emissions modelling efforts. It has been reported that, from 2005 to 2013, over eighteen modelling tools have been developed to study China’s future emissions [10]. Jiang et al. [11] presented a critical review regarding sectoral and provincial CO$_2$ emission in China and indicated that an in-depth examination should be conducted in key provinces.

Because of the notable provincial discrepancies in energy-source mixes, geological conditions, population level, socioeconomic development, etc., in practicality, China’s peak emissions targets are expected to be designed for the sub-administrative region such that the national total peaks by 2030 [12,13]. Therefore, a better understanding of regional peak CO$_2$ emission targets and the establishment of a feature-based emission roadmap is fundamental for determining the energy and carbon emission profile of the nation, and extremely important for achieving national goals [14,15]. At present, more than 10 provinces (municipalities) in China have proposed their peak targets.

A number of studies have been conducted on CO$_2$ or greenhouse gas (GHG) peaking in China at the regional level, as summarized in Table 1. At the provincial level, Yophy et al. [16] and Tian et al. [17] forecasted the CO$_2$ emissions of Taiwan and Jilin [18] using the Low Emissions Analysis Platform (LEAP) model combined with scenario analysis. Several studies adopted the STIRPAT model to analyze the influence factors of carbon emissions from a macroscopic view. Wen and Liu [19], Zhao et al. [20], and Qin [21] employed the STIRPAT model to analyze the CO$_2$ emissions for Beijing–Tianjin–Hebei, Henan province, and Xinjiang Autonomous Region, respectively. From a top-down perspective, Feng and Wang [22], used the input-output model of Structural Decomposition Analysis (SDA) to decompose the carbon emissions of Shanxi Province. Specifically, Zhang et al. integrated the STIRPAT and LEAP model to achieve crosschecks of emission peaks and mitigation roadmaps of Yunnan Province. The results from the combining work indicate that the peak emissions will occur over the prolonged period from 2024 to 2028.

Several studies have focused on the energy consumption, emissions peak, strategies, and the contributing factors at the city level. Feng et al. [15] developed an integrated system dynamics model to predict the energy and CO$_2$ profiles for Beijing city. Lin et al. [7] applied a LEAP-based model to study the CO$_2$ and GHG peak volume and time by integrating energy-related and non-energy-related sectors of Xiamen city. Using the hybrid method, the long-mean divisia index (LMDI) method was coupled with STIRPAT [23], the BP neural network model [24] and system dynamic [18] to decompose the determinations of urban CO$_2$ change and predict emission peaks for Chongqing, Shanghai and Baoding cities.
Table 1. Summary of research on Chinese CO\textsubscript{2} emissions peak at the regional level.

| Study                  | Possible Peak Time | Research Model     | Study Method | Scenario Analysis | Ref. |
|------------------------|-------------------|--------------------|--------------|-------------------|------|
| **Provincial Level**   |                   |                    |              |                   |      |
| Taiwan                 | -                 | Bottom-up LEAP    | ✓            | [16]              |      |
| Shanxi                 | 2029–2030         | Top-down IO-SDA   | ✓            | [22]              |      |
| Jilin                  | 2025–2045         | Bottom-up LEAP    | ✓            | [17]              |      |
| Henan                  | 2035–2040         | Top-down STIRPAT  | ✓            | [20]              |      |
| Beijing-Tianjin-Hebei | 2029–2045         | Top-down STIRPAT  | ✓            | [19]              |      |
| Yunnan                 | 2024–2028         | Bottom-up LEAP    | ✓            | [14]              |      |
| Xinjiang               | After 2030        | Top-down STIRPAT  | ✓            | [21]              |      |
| **City Level**         |                   |                    |              |                   |      |
| Beijing                | –                 | System dynamics model | Beijing-STELLA | -                  | [15] |
| Beijing                | 2019              | Bottom-up LEAP    | ✓            | [25]              |      |
| Kunming                | 2021–2028         | Top-down STIRPAT  | ✓            | [27]              |      |
| Guangzhou              | 2020              | Bottom-up Scenario analysis | ✓ | [28]              |      |
| Chongqing              | 2032–2035         | Hybrid LMDI and STRPAT | ✓ | [23]              |      |
| Qingdao                | 2020–2025         | Top-down STIRPAT  | ✓            | [29]              |      |
| Xiamen                 | 2034–2039 a       | Bottom-up LEAP    | ✓            | [7]               |      |
| Baoding                | 2024              | Hybrid LMDI and BP neural network model | ✓ | [24]              |      |
| Shanghai               | 2025              | Hybrid LMDI and System dynamic model | ✓ | [18]              |      |

a The peak time for total GHG emissions.

As the largest economy and the most populous province in China, the economic and social development stage of Guangdong is typical and representative in the country. Promoting Guangdong’s early achievement of peak carbon emissions will not only accelerate its high-quality economic development but also help accumulate typical experience for China to explore provincial energy-saving and emission-reduction paths and measures. Several studies have been conducted focusing on CO\textsubscript{2} accounting, peak prediction as well as electricity and carbon market of Guangdong Province. Wang et al. [30] examined the impact factors of energy-related CO\textsubscript{2} emissions using an extended STIRPAT model. The results indicate that population has the strongest influence on CO\textsubscript{2} increase. Based on the IPCC territorial emission accounting approach, Zhou et al. [31] firstly complies with emissions inventories of eleven Guangdong–Hong Kong–Macao Greater Bay areas and their surroundings from the year 2000 to 2016. The key emission contributors and characteristics were identified and discussed for different cities. Jiang et al. [32] assessed the economic and CO\textsubscript{2} emissions impacts of electricity market reforms in Guangdong Province. The results indicate that relatively high CO\textsubscript{2} prices at around 260 CNY/tCO\textsubscript{2} would be necessary to avoid emission increases during the market transition. Li and Li [33] developed a multi-scenario ensemble simulation and environmental input-output (MES-EIO) to identify the optimal multi-pollutant and emissions reduction schemes from 2020 to 2030 for Guangdong Province. Integrating the EIO and RAS model, Feng and Bai [34] predicted the energy demand and related CO\textsubscript{2} emissions of Guangdong Province. The results indicate that with the decline in economic growth, the speed of energy efficiency improvement is one of the most critical factors determining the peak time for Guangdong Province.

Compared with a large number of research results on energy demand forecasting at the national level, there are fewer forecasting studies on energy demand and carbon emissions in Guangdong Province. Since the 13th Five-Year Plan, the Guangdong government and local authorities have implemented a series of low-carbon policies. However, previous research rarely considered the local policies. Specifically, the overall layout plant for 5G base stations and data centers for Guangdong Province was released recently. With the large-scale use of data centers and 5G bases stations, the energy consumption per unit of...
value-added and total energy consumption may continue to increase, which may bring a new challenge for the CO\textsubscript{2} peak in Guangdong. Therefore, both low-carbon and energy policies will significantly affect carbon emissions and peak values. However, fewer studies were conducted to predict the CO\textsubscript{2} emissions and quantify the peak values under the current policy environment, which could provide data support for the development of a local low-carbon economy.

The contributions of this study are mainly embodied in the following aspect. In terms of research content, the characteristics of Guangdong’s energy-related CO\textsubscript{2} emissions are analyzed based on a developed bottom-up energy model. Additionally, based on the policies that are already being implemented or policies that appear certain to be implemented in the short to medium term, the CO\textsubscript{2} emissions trends and reduction potentials are forecasted in three macro-economic scenarios at different improvement levels in energy intensity and structure through scenario analysis. The likelihood of meeting the carbon peak goal for Guangdong Province is examined, and practical policy recommendations are proposed. The research results can provide insights into Guangdong’s CO\textsubscript{2} peak as well as develop strategies for carbon emission reduction.

The flowchart of the methodology of this study is shown in Figure 1. Based on this framework, Section 2 introduces the historical data and related policies and strategies of Guangdong Province. On the bases of the historical trends and driving forces, in Section 3 multiple scenarios were proposed and the framework of the end-use energy-base emission model was introduced. Sections 4 and 5 present a depth analysis of the energy-related CO\textsubscript{2} trajectories of Guangdong Province and corresponding policy implications.

Figure 1. Flowchart of the methodology used in this study.
2. Historical Energy-Related Carbon Emissions and Related Policies

2.1. Historical Energy-Related Carbon Emissions

The economic development of Guangdong Province maintained a steady annual growth rate of 7.9% from 2010 to 2019. Figure 2 shows the trend of carbon emissions, total energy consumption, and carbon intensities during this period. The growth of carbon emissions has slowed down with an average annual growth rate of about 1.98%. Meanwhile, carbon intensity also dropped from 1.03 to 0.57 t/10⁴ CNY with an average annual decline rate of 8.9%. From the perspective of energy types, coal consumption kept accounting for the largest share of carbon emissions in 2019, at over 56%, followed by oil consumption, accounting for nearly 28%. Overall, the figure indicates that the economic growth of Guangdong Province is decoupled from carbon emissions.

![Figure 2. Carbon emissions and energy consumption status of Guangdong Province since the 12th Five-Year Period [35].](image)

Figure 2 depicts the energy consumption by sectors from 2010 to 2019. The share of energy consumption of the industrial sector decreased from about 64% in 2010 to about 57% in 2019, mainly from the manufacturing industry. In contrast, the proportion of residential, services and other and transportation sectors witnessed a gradual growth reaching around 16%, 12%, and 11% in 2019, respectively. Specifically, the residential sector plays a key role in the growth of energy consumption, with the proportion increasing from 11% to around 16% in 2019.

![Figure 3. Energy consumption by sectors of Guangdong Province since 2010 [35].](image)
Figure 4 indicates the carbon emissions by region in 2016 based on the updated published work [31]. As one of China’s major centers with massive manufacturing and trade, the Pearl River Delta region (including nine municipalities) made up over 80% of the gross domestic production (GDP) of Guangdong Province. The carbon emissions are closely related to GDP. Consequently, the Pearl River Delta region was the major contributor to total carbon emissions, accounting for over half of the provincial carbon emissions.

![Figure 4](image-url)  
*Figure 4. Carbon emissions by region of Guangdong Province in 2016 [31].*

2.2. Development Planning and Low-Carbon Policies

Table 2 summarizes the development planning and low-carbon policies of Guangdong Province, which are the important bases of this study. New energy is listed as one of the key development industrial clusters, the offshore wind power and hydrogen energy industry of which will become key areas in the next five years. On this basis, the non-fossil energy consumption will account for about 30% of the total energy consumption. However, the large-scale construction planning of data centers and 5G-base stations will bring new challenges to the reduction of total energy consumption. Overall, the impacts of the development of both new energy and data centers and 5G-based stations on carbon peaks needs to be comprehensively considered.

| Items                      | Planning/Policies                                                                 | Key Target                                                                                               | Ref. |
|----------------------------|----------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|------|
| Economic and Social        | Outline of the 14th Five-year Plan for National Economic and Social Development in Guangdong Province and the 2035 Long-range Goals | The province’s GDP will grow at an average annual rate of about 5.0%, and the GDP will be about 14 trillion CNY by 2025. | [36] |
|   | Comprehensive Development Plan for the Coastal Economic Zone of Guangdong Province (2017–2030) | The region’s GDP will grow at 7% and 6.5% in 2025 and 2030, and the GDP will be about 17.7 trillion CNY by 2030. | [37] |
|   | Population Development Plan of Guangdong Province (2017–2030)                   | The total permanent population of Guangdong Province will be around 120 million in 2025 and around 125 million in 2030. | [38] |
3. Methodology

Based on the guidelines for the preparation of provincial CO₂ emission peaking action plans [45], a scenario-based end-use energy model is developed in this study for the calculation of energy consumption and CO₂ emissions in Guangdong Province. The calculation framework is depicted in Figure 5, which is based on the drivers of energy demand on a sectoral level including both demand and supply-side. The model enables detailed consideration of policy constraints and technology development to evaluate Guangdong’s energy demand and emissions. Within the energy consumption side, key drivers of energy use include activity drivers (population growth, vehicle stock, planned industrial projects), economic drivers (total GDP, household income), and energy intensity trends. From the supply side, the energy transformation sector includes a power sector model that can be adapted to reflect the power, generation efficiency, fuel switch, and generation mix.
The 5G base station and data center overall layout plan of Guangdong Province (2021–2025) — The number of 5G-base stations will be up to 660,000 by the end of 2025; Complete 6 data center clusters and around 1 million standard racks with an average design PUE value of less than 1.3 and annual energy consumption of less than 20 million MWh.

Action Plan for Cultivating Strategic Emerging Industry Clusters of Semiconductors and Integrated Circuits of Guangdong Province (2021–2025) — The annual main business revenue will exceed 400 billion CNY, with an average annual growth rate of more than 20%.

Action Plan for Cultivating New Energy Industry Clusters of Guangdong Province (2021–2025) — The proportion of non-fossil energy consumption will be around 30% by 2025; the installed capacity of new energy power generation will reach 60.5 million kW by 2025; build about 3,600 charging stations and 300 hydrogen refueling stations by 2025.

'1 + 20' Strategic Industrial Cluster Policy Document Proposed 20 strategic industrial cluster action plans from 2021 to 2025

Construction — The '14th Five-Year' Development Plan for the Construction Industry of Guangdong Province (Draft for public comments) — Implement the carbon peak plan for the construction sector.

3. Methodology

Based on the guidelines for the preparation of provincial CO2 emission peaking action plans, a scenario-based end-use energy model is developed in this study for the calculation of energy consumption and CO2 emissions in Guangdong Province. The calculation framework is depicted in Figure 5, which is based on the drivers of energy demand on a sectoral level including both demand and supply-side. The model enables detailed consideration of policy constraints and technology development to evaluate Guangdong's energy demand and emissions. Within the energy consumption side, key drivers of energy use include activity drivers (population growth, vehicle stock, planned industrial projects), economic drivers (total GDP, household income), and energy intensity trends. From the supply side, the energy transformation sector includes a power sector model that can be adapted to reflect the power, generation efficiency, fuel switch, and generation mix.

Figure 5. Calculation framework for energy-related CO2 emissions.

3.1. Scenario Examined

The carbon peak refers that shows the annual carbon dioxide emissions of a region reaching the highest value in history and then gradually decreasing, and Guangdong Province is planning to achieve its carbon peak before 2030. In this study, we developed 27 scenarios to explore the possibility of the CO2 peak in Guangdong Province under different combinations of economic and social environments, energy intensity, energy structures, and to reveal the major contributors to CO2 emissions. Each category of factors during 2021–2035 is divided into three levels as summarized in Table 3.

Table 3. Summary of study concerning CO2 accounting of Guangdong Province.

| Study            | Study Period | Method   | Scenario Analysis | Research Object                                                                 |
|------------------|--------------|----------|-------------------|---------------------------------------------------------------------------------|
| Wang et al. [30] | 1980–2010    | Top-down | N.                | Examining the impact factors of energy-related CO2 emissions in Guangdong Province. |
| Zhou et al. [31] | 2000–2016    | Bottom-up| N.                | Accounting energy-related CO2 for Guangdong-Hongkong-Macao Greater Bay area based on IPCC territorial accounting method. |
| Li et al. [33]   | 2020–2030    | Top-down | ✓                 | Identify optimized pollutant and CO2 emission-reduction schemes from different perspectives for Guangdong Province. |
| Feng et al. [34] | 2016–2040    | Top-down | ✓                 | Predicting the energy consumption and CO2 emissions of Guangdong Province.       |
| This study       | 2020–2035    | Bottom-up| ✓                 | Examining the energy-related CO2 emissions of Guangdong Province by taking into consideration of the current policy of Guangdong Province. |

In detail, three levels of GDP growth rate scenarios are considered. The high growth scenario indicates that the regional city economy is booming, and the driving force of new economic growth points is strong. The medium growth scenario indicates that the economic situation is continuously improving with smooth transformation and upgrading in each sector. Nevertheless, it is assumed that there is a lack of new economic growth points under a low economic growth scenario. Regarding energy intensity, three levels of energy-saving potential are reflected as the decline rate of energy consumption per unit of added value and energy consumption per capita, in which the weak scenario indicates that the energy
intensity will remain the same as in the year 2020, and the medium scenario indicates that efficiency improvement is consistent with trends in ‘market-based’ improvement. Similarly, there are three levels in energy structure adjustment being reflected as the proportion of different energy types. The weak scenario maintains the same energy structure in 2019 and the medium and strength scenario will witness different levels of decrease in the proportion of coal and oil consumption in different sectors. The detailed power supply structure can be obtained by contacting the author team. Considering the above assumptions of each influence factor, twenty-seven scenarios are assembled as a combination of the different scenarios for each influence factor.

Particularly, the GDP growth setting is based on related planning and research. In the near term, the Outline of the ‘14th Five-year Plan’ for National Economic and Social Development in Guangdong Province and the 2035 Long-range Goals [36] proposes that the goal of the average economic growth rate of Guangdong Province during the “14th Five-Year Plan” will be around 5.0%. In the near to medium term, according to the prediction of Chinese economic growth during the ‘14th Five-Year Plan’ period, the GDP growth rate is expected to be about 5.1% in 2025 and may drop to 4.5% in 2035 [46,47]. Finally, in the medium and long term, results from [48] indicate that China’s per capita GDP growth rate will still be around 3.0–4.0% from 2036 to 2050. Above all, considering that the economic growth rate of Guangdong was higher than the national level, we made corresponding settings of GDP growth rate at the different periods as listed in Table 4. The population is assumed to be the same for all scenarios.

### Table 4. Parameter setting for scenario analysis from 2021 to 2035 in Guangdong Province.

| Factors                                | Parameters                                | Development Levels | Increase Rate       |
|----------------------------------------|-------------------------------------------|--------------------|---------------------|
|                                        |                                            | 2021–2025          | 2026–2030 | 2031–2035 |
| Economic development [36,47,48]        | GDP                                        | Low (L)            | 5.10%    | 4.03%     | 3.10%     |
|                                        |                                            | Medium (M)         | 5.30%    | 4.26%     | 3.28%     |
|                                        |                                            | High (H)           | 5.50%    | 4.40%     | 3.39%     |
| Energy intensity [35]                  | Energy consumption per unit of added value| Weak (W)           | Remain the same level as in the year 2020 | |
|                                        |                                            | Medium (M)         | −2.43%   | −2.29%    | −1.95%    |
|                                        |                                            | Strength (S)       | −2.65%   | −2.54%    | −2.18%    |
|                                        | Energy consumption per capita               | Weak (W)           | 3.4%     | 3.2%      | 3.0%      |
|                                        |                                            | Medium (M)         | 3.1%     | 3.0%      | 2.8%      |
|                                        |                                            | Strength (S)       | 2.6%     | 2.5%      | 2.3%      |
| Energy structure [49]                  | The proportion of each fuel type           | Weak (W)           | Remain the same proportion as in 2019 | |
|                                        |                                            | Medium (M)         | Keep the same optimization rate as from 2013 to 2019 | |
|                                        |                                            | Strength (S)       | Refer to the terminal energy structure of Germany in 2012 | |

### 3.2. Analysis of Sectoral Drivers

#### 3.2.1. Religious Sector

The growth in total population and household incomes are two main drivers for energy consumption growth in the residential sector. In general, the household energy consumption per capita displayed a growth trend with the increase in household income until the GDP per capita is around 30,000 dollars for the OECD (Organization for Economic Cooperation and Development) countries [50]. According to the medium and long-term economic development expectations of Guangdong, it is expected to become a wealthy economy in around 2035 and its GDP per capita is expected to reach approximately 25,000 [51], indicating that the household energy per capital in the medium and long term will continue to show an increasing trend. The total population is expected to reach 120–125 million in 2025, and 128–133 million in 2035, respectively [36,38].
3.2.2. Agricultural Sector

Due to the improvement of agricultural technology and degree of agricultural mechanization, the energy consumption per unit of the output value of agricultural sector has dropped from 0.12 tce/10^4 CNY to around 0.10 tce/10^4 CNY during 2000–2019, with an average annual decline rate of around 0.8%. Meanwhile, the agricultural output continued to increase by 75% from 2000 to 2019, with an average annual growth rate of 3.0%, and the proportion of total energy consumption remained at around 1.8% for a long time. It is expected that the energy consumption of the agricultural sector will continue to grow steadily in the medium and long term.

3.2.3. Industrial Sector

Within the industrial sector, the subsectors of mining, manufacturing, electricity and water production and supply were considered in this study. Specifically, the industrial sector is dominated by manufacturing, which can be divided into high-energy-consuming manufacturing (HM), medium-energy-consuming manufacturing (MM), labor-intensive low-energy-consuming manufacturing (LLM), and low-energy-consuming manufacturing (LM). (See Table A1 in Appendix A for the specific classification.) The HM will maintain developing before 2030 based on new projects panning. Regarding MM, benefit from industrial restructuring, the ‘coal-to-gas’ policy, and energy prices, the energy consumption per unit of output value will have a certain decline potential. Similarly, with the large-scale deployment of special equipment, the energy consumption per unit of output of LLM is expected to decrease continuously and the total industry scale will also show a downward trend. Finally, the LM is the key area of Guangdong’s industrial development in the future. Specifically, communications, electronics, electrical machinery, automobiles, ships, and medical manufacturing will be the leading industries in Guangdong, and their total economic output will be greatly improved. The energy consumption per unit output value in this field is expected to decline at a low rate and gradually stabilize. However, its production capacity still has a large room for growth. Specifically, Guangdong will vigorously build 5G facilities and data centers during the ‘14th Five-Year Plan’ period; thus, it is expected that its total energy consumption will show a continuous growth trend.

3.2.4. Construction Sector

The construction sector is mainly affected by the active real estate market and the acceleration of urbanization in Guangdong Province. Since the ‘12th five-year plan’ period, the energy consumption of the construction sector has steadily increased with an average annual growth rate of approximately 2.5%. In near future, the construction of the Guangdong–Hongkong–Macao Greater Bay Area will further accelerate the process of urbanization, investment, and development of infrastructure in Guangdong. Thus, the scale of construction is expected to continue to grow.

3.2.5. Transport Sector

In the medium to long term, electric vehicles and hydrogen vehicles will be greatly developed. In addition, traditional energy-saving technologies for motor vehicles will also make greater progress, and energy consumption per unit output value in the transportation sector will steadily decline. On the other hand, the improvement in household income, urban interconnection, and the growth of the rail and aviation field will continuously accelerate the total economic scale of the transportation sector.

3.2.6. Services Sector and Others

The development of urbanization and the adjustment of the industrial structure are key drivers accelerating the total scale of the services sector. Meanwhile, the large number of deployment of data centers and 5G-based stations may promote the energy consumption per unit of value added to the services sector.
3.3. Calculation of CO₂ Emissions

The total energy-related CO₂ emissions are the aggregation of two parts: direct CO₂ emissions from energy activities and indirect CO₂ emissions due to the electricity input within the administrative boundaries of Guangdong Province, as shown in Formula (1).

\[ C = C_d + C_i \]  

where \( C \) is the total energy-related CO₂ emissions, and \( C_d \) and \( C_i \) are CO₂ emissions of direct and indirect sources, respectively.

\[ C_d = C_p + C_r \]  

where \( C_r \) is the carbon emissions from the residential sector; \( C_p \) is the carbon emissions in the rest production department as shown in Figure 5.

The direct CO₂ emissions from production sectors are disaggregated in a hierarchical tree of sectors and subsectors, in which CO₂ emissions of these sectors are calculated from the energy consumption and emission factors of different energy types.

\[ C_p = \sum_i \sum_j \sum_k A_{i,j,k} \times F_{i,j,k} \]  

where \( A \) is energy consumption, \( F \) is the emission factor of each type of fossil energy; \( i, j, \) and \( k \) represent the type of fossil energy, sectors, and technology. \( G_{i,n} \) is the gross value of production of sector \( j \) in year \( n \); \( GA_{j,b} \) is the energy consumption per unit of added value for sector \( j \) in the base year; \( r_{j,n} \) is the increasing rate of energy consumption per unit of added value for sector \( j \) in year \( n \). The emission factors for coal, oil, and gas are 2.66, 1.73, and 1.56 tCO₂/t standard coal.

\[ C_r = N_n \times PA_{r,b} \times (1 + r_{r,n}) \]  

where \( N_n \) is the population in year \( n \); \( PA_{r,b} \) is the energy consumption per capita in the base year; \( r_{r,n} \) is the increasing rate of energy consumption per capita in year \( n \).

\[ C_i = \sum_e I_e \times EF_e \]  

where \( I \) is the capacity of input electricity; \( EF \) is the emission factors for input electricity; and \( e \) denotes the types of input electricity, including coal-fired, gas-fired, and non-fossil power.

4. Results

4.1. Trajectories of Energy-Related Carbon Emissions and Peak Time

The energy-related carbon emission trajectories of Guangdong Province under high, medium, and low economic growth rates during the period 2015–2035 are displayed in Figure 6. Under the condition of high economic growth as shown in Figure 6, upper, only the HSS scenario, which combines strength effort in improving the energy intensity and structure, could achieve a carbon peak by 2030, with a peak value of around 0.65 Gt in around 2027. The changes in energy structure would impose significant impacts on shaping the trajectories of CO₂ emissions. Under the HMW, HSW, and HWW scenarios, when the energy structure remains the same as in 2019, Guangdong’s carbon emissions would not reach a plateau until 2031. Specifically, the worst scenario (HWW) without improvement in both energy intensity and structure would result in a continuous increase to around 0.75 Gt CO₂ in 2035, and no decreasing trend is observed. Contrastingly, under the rest scenario with a certain level of optimization on energy structures (HMM, HSM, HWM, HMS, HWS), CO₂ emissions would reach a plateau at around 2030 and decline slowly after 2030. In addition, the impact of the energy intensity decrease rate is mainly reflected in the peak value. Under the same energy structure, when the energy intensity remains...
unchanged (HWW, HWM, HWS), the CO$_2$ peak values are 4% to 6% higher than the medium energy intensity optimization scenarios (HMM, HMS, HSS) and 5% to 8% higher than the strength energy intensity optimization scenarios (HSW, HSS, HSS), respectively.

Figure 6. CO$_2$ emission trajectories under different scenarios. (The naming method for each scenario is a combination of the mentioned three factors in the orders of economic development, energy intensity, and energy structure at different development levels. For instance, the HMW denotes the scenario of high economic combined with medium energy intensity decrease trend and weak energy structure adjustment level.)
Under the medium economic growth condition as seen in Figure 6, middle, six scenarios (MMM, MSM, MWM, MMS, MSS, MWS) could reach a plateau between 2025 and 2027 by implementing the different levels of optimization on energy structure. Specifically, in the MSS scenario, the carbon peak value is around 6.4 Gt, 1.6% less than the HSS scenario. Similar to the high-speed economic scenarios, the CO\textsubscript{2} cannot achieve a plateau or peak until 2031. Specifically, the peak value of the MWW scenario will also exceed 0.71 Gt.

The CO\textsubscript{2} emissions under the low economic scenarios show similar trajectories to the medium economic growth scenarios, with an emissions peak appearing around 2025 to 2027 under energy structure optimization scenarios. The peak carbon value of the best (LSS) and worst scenario (LWW) would further drop to around 0.61 Gt in around 2027 and 0.69 Gt in around 2031, respectively.

4.2. Carbon Emissions by Sectors

Under scenarios with medium energy intensity and structure improvement level, the energy-saving scheme and energy structure adjustment were taken into account in a moderate pathway, which reflects the conditions of carbon emissions status under the guidance of current policies. Thus, we will select the scenarios of HMM, MMM, and LMM for further analysis in the following sections.

Figure 7 illustrates the contribution of energy-related CO\textsubscript{2} emissions by sectors with medium energy intensity and structure development levels under different economic growth conditions. In general, sectoral emissions show a similar structure under different scenarios. The single largest emission contributor can be seen in the industrial sector accounting for over 55% of total CO\textsubscript{2} emissions during the research period. The industrial sector dominates the overall trend of total CO\textsubscript{2} emissions, and the CO\textsubscript{2} emissions of the industrial sector will reach a plateau/peak around 2025. The CO\textsubscript{2} emissions from transportation and services and the other sectors will also achieve their peak value in around 2030 and 2025, respectively, which strengthens the possibility of the total CO\textsubscript{2} emission peak before 2030. Unlike the above sectors, emissions from residential sectors show a continuing increase over the period. The proportion of CO\textsubscript{2} emissions from residential sectors will increase from less than 15% in 2019 to around 18% in 2035 because of the continued increase in total population and average per capita energy use. Emissions from the agricultural and construction sectors are negligible, the share of which will decrease to less than 1.5% and 2.0%, respectively in 2035.

![Figure 7. CO\textsubscript{2} emissions by industrial sectors of HMM, MMM, and LMM scenarios.](image-url)
4.3. Carbon Emissions by Energy Type

Under the medium energy intensity and structure improvement conditions, the share of carbon emissions from coal will be reduced from nearly 64% in 2010 to about 42% in 2035 in all the economic development scenarios (Figure 8). The decreasing trend of CO$_2$ from coal also dominates the overall trend of total energy-related CO$_2$ emissions. Specifically, the total carbon emissions will not achieve the peak value until the CO$_2$ from coal reaches a peak in around 2025. Instead, CO$_2$ emissions from oil will grow both in absolute terms and relative share to overall CO$_2$ emissions, accounting for around 33% in 2035, attributing to an increase in vehicle ownership as well as industrial projects. Similarly, the share of carbon emissions from gas consumption will experience a continuous increase from about 28% in 2010 to over 33% in 2035. The growth in gas consumption is mainly from the residential and industrial sectors. The carbon emissions from imported electricity will stay relatively stable, accounting for around 6–7% throughout the research period.

5. Discussions

5.1. Impact of Accelerating Wind Power Projects

CO$_2$ emissions derived from power generation accounted for about 45% of total energy-related carbon emissions in Guangdong. Since offshore wind power is the renewable energy with the most large-scale development potential in Guangdong Province, the vigorous development of offshore wind power projects has been included in the planning of Guangdong Province, which might boost the development of offshore wind projects [39]. Therefore, the sensitive analysis of accelerating the wind power installation was conducted to evaluate its impact on CO$_2$ reduction potential. As seen in Figure 9, by accelerating the installed capacity of wind power, the peak carbon emissions can be effectively reduced, and the CO$_2$ emission trajectories can be reshaped significantly. Specifically, the peak value of CO$_2$ emissions under the HMM-AW, MMM-AW, and LMM-AW scenarios is 4.7%, 5.6% and 5.8% less than the HMM, MMM, and LMM scenarios, respectively. However, the peak time kept the same as the base scenarios because coal consumption is still the dominant driver.
5.2. Impact of CO2 Emission Factor of Imported Electricity

The imported electricity in Guangdong Province mainly comes from Yunnan and Guizhou Province, where the installed capacity of clean energy accounts for a relatively high proportion [52]. Therefore, a further assessment was conducted assuming that all the imported electricity is green, as shown in Figure 10. Compared to the base scenarios, the CO2 emissions with green imported green electricity in all the economic scenarios will witness a significant decrease of around 7.1%, 7.5% and 7.8% in 2025, 2030 and 2035. Correspondingly, the peak CO2 will also drop by over 7 percentage points to less than 0.61 Gt under all the economic scenarios.

5.3. Results Comparison

Based on a top-down model, Feng and Bai [34] predict the energy consumption and carbon emission trends of Guangdong Province. The results implied that the energy-related CO2 emissions cannot peak under low energy efficiency improvement conditions for all scenarios, which is consistent with our findings. Under the standard scenario, a most realistic scenario, the CO2 will reach the peak at around 2028, with a peak value of about 6.27 Gt reported by their study, which is within our forecast range. Therefore, although different methodologies, namely, top-down and bottom-up approaches, are used to study

![Figure 9](image_url)

Figure 9. Impact of accelerating wind power on CO2 emission trajectories. (The AW indicates the scenarios with accelerating wind power projects.)

![Figure 10](image_url)

Figure 10. Impact of the imported electricity on CO2 peak value.
Guangdong’s CO₂ emissions with different scenarios and parameter settings in the above study and this study, we arrived at largely consistent conclusions and our research can be complementary to each other.

5.4. Policy Recommendation for Carbon Peak before 2030

According to Figure 6, under the weak energy intensity and structure improvement scenarios, the CO₂ emissions of Guangdong Province will not peak before 2030, even at a low economic growth rate. Therefore, the government plays an important role in the carbon emissions peak. Based on the above analysis, the following policy recommendations are given. (1) Avoid excessive growth in energy consumption. The results indicate that stronger energy structure optimization measures must be implemented to achieve the carbon peak before 2030, which will lead to great challenges regarding technology and cost perspectives. Therefore, it is necessary to control the increased rate of total energy consumption and the total energy consumption is suggested to be within 460 million standard coal by 2030. In this regard, controlling the scale of new energy-intensity projects is one of the effective and critical measures, since the growth of energy consumption in residential and tertiary industry sectors is rigid demand, which is difficult to regulate through policy measures. In addition, it is recommended to allocate the new energy-intensive projects in a timely and appropriate manner. (2) Strengthen the optimization of energy structure and promote the development of nuclear and offshore wind power. The adjustment of the final energy consumption structure is mainly reflected in the reduction and substitution of coal, especially focusing on the non-metallic mineral, paper, and textile industries. It is recommended to gradually reduce the coal consumption of non-power generation sectors and finally achieve coal consumption only in the iron, steel, and cement industries. On this basis, vigorously develop clean energy, especially nuclear and wind power. It is aiming at achieving around 90% of the increase in electricity consumption being met by clean energy by 2030. The proportion of coal, oil, and natural gas in energy consumption is suggested to be adjusted to around 22%, 25%, and 16%. (3) Promote certain cities and industries to take the lead in reaching the CO₂ peak. The Pearl River Delta region accounts for a large proportion of carbon emissions. Therefore, taking the lead in achieving carbon peaks in the Pearl River Delta region is critical for the carbon peak in Guangdong Province. It is recommended to promote some cities (Dongguan, Guangzhou, Shenzhen) in the Pearl River Delta region to reach their peak by 2025 and cities in the Western and Eastern regions by 2030. In addition, it is recommended to promote the electricity and steel industries to take the lead in proposing action plans to reach their peak by 2025. (4) Sector-wise, accelerate the development of high-tech industries and producer services to reduce the proportion of energy-intensive industries. Strengthen the action of energy efficiency benchmarking and low-carbon production certification for high energy consumption industries. Additionally, attention should be paid to the low-carbon development of transportation and buildings to avoid medium- and long-term carbon lock-in effects due to the large influx of population in the Pearl River Delta region. Thus, it is suggested to accelerate the construction of integrated intelligent and green transportation systems, and promote building energy conservation through the utilization of solar energy combined with intelligent building management. (5) Finally, this study only analyzed the energy-related CO₂ emissions for Guangdong Province; thus, further analysis should be conducted to include the CO₂ emissions from industrial processes, agricultural processes, and waste disposal. In addition, the non-CO₂ GHGs should also be evaluated to give a full scope of total GHG emissions for Guangdong Province. From a method perspective, the prediction depends on various variables, which are difficult to be predicted accurately. Top-down and bottom-up methods are recommended to be conducted based on consistent assumptions to provide comparable and comprehensive results for decision-makers. It is also deserved to conduct an in-depth analysis of the implementation cost, technical obstacles, and co-benefit impacts of the large deployment of renewable and energy-saving technologies.
6. Conclusions

As the largest economy and the first batch of the low-carbon pilot province, the research on carbon emission peak in Guangdong Province is of great importance for achieving national reduction goals in China. This study thus investigated Guangdong’s energy-related CO$_2$ emissions with scenario analysis based on the latest data and policy, which can help provide an understanding of the regional CO$_2$ peak in China and help Guangdong to develop a carbon peaking action plan.

Based on the CO$_2$ emission analysis, Guangdong Province cannot reach the emission peak before 2030 by doing nothing, even under low economic growth rate scenarios. Optimization of energy structure, or controlling the share of coal consumption, is critical to achieving the carbon peak in Guangdong. The energy-related CO$_2$ emissions will reach a plateau between 2025 and 2027 by implementing the medium and strengthening optimization of energy structure under medium and slow economic scenarios, with a CO$_2$ peak value between 0.61 and 0.64 Gt.

Sector-wise, the peak of CO$_2$ emissions will keep pace with the CO$_2$ peak in industrial sectors under medium energy intensity and structure scenarios. In addition, CO$_2$ from transportation and other tertiary industrial sectors will also experience a decreasing trend after 2030. Nevertheless, since Guangdong Province is still experiencing rapid growth in population growth, the CO$_2$ increase in residential sectors needs to be balanced by CO$_2$ mitigation in the industry and transportation sectors. Meanwhile, CO$_2$ emissions from coal consumption will still dominate the total CO$_2$ trend throughout the research period. Thus, controlling coal consumption is the key to reaching the CO$_2$ peak goal.

Overall, to achieve Guangdong’s peak target for energy-related CO$_2$ emissions, effective policies are required for both energy efficiency improvement and controlling the increase in coal consumption. The total energy consumption is suggested to be within 460 million standard coal by 2030, of which coal consumption accounts for no more than 22%. The following comprehensive supportive measures are required. The first is to vigorously develop non-fossil energy, especially for offshore wind and nuclear power to meet over 90% power increments in 2030. Second, increase the scale of imported green electricity. Third, accelerate the development of high-tech industries and take actions on low-carbon development for transportation and building sectors. Lastly, strengthening the policy measures on projects including coal-to-gas conversion in the industrial sector, the green hydrogen energy industry, carbon capture, utilization and storage, zero-carbon demonstration, green finance, and the green supply chain is required. Further study is recommended to analyze the CO$_2$ and non-CO$_2$ GHG emissions from the whole society by implementing both top-down and bottom-up methods, and paying more attention to cost, technical and environmental trade-offs, and constraints for the large deployment of low-carbon technologies.

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Abbreviations

| Abbreviation | Description |
|--------------|-------------|
| AW           | Accelerating the wind |
| H            | High |
| IO-SAD       | Input-output Structural Decomposition Analysis |
| LEAP         | Low Emissions Analysis Platform |
| LM           | Low-energy-consuming manufacturing |
| M            | Medium |
| S            | Strength |
| STIRPAT      | Stochastic impacts by regression on population, affluence, and technology |
| GDP          | Gross domestic production |
| HM           | High-energy-consuming manufacturing |
| L            | Low |
| LLM          | Labor-intensive low-energy-consuming manufacturing |
| LMDI         | Long-mean divisia index |
| MM           | Medium-energy-consuming manufacturing |
| S            | Strength |

Nomenclature

| Symbol | Description |
|--------|-------------|
| A      | Energy consumption |
| C_d    | Direct CO₂ emissions |
| C_i    | Indirect CO₂ emissions |
| C_p    | Emissions from the residential sector |
| C_r    | Emissions from production sectors |
| E      | The emission factor of fossil energy |
| G      | Gross product |
| GA     | Energy consumption per unit of added value |
| I      | The capacity of input electricity |
| P      | Population |
| PA     | Energy consumption per capita |
| r      | Increase rate |

Appendix A

Table A1. Classification of Guangdong’s manufacturing industry.

| Category                                      | Sub-Industries                                                                 |
|-----------------------------------------------|-------------------------------------------------------------------------------|
| high-energy-consuming manufacturing (HM)      | Non-ferrous metal smelting and rolling processing industry; petroleum processing, coking, and nuclear fuel processing industry; chemical raw materials and chemical products manufacturing industry. |
| medium-energy-consuming manufacturing (MM)    | Paper and paper products industry; chemical fiber manufacturing industry; textile industry; rubber and plastic products industry; wood processing and wood, bamboo, rattan, palm, and grass products industry; agricultural and sideline food processing industry. |
| Labor-intensive low-energy-consuming manufacturing (LLM) | Furniture manufacturing; textiles and garments; apparel, culture, education, art, sports and entertainment products manufacturing; leather, fur, feathers, and their products, and footwear. |
| low-energy-consuming manufacturing (LM)       | Food manufacturing industry; wine, beverage, and refined tea manufacturing industry; tobacco product industry; printing and recording media reproduction industry; pharmaceutical manufacturing industry; equipment manufacturing industry; automobile manufacturing industry; railway, ship, aerospace, and other transportation equipment manufacturing; electrical machinery and equipment manufacturing; computer, communications, and other electronic equipment manufacturing; instrumentation manufacturing; comprehensive utilization of waste resources; metal products, machinery and equipment repairing, etc. |

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