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CO_2 Emissions Forecast and Emissions Peak Analysis in Shanxi Province, China: An Application of the LEAP Model

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Abstract: Shanxi Province, an important source of coal resources in China, has consumed a large amount of fossil fuels in the past few decades. The CO_2 emissions of Shanxi Province have been increasing annually, reaching 541.8 million tons in 2018, 54.6% higher than the national mean. This will have a negative impact on China's ability to meet its target of peaking CO_2 emissions by 2030. To assist China to achieve this target and reduce CO_2 emissions in Shanxi Province, this study used the Long-range Energy Alternatives Planning (LEAP) model to analyze the CO_2 emissions and peaks in Shanxi Province from 2019 to 2035 under different scenarios. Furthermore, this study analyzed the time to peak CO_2 emissions under different emission reduction measures through a sensitivity analysis. The results show that in the absence of other mitigation policy interventions, CO_2 emissions in Shanxi Province will increase annually, reaching 1646.2 million tons by 2035. Furthermore, this study shows that if shares of industrial gross domestic product (GDP) in Shanxi, energy intensity reduction in the industrial and transport sectors compared to the base scenario, thermal power, and relative clean energy consumption reach 25%, 30%, 50%, and 50%, respectively, by 2035, then CO_2 emissions of Shanxi would peak at 801.2 million tons in 2029 and GDP per capita would increase to USD 2000 by 2035. Finally, according to the results of this study, we have made some recommendations for emission reduction in Shanxi Province. The limitation of this study was that the implementation cost of the abatement policy was not considered.

Keywords: LEAP; CO_2 emissions peak; emission reduction recommendations; Shanxi Province

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1. Introduction

1.1. Motivation

Excessive reliance on fossil fuels such as coal and oil not only places a burden on economic development, but also directly contributes to a series of environmental problems such as global warming and CO_2 emissions [1], thereby seriously constraining human security and sustainable economic and social development. Iqbal et al. [2] believe that a slight increase in air pollution could lead to a dramatic increase in the number of cases and deaths in NCOV-2019. In fact, the issue of CO_2 emissions has become a serious threat at the international level, and low-carbon green development has become the goal of all countries [3].

After nearly four decades of rapid economic development, China has consumed a large amount of fossil fuels and produced enormous CO_2 emissions [4]. A study by the International Energy Agency (IEA) shows that China overtook the United States (U.S.) as the world's largest CO_2 emitter in 2007 [5], for which CO_2 emissions are increasing annually, and accounted for 28.8% of global CO_2 emissions in 2019 [6]. As a responsible power, the Chinese government has set a series of emission reduction targets to address global climate issues [7]. In 2015, China's government announced that China would peak CO_2 emissions before 2030 and reduce 60–65% of CO_2 emissions intensity compared to 2005 [8]. At the 75th Session of the UN General Assembly on 22 September 2020, Chinese President Xi Jinping announced that China would strive to peak its CO_2 emissions before 2030 and achieve carbon neutralization by 2060 [9]. To meet this commitment, 31 Chinese provinces have set CO_2 reduction targets by 2030 [10]. Many factors affect CO_2 emissions, and the characteristics of CO_2 emissions vary among provinces because of differences in geographical location, economic development level, industrial structure, etc. [11]. Therefore, it is necessary to study emission reduction measures and policies to achieve regional low-carbon economic development goals at the provincial level, which requires accurate forecasting of CO_2 emission trends in each province.

As an important source of coal resources in China, Shanxi Province plays a crucial role in promoting China's economic development [12]. However, Shanxi Province has also consumed a large amount of fossil fuels and produced enormous CO_2 emissions in the past few decades. In 2018, the CO_2 emissions of Shanxi Province reached 541.8 million tons, which is 54.6% higher than the national mean [13]. In the context of carbon peaking and neutrality, in the "14th Five-Year Plan for National Economic and Social Development", the Shanxi provincial government declared that Shanxi Province will develop a low-carbon economy in the following ways [14]: (1) by establishing a green and diversified energy supply system; (2) by building a green low-carbon consumption system; and (3) by enhancing the level of energy openness and cooperation by joining the Beijing-Tianjin-Hebei Energy Collaborative Development Initiative. Therefore, in order to alleviate the contradiction between regional economic development and environmental protection, achieve the goal of carbon peak and carbon neutrality, and promote sustainable socio-economic development, there is an urgent need to accurately predict the peak of CO_2 emissions in Shanxi Province and prepare effective emission reduction recommendations.

1.2. Literature Review

In recent years, much research has focused on energy demand and CO_2 emissions, of which a number of studies formulated top-down models from a macro perspective [15–21]. Alajmi [15] studied the factors that affect greenhouse gas (GHG) emissions in nine sectors by using the logarithmic mean deivisia index (LMDI) method for 1990–2016 in Saudi Arabia, and the analysis showed that the energy effects are a major factor in increasing GHG emissions and activity, and that energy and population effects are greater in the electricity sector than in the transport sector. Gu et al. [16] integrated the extended logarithmic mean divisia index (LMDI) model and the system dynamics (SD) model to explore the determinants of CO_2 emission change during 1995–2016 and predict the emission mitigation potential from 2016 to 2030 in Shanghai, China. The results showed that energy intensity and GDP per capita are the main positive and negative driving forces on carbon emissions mitigation and that the CO_2 emissions and emission per capita would peak by 2025 in Shanghai. Liu et al. [19] used China as an example and studied the main factors of carbon emissions in the transport sector using the LMDI approach combined with the C–D production function. These results showed that from 2001 to 2018, the key factor affecting carbon emissions in China's transportation sector was the capital input effect, followed by the energy structure effect, with the labor input effect being the weakest. Zhang et al. [20] developed the traditional computable general equilibrium (CGE) model of nuclear power and input China's economy into a dynamic general equilibrium model to comprehensively evaluate and compare the effects of different nuclear policies under the same background. The results showed that government subsidies have the greatest impact on nuclear power generation, and that energy taxes have the greatest impact on CO_2 emission reduction. Xiao et al. [21] established a CGE model to explore the impacts of energy efficiency, energy mix, and economy structure on the economy and CO_2 emissions in China; this study found that the decline of secondary industry can cause an emission reduction effect, but that this could sacrifice GDP, whereas the development of a tertiary industry can boost the economy and assist in reducing CO_2 emissions. However, although these models can analyze and predict the carbon emissions of a particular region or sector, they all focus on the macro perspective and do not fully consider the technical energy-saving factors [22].

Several studies have developed bottom-up models from the perspective of energy alternatives and advances in energy-saving technologies [23–27]. Leo et al. [23] used GDP and total population as independent variables to determine the energy demand trends over a long-term horizon in end-use sectors using a TIMES model. Musonye et al. [25] developed a new national-scale, bottom-up energy system optimization model referred to as the Kenya-TIMES model to evaluate the implications of GHG emissions reduction on the techno-economic and environmental evolution of Kenya's power system during the period from 2020 to 2045. The results show that in order to meet its emission reduction targets, the Kenyan government needs to develop and implement policies to enhance the use of renewable energy technologies. Jaskólski [26] studied the impact of the European Union (EU) Emission Trading Scheme (EUETS) for CO_2 combined with SO_2 and NOx emission trading mechanisms on power technology choice by using the market allocation (MARKAL) model of the Polish power system. The results show that high emission allowance prices will lead to decarbonization of electricity production. Nieves et al. [27] used the Long-range Energy Alternatives Planning System (LEAP) software to analyze the energy demand and greenhouse gas (GHG) emissions produced in Colombia with two future scenarios (positive and negative). These models considered the influence of technology factors on energy demand and CO_2 emissions; however, detailed data on the technology are required.

LEAP is an energy and environmental accounting tool based on scenario analysis that was developed by the Stockholm Environment Agency [28]. It can record the energy consumption, production, and resource extraction of all sectors in an economy [27]. In addition, LEAP can be used for the long-term forecasting of energy demand and related environmental issues in energy planning [29,30]. Therefore, the LEAP model is widely used to study energy demand, GHG emissions, and energy policy making in different regions and sectors [31]. For example, in terms of predicting regional energy demand and GHG emissions, Dong et al. [32] established a bottom-up accounting framework and used the LEAP energy modeling tool to forecast the future of China's energy consumption structure under three scenarios. According to the estimates, China's total energy consumption will increase to 4470 Mtoe (million tons oil equivalent) in 2040 under the current policies scenario, 4040 Mtoe in 2040 under the moderate policies scenario, and 3320 Mtoe in 2040 under the strong policies scenario. Mirjat et al. [33] forecasted the long-term electricity demand and supply for Pakistan (2015–2050) to analysis the policy implementation by using LEAP model. The model results estimate the demand forecast of 1706.3 Tera Watt Hours in 2050, which is 19 times higher than the base year demand. Emodi et al. [29] applied a scenario-based analysis to explore Nigeria's future energy demand, supply, and associated GHG emissions from 2010 to 2040 using the LEAP model. The results found that more aggressive policy intervention by the Nigerian government, as in a green optimistic scenario (GO), would lead to a decrease in energy demand (2249 Petajoule) and GHG emissions (124.4 million tons) in 2040. Kumar and Madlener [34] examined the effects of renewable energy use in electricity supply systems and used the LEAP model to estimate CO_2 emissions by developing various scenarios using the least cost approach. The results show that in an accelerated renewable energy technology (ARET) scenario, 23% of electricity is generated by renewables only, and 74% of CO_2 reduction is possible by 2050. Many studies have used the LEAP model to study energy demand, GHG emissions, and energy planning policy in various sectors. For example, Hernandez and Fajardo [28] used the LEAP software to estimate air pollutant emissions from fixed sources in Bogota D.C., projected to the year 2050. Under the three scenarios, Hernandez and Fajardo [28] also estimated the variation of emissions for different assumptions of industrial energy matrixes, providing proposals for emissions reduction in the city. Jiao et al. [35] used Guangzhou as a case study city to quantitatively analyze the co-benefits of reducing CO_2 and air pollutant emissions under a sustainable scenario in the transport sector by developing a quantitative analysis model based on the LEAP framework. The model results in significant co-benefits for the development of adjusted transportation modes and electrification, and fewer co-benefits for promoting the use of LNG vehicles and ships. Katta et al. [36] developed a bottom-up integrated resource planning model for oil sand extraction and upgrading processes; this model is a novel application of an energy accounting-based framework and accurately simulates the energy demand and supply in oil sands from 2007 to 2050. The assessment using this model shows that Canadian oil sands have an annual average of 7.6 million tons of GHG emissions that could be mitigated, and that 65% of the GHG reduction potential comes from institution extraction. Maduekwe et al. [37] employed the LEAP model to project future energy demand and GHG emissions to determine the most efficient A-S-I ("Avoid", "Shift", and "Improve") scenario for the city. The research concluded that the largest obstacle to Lagos meeting its emission reduction targets is the very old vehicles on its roads. Furthermore, the model data show that from 2020 to 2032, Lagos may not meet its 50% reduction target unless its vehicle life limit is reduced from 40 years to 22 years, its vehicle growth rate is reduced from 5% to 2%, and its mileage increases by 2% per year.

1.3. Objectives

Based on the aforementioned literature, many studies have been conducted to predict CO_2 emissions. Most of the research has studied CO_2 emissions at the national or sectoral level, and only a few researchers have studied peak CO_2 emissions at the provincial level [38]. However, it is worth noting that the differences in geographic location, environment, and economic development of different provinces lead to different characteristics of CO_2 emissions in each province [11]; therefore, the conclusions obtained from studying CO_2 emissions only from national and sectors perspectives cannot be well adapted to the emission reduction of each region. To fill this gap, this paper proposes a bottom-up model for predicting and analyzing the peak of CO_2 emissions for Shanxi Province based on LEAP. Compared to top-down models, this model allows for a more comprehensive and detailed study of the energy demand and carbon emissions of regional sectors at the micro level, such as technology [38], and thus is more conducive to the study of energy conservation and emission reduction issues at the provincial level. The objectives of this study were as follows:

(1) Forecast the CO_2 emission trends in Shanxi Province from 2019 to 2035 under different scenarios and identify the conditions for achieving the goal of reaching the CO_2 emissions peak in 2030.
(2) Analyze the impacts of different levels of economic development, industrial structure, energy intensity, and power supply structure on the time of reaching CO_2 emissions peak in Shanxi Province through sensitivity analysis.
(3) Propose relevant proposals for emission reduction in Shanxi Province based on the results of the analysis described in (1) and (2).

The remainder of this paper is organized as follows: Section 2 introduces the construction of the Shanxi-LEAP model, including the model framework, data sources, scenario settings, and parameter settings for sensitivity analysis; Section 3 discusses the results of the Shanxi-LEAP model, including CO_2 emissions in Shanxi Province between 2019 and 2035 under different scenarios and the sensitivity of different factors to peak CO_2 emissions; and Section 4 presents the conclusions and relevant policy recommendations for energy conservation and emission reduction in Shanxi Province.

2. Proposed Model

2.1. Framework

This paper proposes a LEAP model to forecast and analyze future CO_2 emissions and the time of reaching the CO_2 emissions peak in Shanxi Province (abbreviated as the Shanxi-LEAP model). As shown in Figure 1, this model consists of three modules: Final energy demand, energy conversion, and scenario setting. Given the accessibility and applicability of data information, we divided the module of final energy demand into six sectors: agriculture, industrial, building, transport, service, and residential. The energy conversion module consists of four sectors: coking, heating, oil refining, and thermal power generation (including electric transportation losses). There are 12 types of energy consumed by sectors: raw coal, washed coal, coke, coke oven gas, other coal products, crude oil, gasoline, diesel, other petroleum products, natural gas, heat, and electricity. In the scenario setting module, we set up a base scenario (BS) and a comprehensive scenario (CS). Then, a sensitivity analysis of the peak CO_2 emissions in Shanxi Province under the CS was conducted for four parameter types: economic development level, industrial structure, energy intensity, and power supply structure.

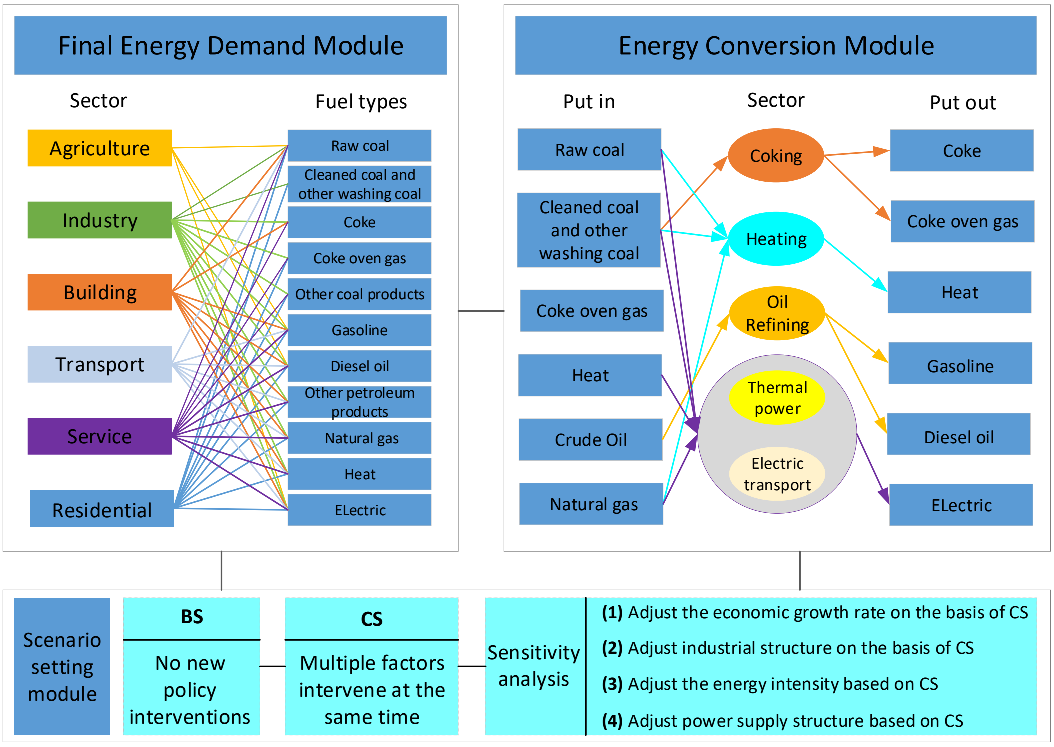

Figure 1. Shanxi long-range energy alternatives planning (Shanxi-LEAP) model framework. BS—base scenario, CS—comprehensive scenario.

Total CO_2 emissions consist of two parts and can be calculated as follows:

$$CE_T = CE_f + CE_c \tag{1}$$

where CE_T is the total CO_2 emissions and CE_f and CE_c are the CO_2 emissions from the final energy demand and energy conversion, respectively.

The CO_2 emissions of final energy demand is calculated by:

$$CE_f = \sum_i \sum_j AL_i \times EI_i \times \theta_{ij} \times EF_j \tag{2}$$

where AL_i is the level of activity in sector i, representing GDP in sectors of agriculture, industry, building, transport, and service as well as the population in the residential sector; EI_i is the energy intensity of sector i; θ_{ij} is the ratio of the demand for j energy in sector i to the total energy demand in sector i; and EF_j is the CO_2 emission factor of fuel type j.

The CO_2 emissions of energy conversion are calculated by:

$$CE_c = \sum_m \sum_t \sum_j \frac{ETO_{t\ m}}{f_{j\ m\ t}} \times EF_j \tag{3}$$

where *ETO* is the production of energy conversion, *f* is the transformation efficiency, *EF* is the CO_2 emissions factor, *m* represents the energy conversion modules, and *j* and *t* represent the fuel type of consumption and production in energy transformation, respectively.

2.2. Data Sources

The input parameters for the Shanxi-LEAP model included data on GDP per capita, industrial structure, population, energy intensity, and energy consumption structure. These data can be obtained from: (1) official government reports, such as the "Shanxi Provincial Statistical Yearbook" [39], the "China Energy Statistical Yearbook" [40], National Population Development Plan (2016–2030) [41], and the "Outline of the 14th Five-Year Plan and 2035 Visionary Goals for the National Economic and Social Development of Shanxi Province" [14]; (2) published research literature; and (3) research reports published by relevant institutions, such as the World Bank Open Data [6], China Energy and Electricity Development Planning Study 2030, and Outlook 2060 [42].

To facilitate analysis and ensure comparability after data collection, data expressed in the various units of different fuels were converted to the same units in this study; for example, energy consumption was expressed in million tons of standard coal. In addition, considering data availability, this study used 2019 as the base year to analyze the trends and peaks of CO_2 emissions for Shanxi Province.

2.3. Scenario Setting

2.3.1. Base Scenario (BS)

In this scenario, no new policies for reducing CO_2 emissions were implemented, leaving the energy demand and CO_2 emissions of Shanxi Province to evolve naturally under the current policy conditions. The Shanxi Provincial Government stated in the Shanxi Development and Reform Commission [14] that the visionary goal for Shanxi Province in 2035 is to reach a per capita GDP of USD 20,000 and achieve basic socialist modernization in tandem with the nation [43]. Therefore, the BS assumed that GDP per capita in Shanxi Province will increase at a mean annual rate of 6.7% from 2019 to 2035 to reach RMB 129,358 (converted to USD 20,000) in 2035. According to the Shanxi Statistic Bureau [43], the resident population of Shanxi Province has accounted for approximately 2.66% of the national total resident population since 2010. To facilitate the study, the BS assumed that the resident population of Shanxi Province will remain at this ratio with the national resident population from 2019 to 2035. Considering that China's resident population is expected to peak in approximately 2030 [41], the BS assumed that the population of Shanxi Province will also peak in 2030. The industrial structure of Shanxi Province, the energy intensity of each sector, and the energy consumption structure of each sector were determined by extrapolating the trend from historical data [39,40]. The conversion rate of each energy conversion sector was calculated based on the "Energy Balance of Shanxi Province in the China Energy Statistical Yearbook" [40] and data obtained from the "Shanxi Statistical Yearbook" [39]. The detailed parameter settings of the BS are shown in Table 1, and the structure of energy consumption by sector in Shanxi Province under the BS is shown in Appendix A.

Table 1. Detailed parameter settings of gross domestic product (GDP), resident population, and the energy intensity and GDP share of sectors in the base scenario (BS) and comprehensive scenario (CS).

Parameter Settings	Base Year	BS		CS	
	2019	2030	2035	2030	2035
GDP per capita (RMB 10,000)	4.58	10.26	12.94	10.26	12.94
Resident population (million)	37.21	37.56	37.36	37.56	37.36
Energy intensity for sectors	**2019**	**2030**	**2035**	**2030**	**2035**
Agricultural	0.26	0.29	0.29	0.29	0.29
Industrial	1.63	1.78	1.78	1.36	1.24
Building	0.15	0.15	0.15	0.15	0.15
Transport	1.02	1.03	1.03	0.82	0.72
Services	0.09	0.10	0.10	0.10	0.10
Residential	0.34	0.33	0.33	0.33	0.33
GDP share (%) for sectors	**2019**	**2030**	**2035**	**2030**	**2035**
Agricultural	5.14	5.28	5.28	4.36	4.00
Industrial	38.58	37.21	37.23	29.24	25.00
Building	5.26	5.81	5.80	5.08	5.00
Transport	5.91	6.40	6.40	5.97	6.00
Services	45.11	45.30	45.29	55.35	60.00

The units of energy intensity for sectors are 10,000 tons standard coal/10,000 yuan.

2.3.2. Comprehensive Scenario (CS)

This scenario aimed to analyze the trend and peak of CO_2 emissions in Shanxi Province by considering multiple emission reduction measures. The first measure was the optimization of industrial structure, which reduces the GDP share of energy-intensive sectors (such as industry and transport) while increasing the GDP share of services. Using developed economies as a reference [6], the CS assumed that the GDP share of the service sector of Shanxi Province will reach 60% by 2035, while the GDP shares of the industry and transportation sectors will decrease to 25% and 5%, respectively. The shares of agriculture and the building sector will also decrease slightly. The second measure was the restructuring of energy consumption in the different final energy demand sectors. It assumed that the share of consumption of relatively clean energy sources such as natural gas, heat, and electricity will exceed 50% by 2035. The third measure was the implementation of energy conservation policies and incentives, with the aim of improving energy use efficiency and reducing the energy intensity of the industry and transport sectors. Specifically, the CS assumed a 30% reduction in the energy intensity of the industrial and transport sectors in Shanxi Province by 2035 compared with that in the BS. The fourth measure was the optimization of the power supply structure. According to the "China Energy and Electricity Development Planning Study 2030 and Outlook 2060" [42], the installed capacity of thermal power in China is expected to be reduced to 27.6% by 2030. However, considering that the current thermal power generation in Shanxi Province accounts for a relatively large proportion (88.1% in 2019) [40], we assume that the installed capacity of thermal power in Shanxi Province will decrease to 50% by 2035. Other parameters were set in line with the BS. The detailed parameter settings for the CS are shown in Table 1, and the structure of energy consumption by sectors in Shanxi Province under the CS is given in Appendix A.

2.4. Sensitivity Analysis

The sensitivity analysis was based on the CS and aimed to analyze how changes in the economic development level, industrial structure, energy intensity, and power supply structure affect the trend and peak of CO_2 emissions in Shanxi Province.

(1) Economic Development Level

The CS assumed a mean annual growth rate of 6.7% in GDP per capita from 2019 to 2035. To analyze the impact of different levels of economic development on the trends and peaks of CO_2 emissions, two additional scenarios were considered. The first was the high GDP scenario, which assumed a mean annual growth rate of 7.7% in GDP per capita from 2019 to 2035, reaching USD 23,000 by 2035, denoted by $CS_{high-GDP}$. The second was the low GDP scenario, which assumed a mean annual growth rate of 5.7% in GDP per capita from 2019 to 2035, reaching USD 17,000 by 2035, denoted by $CS_{low-GDP}$. The settings of the other parameters for $CS_{low-GDP}$ and $CS_{high-GDP}$ were the same as those for the CS.

(2) Industrial Structure

The CS assumed a 25% GDP share of the industrial sector in 2035. The impact of different industrial structures on the trend and peak of CO_2 emissions was investigated by adjusting the GDP share of the industrial sector. CS_{IS-20}, $CS_{IS-22.5}$, CS_{IS-25}, $CS_{IS-27.5}$, and CS_{IS-30} denoted the scenarios in which the GDP shares of the industrial sector in 2035 were 20%, 22.5%, 25%, 27.5%, and 30%, respectively. The GDP shares of the other sectors under the different scenarios are shown in Table 2. The settings of the other parameters for these scenarios were set the same as for the CS; therefore, CS_{IS-25} corresponded to the CS.

(3) Energy Intensity

The CS assumed that the energy intensity of the industrial and transport sectors in 2035 will be 30% lower than that under the BS. To analyze the impact of different levels of energy intensity on the trend and peak of CO_2 emissions, we set the value of this ratio to vary from 20% to 40% in 5% increments, resulting in five different scenarios, denoted by CS_{EI-20}, CS_{EI-25}, CS_{EI-30}, CS_{EI-35}, and CS_{EI-40}. The settings of the other parameters for these scenarios were the same as those for the CS; therefore, CS_{EI-30} corresponded to the CS.

(4) Power Supply Structure

The CS assumed a 50% installed capacity of thermal power in 2035. The impact of different power supply structures on the trend and peak of CO_2 emissions was analyzed by varying the installed capacity of thermal power from 40% to 60% in 5% increments, leading to five different scenarios: CS_{PS-40}, CS_{PS-45}, CS_{PS-50}, CS_{PS-55}, and CS_{PS-60}. The settings of the other parameters for these scenarios were the same as those for the CS; therefore, CS_{PS-50} corresponded to the CS.

Table 2. Parameter settings for major years of gross domestic product (GDP) share by sector under the comprehensive scenario (CS) and CS_{IS}.

Sector GDP Ratio (%)	2019	2030					2035				
	Base Year	CS_{IS-20}	$CS_{IS-22.5}$	CS_{IS-25}	$CS_{IS-27.5}$	CS_{IS-30}	CS_{IS-20}	$CS_{IS-22.5}$	CS_{IS-25}	$CS_{IS-27.5}$	CS_{IS-30}
Agriculture	5.1	4.4	4.4	4.4	4.4	4.4	4.0	4.0	4.0	4.0	4.0
Industrial	38.6	25.8	27.5	29.2	31.0	32.7	20.0	22.5	25.0	27.5	30.0
Building	5.3	5.1	5.1	5.1	5.1	5.1	5.0	5.0	5.0	5.0	5.0
Transport	5.9	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
Service	45.1	58.8	57.1	55.3	53.6	51.9	65.0	62.5	60.0	57.5	55.0

3. Results

3.1. CO_2 Emission Trends under the BS and CS

The computation results of the Shanxi-LEAP model for the BS during the period from 2019 to 2035 are shown in Figure 2a. These results showed a gradually increasing annual trend of total CO_2 emissions in Shanxi Province, reaching 1646.2 million tons in 2035 with an increase of 1065.4 million tons from 2019. Under the BS, the CO_2 emissions of different final energy demand sectors (agriculture, industry, building, transportation, service, and residential) and different energy conversion sectors (thermal power, heat supply, coking, and oil refining) will continue to increase. The CO_2 emissions of different sectors in Shanxi Province will decrease from industry > thermal power > coking > heat supply > oil refining > transportation > service > residential > agriculture > building, reaching 621.6, 431.4, 279.8, 116.8, 72.7, 58.2, 30.4, 15.4, 13.5, and 6.6 million tons in 2035, respectively.

Figure 2b depicts the CO_2 emissions trends in Shanxi Province under CS during 2019–2035, when the CO_2 emissions growth rate in Shanxi Province will decrease annually. Total CO_2 emissions will peak at 801.2 million tons in 2029 and then decline to 749.9 million tons in 2035. In comparison, the total CO_2 emissions of Shanxi Province in 2029 and 2035 under the BS will be 12578.0 and 1646.2 million tons, respectively. The results showed that the combined effect of multiple emission reduction measures (as mentioned previously) can significantly slow down the CO_2 emissions growth rate in Shanxi Province. In addition, we also conclude that by 2035, if the industrial GDP share in Shanxi Province is reduced to 25%, energy intensity in the industrial and transport sectors will be reduced by 30% compared to that in the BS scenario. Furthermore, the share of thermal power generation will be reduced to 50%, and that of relatively clean energy consumption, such as natural gas and electricity, will exceed 50%. Consequently, Shanxi will be able to achieve the target of peaking CO_2 emissions by 2030 as scheduled, and will also be able to achieve the goal of maintaining GDP at a mean annual growth rate of 6.7%.

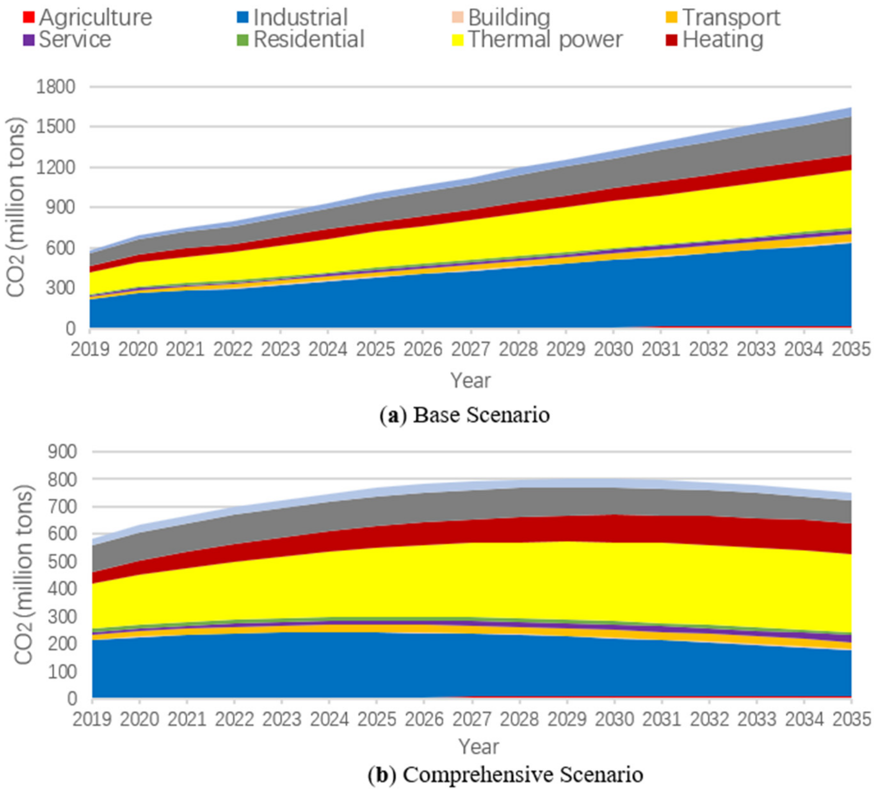

Figure 2. CO_2 emission trends in Shanxi Province under the base scenario (BS) and comprehensive scenario (CS) from 2019 to 2035.

In addition, as Figure 2b shows, the CO_2 emissions will peak earlier for most sectors in Shanxi Province under the CS than under the BS. In the final energy demand modules, the CO_2 emissions of the agriculture, industrial, and transport sectors will peak at 6.2 million tons in 2031, 235.5 million tons in 2024, and 27.8 million tons in 2033; residential CO_2 emissions will decrease annually, and the building and service sectors will not reach peak CO_2 emissions. In energy conversion modules, the CO_2 emissions of oil refining, coking, and thermal power sectors will peak at 31.0 million tons in 2028, 110.1 million tons in 2025, and 290.9 million tons in 2032, and the heating sector will not reach peak CO_2 emissions. This indicates that the peak of CO_2 emissions will occur earlier in most sectors with higher carbon emission intensity in Shanxi Province (such as industrial, coking, and oil refining) under the combined effect of multiple emission reduction measures. Moreover, although the CO_2 emissions from the industrial and coking sectors in 2019–2035 continue to be large, they have exhibited a clear downward trend, and the energy conversion sector, mainly thermal power generation and heat supply, has had an increasing impact on total CO_2 emissions in Shanxi Province.

3.2. Sensitivity Analysis to Peak CO_2 Emissions under the CS

(1) Economic Development Level

Figure 3 shows the trends of total CO_2 emissions in Shanxi Province under different economic development levels based on the CS from 2019 to 2035. The total CO_2 emissions will peak at 898.7 million tons in 2030 under $CS_{high-GDP}$, and then decline to 856.5 million tons in 2035. In comparison, the total CO_2 emissions under $CS_{low-GDP}$ will peak in 2028 at 709.2 million tons and then decrease to 643.4 million tons by 2035. The results show that reducing the mean annual growth rate of GDP per capita in Shanxi Province can significantly reduce the total CO_2 emissions and advance the time of peaking CO_2 emissions. Since the GDP growth rate with the economic status and development level of a country or region are positively correlated, it is not recommended that the economic development level be suppressed in order to reduce CO_2 emissions. As an alternative, we should include "carbon peaking and carbon neutral" as one of the main decision-making factors to reasonably set the medium- and long-term GDP growth targets of Shanxi Province and formulate corresponding economic development strategies.

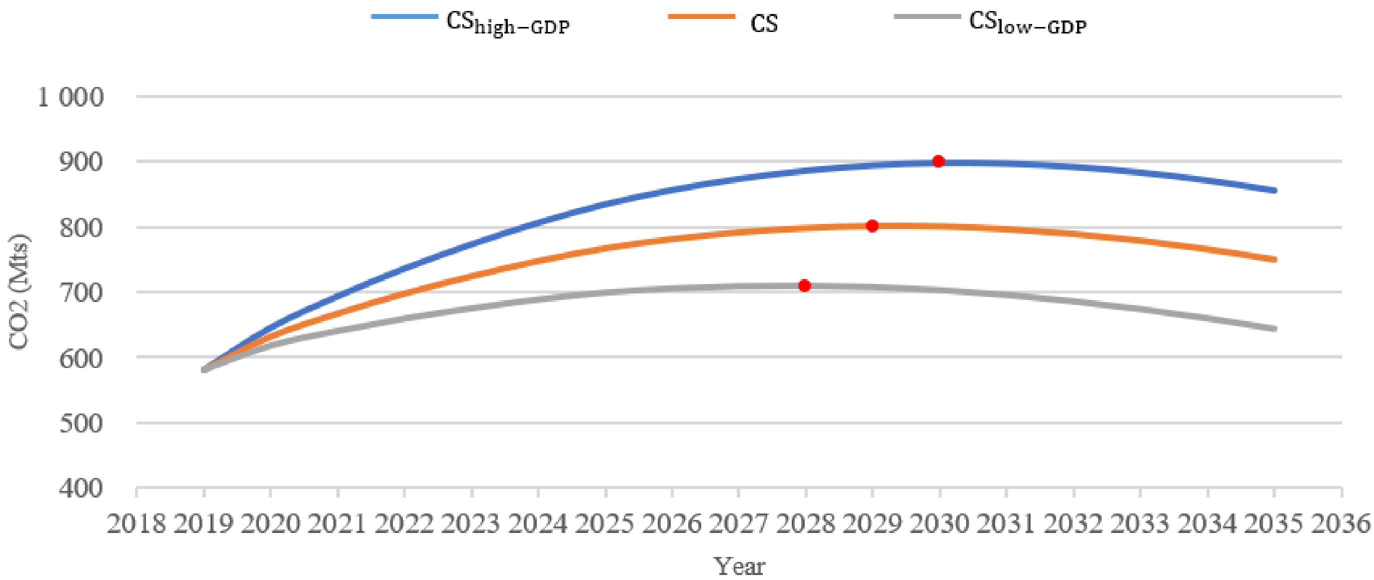

Figure 3. Development of total CO_2 emissions under different economic development level based on the comprehensive scenario (CS). $CS_{high-GDP}$—high GDP scenario, $CS_{low-GDP}$—low GDP scenario.

(2) Industrial Structure

Figure 4 displays the trend of total CO_2 emissions in Shanxi Province under different industrial structures based on the CS from 2019 to 2035. It can be seen that the total CO_2 emissions under CS_{IS-20} and $CS_{IS-22.5}$ are both lower than that under the CS (i.e., CS_{IS-25}). CS_{IS-20} (or $CS_{IS-22.5}$) will peak at 747.2 (or 772.5) million tons of total CO_2 emissions in 2027 (or 2028), and then decline to 652.9 (or 701.4) million tons by 2035. In comparison, the total CO_2 emissions under $CS_{IS-27.5}$ and CS_{IS-30} were higher than those under the CS. $CS_{IS-27.5}$ (or CS_{IS-30}) will reach a peak of 833.2 (or 868.3) million tons of total CO_2 emissions in 2030 (or 2031), which will then decrease to 798.5 (or 847.0) million tons in 2035. The results highlight that shifting the GDP share of industry to services can effectively reduce CO_2 emissions in Shanxi Province and advance the time of peaking CO_2 emissions. Using the CS as a reference, each additional 2.5% shift in industrial sector GDP to services would advance the peak CO_2 emissions in Shanxi by 1 year, and result in the reduction of CO_2 emissions by 48.53 million tons by 2035.

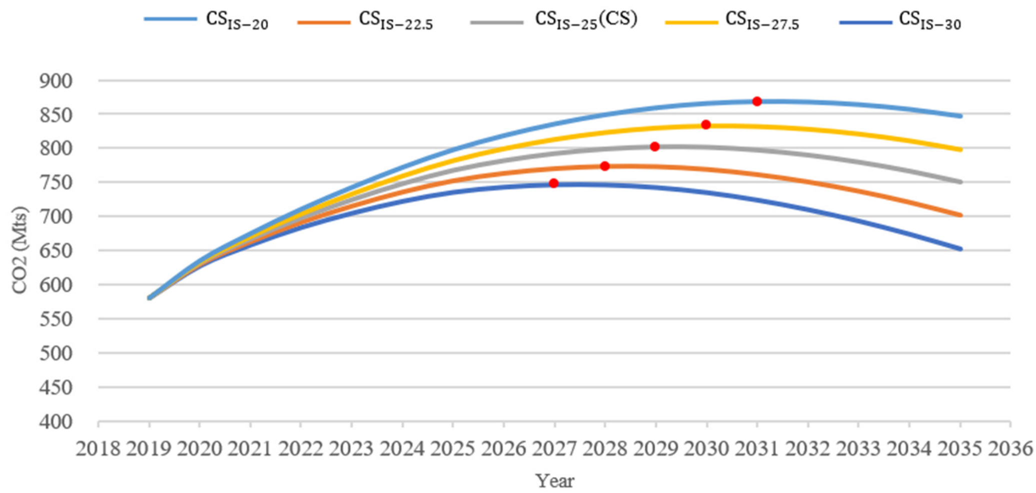

Figure 4. Development of total CO_2 emissions under different industrial structures based on the comprehensive scenario (CS). CS_{IS-x}—assumes a x% GDP share of the industrial sector in 2035.

(3) Energy Intensity

Figure 5 shows the total CO_2 emissions trend in Shanxi Province under different energy intensities based on the CS from 2019 to 2035. It can be seen that the total CO_2 emissions under CS_{EI-20} and CS_{EI-25} are both higher than those under the CS (i.e., CS_{EI-30}). CS_{EI-20} (or CS_{EI-25}) will peak at 860.9 (or 830.0) million tons of total CO_2 emissions in 2031 (or 2030), and then decline to 834.1 (or 792.0) million tons by 2035. In contrast, the total CO_2 emissions under CS_{EI-35} and CS_{EI-40} are lower than those under the CS. CS_{EI-35} (or CS_{EI-40}) will peak at 774.8 (or 751.3) million tons of total CO_2 emissions in 2029 (or 2028), and then decline to 707.9 (or 665.8) million tons by 2035. The results show that strengthening the implementation of energy conservation policies to decrease the energy intensity of high carbon emissions, such as those from industrial and transport sectors, can significantly reduce CO_2 emissions in Shanxi Province and advance the time of peaking CO_2 emissions. Using the CS as a reference, for every 5% reduction in the proportion of decline in energy intensity of industrial and transport sectors compared with BS, the time to peak CO_2 emissions in Shanxi Province will occur 1 year later, and CO_2 emissions will increase by 42.07 million tons by 2035.

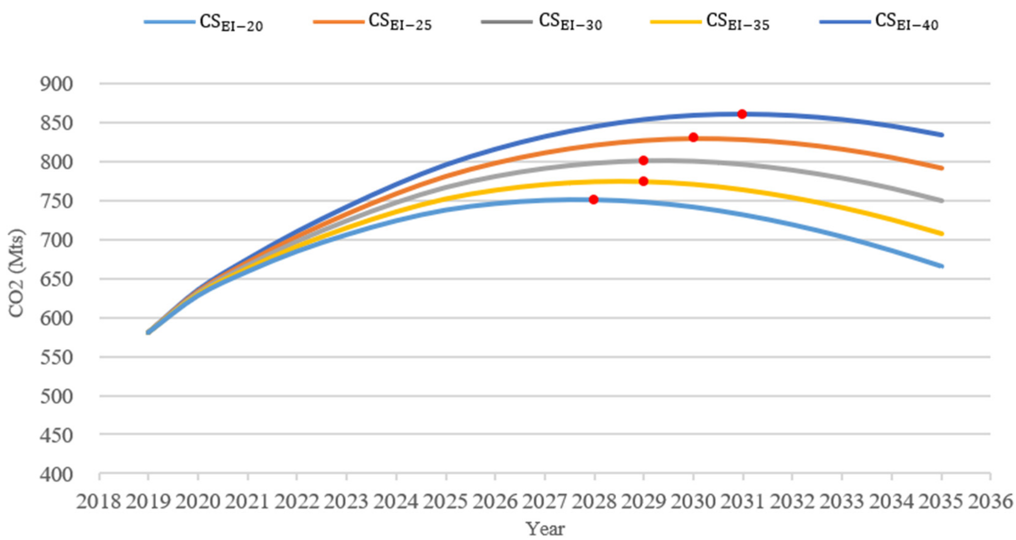

Figure 5. Development of total CO_2 emissions under different energy intensity of sectors based on the comprehensive scenario (CS). CS_{EI-x}—assumes that the energy intensity of the industrial and transport sectors in 2035 will be x% lower than that under the BS.

(4) Power Supply Structure

Figure 6 presents the total CO_2 emissions trend in Shanxi Province under different power supply structures based on the CS from 2019 to 2035. The total CO_2 emissions under CS_{PS-40} and CS_{PS-45} are both lower than those under the CS (i.e., CS_{PS-50}). CS_{PS-40} (or CS_{PS-45}) will peak at 773.7 (or 786.8) million tons of total CO_2 emissions in 2028 (or 2029), and then decline to 690.9 (or 720.4) million tons by 2035. In comparison, the total CO_2 emissions under CS_{PS-55} and CS_{PS-60} are higher than those under the CS. CS_{PS-55} (or CS_{PS-60}) will reach a peak of 817.3 (or 834.5) million tons of total CO_2 emissions in 2030 (or 2031), and then decrease to 779.5 (or 809.0) million tons in 2035. The results highlight that reducing the proportion of thermal power generation in the power supply structure can effectively reduce CO_2 emissions in Shanxi Province and significantly accelerate the peak of CO_2 emissions. Using the CS as a reference, for every 5% increase in the share of thermal power generation in 2035, the peak of CO_2 emissions in Shanxi Province will occur 1 year later, and CO_2 emissions will increase by 29.51 million tons by 2035.

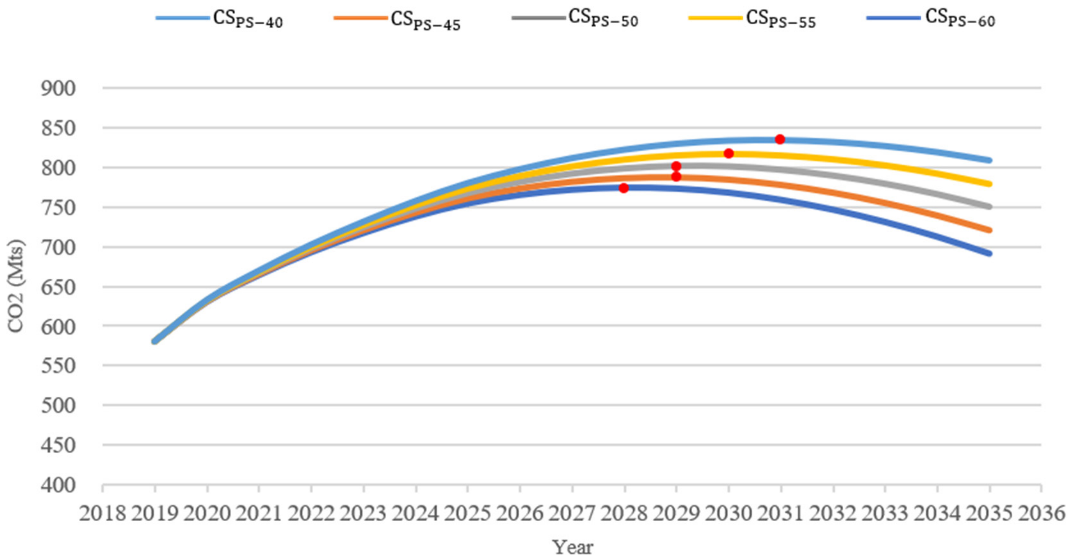

Figure 6. Development of total CO_2 emissions under different power supply structure based on the comprehensive scenario (CS). CS_{PS-x}—assumes a x% installed capacity of thermal power in 2035.

4. Conclusions

In this study, the CO_2 emissions and the time of peaking CO_2 emissions in Shanxi Province were estimated using the LEAP model under different scenarios from 2019 to 2035. The main findings are summarized as follows:

(1) In terms of total CO_2 emissions and the time to peak emissions, under the condition that no other energy policies are adopted (i.e., the BS), CO_2 emissions in Shanxi Province will continue to increase, reaching 1646.2 million tons by 2035, and will not peak in 2019–2035. Under the comprehensive effect of the factors mentioned in the paper (i.e., the CS), the growth rate of CO_2 emissions in Shanxi Province will slow down significantly and peak at 801.2 million tons in 2029 before decreasing to 749.9 million tons in 2035. The peak time was earlier than that in most of the scenarios for Guangdong Province in the study by Ren et al. [44], and the value of the peak was lower than the peak of Guangdong Province (984.78 million tons) in the Ren et al. [44] study. The results of the CS analysis suggest that for Shanxi Province to reach peak CO_2 emissions by 2030 without sacrificing economic development, the share of GDP in the industrial sector for Shanxi Province needs to decrease to <25% by 2035 (through a shift to services), the share of relatively clean energy consumption (such as natural gas and electricity) needs to exceed 50%, energy intensity in the industrial and transport sectors needs to be reduced by 30% compared to that in the BS, and the share of thermal power generation needs to be reduced to <50%. Therefore,

we conclude that Shanxi Province can achieve the goal of "carbon peaking" on schedule without sacrificing regional economic development, but it requires the concerted efforts of all sectors. For example, the industrial sector should consider accelerating the elimination of backward production capacity, strictly limiting the expansion of high energy consuming industries, shifting the industrial sector's GDP to high-tech industries as appropriate, and striving to reduce the industrial sector's GDP share to 25% by 2035. Policy makers should consider moderately increasing clean energy promotion and subsidies, optimizing the energy consumption structure, and striving to reach more than 50% of relatively clean energy consumption such as natural gas and electricity by 2035. At the same time, government investment departments should consider increasing investment in research and development of emission reduction strategies for sectors with high carbon intensity, such as industry and transportation, in order to reduce the energy intensity of these high carbon emission sectors and strive to reduce the energy intensity of the industry and transportation sectors by more than 30% by 2035 compared to that in the BS. In addition, the power development sector should also consider accelerating the retirement of thermal power generation units and other high carbon emission-generating units, while increasing the proportion of clean power units in service to replace retired generating units to ensure the stability of power supply, with the aim of reducing the share of thermal power to less than 50% by 2035.

(2) In terms of sectoral CO_2 emissions and the time to peak emissions, under the BS, the CO_2 emissions of all sectors in Shanxi Province will increase annually from 2019 to 2035, and will not peak prior to 2035. Moreover, Shanxi Province, as a heavy industrial province in China, is rich in coal resources and has a large proportion of thermal power generation in its power supply structure. Thus, CO_2 emissions from both the industrial and energy conversion sectors are large in the BS. However, it is worth noting that CO_2 emissions in most of the sectors in Shanxi Province (such as industrial, coking, agriculture, and transport) will peak earlier than will occur under the BS under the combined effect of various factors mentioned in this paper. In addition, there is a clear downward trend in CO_2 emissions from the industrial sector, and the CO_2 emissions from energy conversion sectors (mainly the heating sector) have an increasing impact on the total CO_2 emissions in Shanxi Province. We conclude that the industrial sector in Shanxi Province has a large potential for emission reduction, but the share of CO_2 emissions from the energy conversion sector is gradually increasing with the implementation of energy consumption structure optimization and other emission reduction measures. Therefore, we suggest that government departments in Shanxi Province consider strengthening the implementation of emission reduction policies for the industrial sector, while also paying more attention to the energy conversion sector, such as by promoting the deep integration of "industry-university-research", improving the efficiency of energy conversion, and accelerating the optimization of power supply structure in order to successfully achieve the "carbon neutral" strategic emission reduction goal by 2060.

(3) According to the sensitivity analysis, each of the following can effectively reduce CO_2 emissions in Shanxi Province and result in the peak time occurring earlier: moderately slowing down economic growth; shifting the GDP share of industry to services; decreasing the energy intensity of high carbon emissions sectors, such as industrial and transport sectors; and reducing the proportion of thermal power in the power structure. Therefore, when formulating energy planning, energy conservation, and emission reduction policies, Shanxi Province should consider making moderate adjustments to the above-mentioned targets to ensure the smooth operation of the economy and the stable development of all aspects of society, while ensuring that the peak of CO_2 emissions is reached by 2030.

Regarding the significance of the results, although this paper is concerned with a specific region (Shanxi Province, China), the methodology used in this study is also applicable to the analysis of emission reduction strategies in other provinces. Furthermore, the strategies analyzed in this paper, such as reducing the economic growth rate and optimizing the industrial structure and energy consumption structure, are also applicable to other provinces. However, it is worth noting that the specific values corresponding to these strategies need to be determined according to the actual situation of each region and cannot be generalized.

This paper only studies the emission reduction strategies in Shanxi Province in terms of the effects of policy implementation, without considering the implementation costs of these measures; therefore, the trade-offs between the implementation costs of emission reduction measures and the effects of emission reduction can be studied in future research.

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Abbreviations

CE_T	total CO_2 emissions
CE_f	the CO_2 emissions from the final energy demand
CE_c	the CO_2 emissions from the energy conversion
AL_i	the level of activity in sector *i*
EI_i	the energy intensity of sector *i*
θ_{ij}	the ratio of the demand for *j* energy in sector *i* to the total energy demand in sector *i*
EF_j	the CO_2 emissions factor of fuel type *j*
ETO	the production of energy conversion
f	the transformation efficiency
EF	the CO_2 emissions factor
m	the energy conversion modules
j	the fuel type of consumption in energy transformation
t	the fuel type of production in energy transformation

Abbreviation of scenario name

BS	Base Scenario
CS	Comprehensive Scenario
$\mathrm{CS}_{\mathrm{high-GDP}}$	a scenario which assumed 1% increase in annual GDP per capita growth rate based on the comprehensive scenario
$\mathrm{CS}_{\mathrm{low-GDP}}$	a scenario which assumed 1% decrease in annual GDP per capita growth rate based on the comprehensive scenario
$\mathrm{CS}_{\mathrm{IS}-x}$	a scenario which assumed a x% GDP share of the industrial sector in 2035 under the comprehensive scenario
$\mathrm{CS}_{\mathrm{EI}-x}$	a scenario which assumed the energy intensity of the industrial and transport sectors in 2035 will be x% lower than that under the BS, other parameter settings are the same as Comprehensive scenario
$\mathrm{CS}_{\mathrm{PS}-x}$	a scenario which assumed a x% installed capacity of thermal power in 2035, other parameter settings are the same as Comprehensive scenario

Appendix A

Parameter settings of energy consumption structure of Shanxi Province's final energy consumption sector for major years under the base scenario (BS) and comprehensive scenario (CS).

Energy Consumption Structure by Sector (%)		Year	Raw Coal	Washed and Other Washed Coal	Coke	Coke Oven Gas	Other Coal Products	Gasoline	Diesel	Other Petroleum Products	Natural Gas	Heat	Electricity
Agriculture	Base year	2019	38.83					9.33	25.44				26.40
	BS	2030	45.69					10.53	20.87				22.92
		2035	45.60					10.50	20.94				22.96
	CS	2030	32.76					7.73	13.45				46.06
		2035	30.00					7.00	8.00				55.00
Industrial	Base year	2019	24.53	1.17	22.97	9.75	12.32	0.07	0.93	0.01	3.48	5.29	19.49
	BS	2030	28.20	1.33	21.96	9.63	10.21	0.18	1.11	0.04	3.02	5.50	18.83
		2035	28.14	1.33	21.97	9.63	10.24	0.17	1.11	0.04	3.02	5.50	18.85
	CS	2030	17.98	1.05	15.22	8.55	5.91	0.16	0.98	0.07	7.96	8.53	33.59
		2035	15.00	1.00	11.70	8.00	3.00	0.20	1.00	0.10	10.00	10.00	40.00
Building	Base year	2019	2.69		0.00			16.69	54.09	0.29	1.01	1.37	23.86
	BS	2030	6.12		0.05			17.69	48.92	0.81	2.34	2.31	21.76
		2035	6.06		0.05			17.67	49.02	0.81	2.32	2.29	21.79
	CS	2030	4.28		0.00			12.09	30.65	0.78	9.94	3.87	38.39
		2035	5.00		0.00			10.00	20.00	1.00	14.00	5.00	45.00
Transport	Base year	2019	0.62					20.86	47.15	6.45	12.87	2.53	9.52
	BS	2030	3.65					18.90	49.79	5.10	12.21	1.91	8.44
		2035	3.62					18.93	49.73	5.12	12.22	1.92	8.46
	CS	2030	1.57					13.39	31.92	4.08	24.65	2.85	21.54
		2035	2.00					10.00	25.00	3.00	30.00	3.00	27.00
Service	Base year	2019	31.64		0.00	0.00	0.20	5.76	1.67	0.14	19.33	11.88	29.37
	BS	2030	38.53		0.10	0.13	0.41	5.18	1.81	0.08	14.02	14.16	25.59
		2035	38.46		0.10	0.13	0.41	5.18	1.80	0.09	14.07	14.12	25.65
	CS	2030	20.20		0.07	0.07	0.27	3.86	1.49	0.11	19.79	17.46	36.68
		2035	15.00		0.10	0.10	0.30	3.00	1.40	0.10	20.00	20.00	40.00
Residential	Base year	2019	22.95	0.00		0.00	4.09	4.58	0.30	0.86	14.94	31.61	20.66
	BS	2030	25.59	4.75		0.26	3.22	4.74	0.27	0.79	13.69	27.40	19.29
		2035	25.57	4.68		0.25	3.23	4.74	0.27	0.79	13.70	27.45	19.31
	CS	2030	17.48	2.06		0.69	2.65	2.81	0.16	0.54	17.04	32.91	23.64
		2035	15.00	3.00		1.00	2.00	2.00	0.10	0.40	18.00	33.50	25.00

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