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Forecasting and Scenario Analysis of Carbon Emissions in Key Industries: A Case Study in Henan Province, China

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Abstract: In a global context where sustainable growth is imperative, understanding carbon emissions in significant regions is essential. Henan Province, being a vital region in China for population, agriculture, industry, and energy consumption, plays a crucial role in this understanding. This study, rooted in the need to identify strategies that not only meet China's broader carbon neutrality objectives but also offer insights regarding global sustainability models, utilizes the STIRPAT model combined with scenario analysis. The aim was to forecast carbon emission trajectories from 2020 to 2060 across the key industries—electricity, steel, cement, transportation, coal, and chemical—that are responsible for over 80% of the total emissions in Henan. The findings suggest a varied carbon peak timeline: the steel and cement industries might achieve their peak before 2025, and the transportation, coal, and chemical sectors might achieve theirs around 2030, whereas that of the power industry could be delayed until 2033. Significantly, by 2060—a landmark year for Chinese carbon neutrality ambitions—only the electricity sector in Henan shows potential for zero emissions under an extreme scenario. This study's results underscore the importance of region-specific strategies for achieving global carbon neutrality and offer a blueprint for other populous, industrialized regions worldwide.

Keywords: STIRPAT extended model; carbon emission trajectories; carbon neutrality; key industries in Henan Province; scenario analysis

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1. Introduction

Climate change is an urgent global challenge that has garnered significant attention over recent decades [1]. To counteract the detrimental effects of climate change, nations are actively striving to achieve peak carbon emissions and carbon neutrality [2]. As the largest carbon emitter globally, China's role in global climate change mitigation is paramount. Among the various provinces in China, Henan stands out, not only due to its dense population and significant industrial and agricultural activities but also for its strategic position as a key national transportation hub designated by the Ministry of Transportation [3]. Therefore, a comprehensive study of the carbon emission status of Henan Province holds not only guiding significance for local low-carbon development strategy but also has profound implications for achieving carbon neutrality targets, both in China and globally [4].

The total carbon dioxide (CO_2) emissions in Henan Province in 2019 amounted to 460.63 million metric tons. Among the 34 provinces in China, this figure places Henan Province as the sixth highest in terms of CO_2 emissions. Among them, emissions from the production and supply of electricity, steam, and hot water accounted for 48.38%; emissions from the ferrous metal smelting and rolling processing industry accounted for 9.53%; emissions from non-metallic mineral production accounted for 9.12%; emissions from transportation, warehousing, and postal services accounted for 6.73%; emissions from natural gas production and supply accounted for 5.79%; and emissions from coal mining and dressing accounted for 4.05% [5–8]. Promoting the technological upgrade of these key industries and increasing the use of new energy sources are of paramount importance for Henan Province to achieve a carbon peak and reduce carbon emissions. Accounting for and forecasting carbon emissions in the relevant industries can provide insights into future emission trends, facilitating the development of targeted policy recommendations and achieving the carbon peak goal before 2030.

In recent years, numerous studies worldwide, including in China, have focused on forecasting key carbon-emitting industries, with the aim of better understanding and addressing global climate change issues. Zhou et al. (2011) analyzed China's energy consumption and carbon emissions in 2050 using a bottom-up energy end-use model [9], yet they did not address the specific challenges faced by different regions in implementing these policies. Wu et al. (2019) took significant strides in the Chinese power sector, conducting an optimization study for carbon emission reductions with the target of 2035 [10]. Despite their commendable efforts, the scope of their forecast was notably limited to 2035. From a carbon neutrality perspective, Li et al. (2022) investigated the driving factors and pathways for carbon emission reduction in the Chinese steel industry, exploring the challenges of and effective strategies for achieving carbon neutrality goals [11]. Ofosu-Adarkwa et al. (2022) predicted the CO_2 emissions in the Chinese cement industry using a hybrid Verhulst-GM (1, N) model and the emission technology conversion method [12]. Lin et al. (2014) analyzed the CO_2 emission reduction potential in the Chinese transportation sector [13]. Wang et al. (2018) used a system dynamics model to predict the future scenarios of China's coal production capacity, providing theoretical support for the formulation of coal production capacity adjustment policies and carbon emission reduction [14]. Geng et al. (2020) introduced a new method for energy optimization and forecast modeling in the petrochemical industry by improving the cross-feature-based convolutional neural network [15]. However, these studies are limited to specific industries and lack comprehensive examination across various sectors within particular regions.

Additionally, the STIRPAT model has emerged as a crucial analytical tool that is widely applied in carbon emission forecasting research. York et al. (2003) introduced the concept and empirical application of the STIRPAT model, applying it to global carbon emission forecasting [16]. Shi (2003) employed the STIRPAT model and cross-national data from 1975 to 1996 to analyze the impact of population pressure on global carbon emissions [17], yet the study's influential factors were overly simplistic. Liddle (2004) used the STIRPAT model to examine the relationship between population dynamics and per capita environmental impact, with a specific focus on the relationship between population and transportation [18]. Wang et al. (2013) applied the STIRPAT model to analyze the influencing factors of CO_2 emissions related to energy in Guangdong Province, China [19]. A limitation was the lack of differentiated treatment for individual industries, potentially affecting the accuracy of predictions. Martínez-Zarzoso and Maruotti (2011) used the STIRPAT model to study the impact of urbanization on CO_2 emissions in developing countries and found that urbanization had a significant influence on carbon emissions in these countries [20].

In the vast expanse of the literature, carbon emission research for specific industries has garnered significant attention. However, despite the depth of these studies, many tend to focus on a single industry or domain. This often overlooks the complexities of capturing interconnected industries within a specific region. Moreover, another notable limitation in the existing research is the forecasting time span. Many studies tend to offer relatively short-term predictions. While these forecasts may be valuable in the short term, they might hinder a comprehensive understanding of long-term carbon emission trajectories, which is crucial for planning sustainable efforts spanning several decades.

In contrast, the novelty of our paper lies in its broader perspective and unique research methodology. We have synthesized carbon accounting and forecasting methods across various industries, diving deep into the carbon emission characteristics of each one. Building on the STIRPAT model, we have adapted and considered distinct carbon emission factors that are tailored to each industry, rendering our study more detailed and targeted. Specifically, for the power sector, which significantly differs from other industrial sectors, we employed the electricity consumption elasticity coefficient method to enhance the accuracy of our predictions. Thus, our paper not only forecasts peak carbon emission timeframes and values for different industries but also delves deeper into analyzing the potential for emission reductions in various scenarios until 2060. This approach offers policymakers and relevant stakeholders a more comprehensive and long-term perspective.

This paper is structured as follows: Section 2 introduces the research methodology, encompassing carbon emission accounting and forecasting for key industries. Section 3 delves into the historical carbon emission data and trends of these industries. Forecasting model parameters and outcomes are presented in Section 4. The paper concludes in Section 5 with a summary and recommendations for further research.

2. Research Methodology

This study primarily focuses on predicting carbon emissions in the key industries of Henan Province to facilitate the achievement of carbon peak and carbon neutrality goals. The research is based on historical carbon emission data from Henan Province, providing a solid foundation for the analysis [5–8]. By utilizing the Chinese Classification of National Economic Industries and the statistical practices of energy in Henan Province [21,22], we have organized and summarized the 47 sub-industries listed in the provincial carbon emission inventory, consolidating them into 6 key carbon-emitting industries in Henan Province, namely, power, steel, cement, transportation, coal, and chemical industries, as shown in Table 1.

Table 1. Integration of key carbon-emitting industries in Henan Province.

Key Industries in Henan Province	Industry Classification
Electricity Industry	Production and Supply of Electric Power, Steam and Hot Water
Steel Industry	Smelting and Pressing of Ferrous Metals
Cement Industry	Nonmetal Mineral Products
Transportation Industry	Transportation, Storage, Post and Telecommunication Services
Coal Industry	Coal Mining and Dressing
	Petroleum Processing and Coking
Chemical Industry	Raw Chemical Materials and Chemical Products
	Petroleum and Natural Gas Extraction

As seen in historical carbon emission data from 2010 to 2019, the electricity industry in Henan Province exhibited a significantly higher carbon emission contribution compared to other industries, accounting for an average of 45% of the cumulative carbon emissions during the same period. The cumulative carbon emissions from the electricity industry and the other 5 key carbon-emitting industries (steel, cement, transportation, coal, and chemical industries) accounted for approximately 80% of the total emissions in Henan Province, as illustrated in Figure 1. These findings underscore the crucial role played by these industries in the overall carbon emission profile of the province.

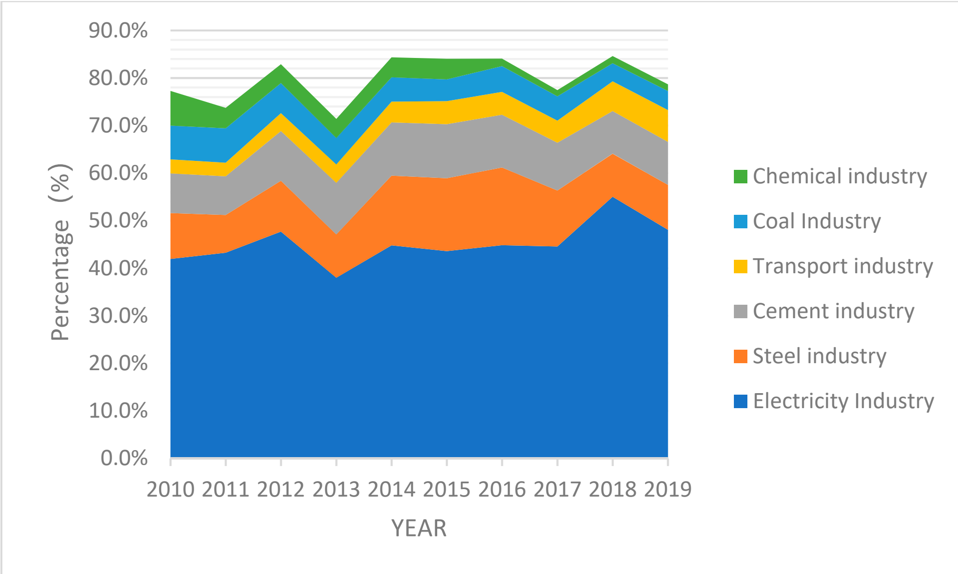


Figure 1. Historical carbon emission contributions from key industries in Henan Province.

2.1. Carbon Accounting Methods

2.1.1. Electricity Industry

Based on the "Requirements of greenhouse gas emission accounting and reporting—Part 1: Power generation enterprise", this study simplified the carbon emission accounting method used for the electricity industry in Henan Province [23]. Specifically, this study focused on the carbon emissions generated from the combustion of fossil fuels (including thermal power co-generation fuel consumption) in coal-fired power plants and gas-fired power plants (including self-supplied power plants). Factors influencing carbon emissions include electricity demand, changes in power generation from various sources, and variations in coal consumption for power generation. To estimate the carbon dioxide emissions from the electricity industry, we used the corresponding carbon emission coefficients for coal consumption and gas consumption in power generation. The calculation formula is as follows:

$$E_{ele} = A_{coal} \times EF_{coal} + A_{gas} \times EF_{gas} \quad (1)$$

where E_{ele} represents the total CO_2 emissions from the electricity industry; A_{coal} represents the amount of coal consumption for power generation; A_{gas} represents the amount of natural gas consumption for power generation; and EF_{coal} and EF_{gas} represent the carbon emission coefficients of coal and natural gas, respectively.

2.1.2. Steel Industry

The carbon emission accounting of the steel industry is conducted following the "Requirements of greenhouse gas emission accounting and reporting—Part 5: Iron and steel production enterprise" [24]. The accounting process for the steel industry in Henan Province includes three categories of carbon emissions: direct carbon emissions from fossil fuel combustion, indirect carbon emissions from chemical processes, and indirect carbon emissions from electricity production and consumption. Indirect carbon emissions in the steel production process mainly result from the decomposition of limestone and dolomite, while the corresponding emissions from the consumption of purchased electricity in the production process are estimated using emission factors from the regional power grid. The total carbon emissions of the steel industry are determined using the following calculation formulae:

$$E_{steel} = E_{s1} + E_{s2} + E_{s3} \quad (2)$$

$$E_{s1} = \sum_{s=1}^{n} NCV_s \times FC_s \times CC_s \times OF_s \times \frac{44}{12} \quad (3)$$

$$E_{s2} = A_{li} \times EF_{li} + A_{do} \times EF_{do} \quad (4)$$

$$E_{s3} = A_{se} \times EF_{ne} \quad (5)$$

where E_{steel} represents the total CO_2 emissions from the steel industry; E_{s1} represents the emissions from fuel combustion; E_{s2} represents the process emissions; E_{s3} represents the emissions corresponding to purchased electricity consumption; NCV_s represents the average lower heating value of the fuel s; FC_s represents the consumption of the fossil fuel s; CC_s represents the carbon content per unit calorific value of the fossil fuel s; OF_s is the carbon oxidation rate of the fossil fuel s; 44/12 is the relative molecular weight ratio of carbon dioxide to carbon; A_{li} and A_{do} represent the consumption of limestone and dolomite; EF_{li} and EF_{do} represent the carbon emission factors of limestone and dolomite; A_{se} is the external purchased electricity consumption value during the production process; and EF_{ne} is the annual average grid emission factor for electricity supply. The recommended values for common fossil-fuel characteristic parameters are shown in Table 2.

2.1.3. Cement Industry

Based on the "Requirements of the greenhouse gas emission accounting and reporting—Part 8: Cement enterprise", this study outlines the carbon emission scope for Henan's cement industry, covering direct emissions from fossil fuels, indirect emissions from chemical processes, and electricity-related emissions [25]. The indirect carbon emissions in the cement production process mainly originate from the carbon dioxide emissions produced during the carbonate decomposition process in clinker preparation. The formulae for calculating the total carbon emissions in the cement industry are as follows:

$$E_{cement} = E_{c1} + E_{c2} + E_{c3} \quad (6)$$

$$E_{c1} = \sum_{c=1}^{n} NCV_c \times FC_c \times CC_c \times OF_c \times \frac{44}{12} \quad (7)$$

$$E_{c2} = A_{cl} \times EF_{cl} \quad (8)$$

$$E_{c3} = A_{ce} \times EF_{ne} \quad (9)$$

where E_{cement} represents the total CO_2 emissions from the cement industry; E_{c1} represents the emissions from fuel combustion; E_{c2} represents the process emissions; E_{c3} represents the emissions corresponding to purchased electricity consumption; NCV_c represents the average lower heating value of the fuel c; FC_c represents the consumption of the fossil fuel c; CC_c the carbon content per unit calorific value of the fossil fuel c; OF_c is the carbon oxidation rate of the fossil fuel c; 44/12 is the relative molecular weight ratio of carbon dioxide to carbon; A_{cl} represents the consumption of clinker; EF_{cl} represents the carbon emission factors of clinker; A_{ce} is the external purchased electricity consumption during the production process; and EF_{ne} is the annual average grid emission factor for the electricity supply. The recommended values for common fossil-fuel characteristic parameters are shown in Table 2.

2.1.4. Transportation Industry

The carbon emission accounting method used for the transportation industry in Henan Province in this study is based on "the provincial greenhouse gas inventories" [26]. When calculating the carbon emissions from the transportation system in Henan Province, this study mainly focused on six modes (railways, highways, waterways, private cars, buses, and taxis), and calculated the carbon dioxide emissions from fossil fuel combustion for each transportation mode. Among them, the emissions from highways, railways, and waterways were evaluated using the turnover volume-based approach, while the emissions from buses, taxis, and private cars were calculated based on ownership. Using these evaluations, the following formulae for calculating the total carbon emissions in the transportation industry were derived:

$$E_{tran} = E_{t1} + E_{t2} \tag{10}$$

$$E_{t1} = \sum_{i=1}^{3} T_i \times E_i \times EF_i \tag{11}$$

$$E_{t2} = \sum_{j=1}^{3} A_j \times M_j \times f_j \times EF_j \tag{12}$$

where E_{tran} represents the total CO_2 emissions from the transportation industry; E_{t1} represents the carbon emissions from highways, railways, and waterways; E_{t2} represents the carbon emissions from buses, taxis, and private cars; T_i is the freight turnover volume of the transportation mode i; E_i is the energy consumption per unit of turnover volume of the transportation mode i; EF_i represents the unit energy CO_2 emissions of the transportation mode i; A_j is the ownership of the transportation mode j; M_j is the average annual mileage of the transportation mode j; f_j is the fuel consumption per 100 km of the transportation mode j; and EF_j represents the unit energy CO_2 emissions of the transportation mode j.

2.1.5. Coal Industry

Based on the "Greenhouse gas emission accounting methodology and reporting guidelines for coal producers in China (Trial)", this study simplifies the carbon accounting scope of the coal industry in Henan Province to include carbon emissions from fossil fuel combustion in the coal development process, methane emissions, and carbon emissions from electricity production and consumption [27]. Previous research has shown that the main component of coalmine gas, methane, has a greenhouse effect of 21 times that of carbon dioxide [28]. The formulae for calculating the total carbon emissions in the coal industry are as follows:

$$E_{coal} = E_{coal1} + E_{coal2} + E_{coal3} \tag{13}$$

$$E_{coal1} = \sum_{a=1}^{n} NCV_a \times FC_a \times CC_a \times OF_a \times \frac{44}{12} \tag{14}$$

$$E_{coal2} = A_g \times EF_g \tag{15}$$

$$E_{coal3} = A_{ae} \times EF_{ne} \tag{16}$$

where E_{coal} represents the total CO_2 emissions from the coal industry; E_{coal1} represents the emissions from fuel combustion; E_{coal2} represents the process emissions; E_{coal3} represents the emissions corresponding to purchased electricity consumption; NCV_a represents the average lower heating value of the fuel a; FC_a represents the consumption of the fossil fuel a; CC_a represents the carbon content per unit calorific value of the fossil fuel a; OF_a is the carbon oxidation rate of the fossil fuel a; 44/12 is the relative molecular weight ratio of carbon dioxide to carbon; A_g represents the consumption of gas; EF_g represents the carbon emission factors of gas; A_{ae} is the external purchased electricity consumption during the production process; and EF_{ne} is the annual average grid emission factor for electricity supply. The recommended values for common fossil fuel characteristic parameters are shown in Table 2.

2.1.6. Chemical Industry

According to "Greenhouse gas emission accounting methodology and reporting guidelines for chemical manufacturing enterprises in China (Trial)" [29], this study considers the carbon accounting scope of the chemical industry in Henan Province, which includes direct carbon dioxide emissions from fossil fuel combustion and indirect carbon dioxide emissions from electricity production and consumption. The formulae for calculating the total carbon emissions in the chemical industry are as follows:

$$E_{chemical} = E_{chemical1} + E_{chemical2} \tag{17}$$

$$E_{chemical} = \sum_{b=1}^{n} NCV_b \times FC_b \times CC_b \times OF_b \times \frac{44}{12} \tag{18}$$

$$E_{chemical2} = A_{be} \times EF_{ne}, \tag{19}$$

where $E_{chemical}$ represents the total CO_2 emissions from the chemical industry; $E_{chemical1}$ represents the process emissions; $E_{chemical2}$ represents the emissions corresponding to purchased electricity consumption; NCV_b represents the average lower heating value of the fuel b; FC_b represents the consumption of the fossil fuel b; CC_b represents the carbon content per unit calorific value of the fossil fuel b; OF_b is the carbon oxidation rate of the fossil fuel b; $44/12$ is the relative molecular weight ratio of carbon dioxide to carbon; A_{be} represents the external purchased electricity consumption during the production process; and EF_{ne} is the annual average grid emission factor for electricity supply. The recommended values for common fossil fuel characteristic parameters are shown in Table 2.

Table 2. Recommended values for common fossil fuel characteristic calculation parameters.

Fuel Type	Unit of Measurement	Low Heating Value (GJ/t, GJ/10^4 Nm^3)	Carbon Content per Unit Heat (tC/GJ)	Fuel Carbon Oxidation Rate (%)
Crude Oil	t	42.62	20.1×10^{-3}	98%
Gasoline	t	44.8	18.9×10^{-3}	98%
Diesel	t	43.33	20.2×10^{-3}	98%
Kerosene	t	44.75	19.6×10^{-3}	98%
Fuel Oil	t	40.19	21.1×10^{-3}	98%
Liquefied Petroleum Gas	t	47.31	17.2×10^{-3}	98%
Refinery Dry Gas	t	46.05	18.2×10^{-3}	98%
Petroleum Coke	t	31.998	27.5×10^{-3}	98%
Other Oil Products	t	41.031	20.0×10^{-3}	98%
Natural Gas	10^4 Nm^3	389.31	15.3×10^{-3}	99%

2.2. Carbon Emission Forecasting Methodology

In this study, different carbon emission prediction methods were applied to the electricity industry and five other key industries in Henan Province. The prediction analysis for the electricity industry comprehensively considers factors such as social electricity demand, power generation structure, and fossil fuel consumption. The electricity demand analysis module, which is closely related to social economic development and the electricity demand of various sectors, adopts the elasticity coefficient method for forecasting [30]. The power generation structure analysis module, based on electricity demand forecasts, comprehensively considers various factors such as energy policies, environmental issues, and technological advancements [31]. In contrast, carbon emissions in the steel, cement, transportation, coal, and chemical industries mainly originate from fossil fuel consumption, production processes, and purchased electricity [23–27]. Additionally, population, economy, technology, and other factors significantly influence the carbon emissions of these industries [32]. Hence, the STIRPAT extended model is employed here for forecasting.

2.2.1. Electricity Industry

In the prediction of carbon emissions in the electricity industry of Henan Province, the elasticity coefficient method was first applied to analyze future electricity demand. The electricity consumption elasticity coefficient represents the ratio of the electricity consumption growth rate to the gross domestic product (GDP) growth rate and exhibits a certain regularity. As the proportion of industrial value being added decreases, the electricity consumption elasticity coefficient tends to decline. Based on the relationship between the electricity consumption elasticity coefficient and industrialization stages in China, during the period of 2021–2025, Henan Province is in the late stage of industrialization, and the projected electricity elasticity coefficient is 0.8 [33]. With the decline in the proportion of industrial value being added, the electricity elasticity coefficient is expected to exhibit a clear downward trend [34]. Referring to the decreasing trend of elasticity coefficient seen in the United States, the electricity elasticity coefficient for the periods 2026–2030 and 2031–2035 in Henan Province is set at 0.6 and 0.5, respectively, and then gradually decreases to 0.3 after 2035 [35]. Combining the electricity consumption elasticity coefficient of Henan Province with the economic growth rate, the research establishes the formula for predicting the total social electricity consumption as follows:

$$Ed(t) = Ed(t-1) \times (1 + eco \times GDP_{rate}) \tag{20}$$

where $Ed(t)$ represents the total electricity demand in year t; eco represents the electricity consumption elasticity coefficient, which denotes the ratio of the annual average growth rate of total electricity consumption to the annual average growth rate of gross domestic product (GDP) during a certain period; and GDP_{rate} represents the GDP growth rate.

Henan Province has abundant coal resources, and coal-fired power has been the main source of electricity supply in the province for many years. Therefore, an adjustment of the power structure is crucial for achieving carbon peak levels and reduction in the electricity industry. This study, based on electricity demand forecasting, determines the future scale of hydropower and biomass power generation in Henan Province, considering factors such as exploitable resource capacity, the power project construction cycle, and energy prices. Additionally, the scale of wind and solar power generation is determined based on the proportion of non-fossil energy consumption. The analysis covers the period from 2020 to 2060, including thermal power, hydropower, biomass, wind power, and photovoltaic installed capacity and power generation in Henan Province. Finally, through a comprehensive analysis of social electricity demand and power structure, the carbon emission trend in the electricity industry of Henan Province is predicted.

2.2.2. Other Industries: STIRPAT Model

The STIRPAT (stochastic impacts by regression on population, affluence, and technology) model is an environmental impact model based on regression analysis, which has been widely used for predicting carbon emissions in various industries. Compared to other models, the STIRPAT model offers better applicability and flexibility as it incorporates key factors that contribute to carbon emissions, such as population growth, economic development, and technological progress. By employing the STIRPAT model, it becomes possible to comprehensively describe the influence of these factors on carbon emissions in different industries, thereby enabling more accurate predictions of carbon emission variations and the formulation of sector-specific carbon reduction policies. Dietz et al. introduced the STIRPAT model as an extension of the traditional IPAT model [32], and its standard form is as follows:

$$I = aP^b A^c T^d e \tag{21}$$

where I, P, A, and T represent environmental impact, population, affluence, and technology level, respectively; a is the model coefficient; b, c, and d are the exponents to be estimated; and e represents the error term. Taking the logarithm of both sides of Equation (21) yields the following equation:

$$\ln I = \ln a + b\ln P + c\ln A + d\ln T + \ln e \tag{22}$$

The STIRPAT model employs a multiplicative form to capture the interactions and exponential influences among population, affluence, and technology, allowing for a more nuanced understanding and prediction of environmental impact variations. The model coefficients and exponents (a, b, c, and d) are empirically derived through robust regression methods, utilizing comprehensive datasets sourced from varied sectors and regions, thereby ensuring the reliability and applicability of the model across different industrial contexts.

In predicting the carbon emissions of key industries in Henan Province, this study employed the STIRPAT model, incorporating a series of crucial influencing factors. Firstly, the population metric was integrated, given that a larger population might result in heightened production and consumption, subsequently influencing energy demands and carbon emissions. Additionally, the level of urbanization was factored in, given its significant correlation with energy consumption and carbon emissions, as urbanized regions typically command greater resource utilization. The economic development level was also considered, using GDP per capita as a pivotal indicator. Furthermore, the proportion of the secondary sector was employed to represent the industry structure, as it is often more energy-intensive than other sectors. In terms of energy structure, emphasis was placed on the consumption ratios of natural gas and electricity, considering the distinctive carbon emission coefficients associated with different energy sources. Finally, concerning industry technological levels, specific metrics reflecting the scale, efficiency, and production modes of industries such as steel, cement, transportation, coal, and chemical manufacture were meticulously incorporated. The holistic consideration of these factors not only facilitates a more accurate prediction of carbon emissions in Henan Province but also offers insights for relevant policymaking. The final STIRPAT extended model for predicting carbon emissions in various industries is as follows:

$$\ln C_i = \ln a + b\ln Pop + c\ln U + d\ln PGDP + e\ln IS + f\ln ES + g_i\ln IT_{i1} + h_i\ln IT_{i2} + \ln j \quad (23)$$

where C represents industry carbon emissions; i represents the industry in question; a is the model coefficient; b, c, d, e, f, g, h are model parameters; and j represents the error term. An explanation of other variables is given in Table 3.

Table 3. Industry carbon emission impact factors.

Variables	Definitions	Indicators and Units	
Pop	Population	Annual total population (million)	
U	Urbanization Level	Urbanization rate (%)	
PGDP	Economic Development Level	GDP per capita (CNY)	
IS	Industry Structure	Proportion of the secondary sector (%)	
ES	Energy Structure	Proportion of natural gas and electricity consumption (%)	
IT	Industry Technology Level	Steel Industry	Crude steel production (t) Energy use per unit of steel produced (kgce/t)
		Cement Industry	Cement production (t) Proportion of clinker (%)
		Transportation Industry	Proportion of road transport turnover volume (%) Transportation intensity (pkm)
		Coal Industry	Coal production (t) Energy use per unit of coal produced (kgce/t)
		Chemical Industry	Output per capita (CNY) Investment in fixed assets (CNY)

2.3. Scenario Setting

This study employs scenario analysis to forecast carbon emissions in key industrial sectors in Henan Province. Based on the actual economic and social development in Henan Province and the relevant policies [36], three scenarios have been defined to project the development and carbon emissions of each industry:

- The established policy scenario (conservative scenario) assumes that the future development and carbon emissions of each industry will follow existing policies and plans without significant adjustments or changes. Specifically, the industries are expected to remain reliant on traditional energy sources in the short term, with their development rates remaining relatively stable;
- The energy transition scenario (reference scenario) assumes that industries will gradually transition to new and clean energy sources in the future, adopting more carbon reduction measures. In this scenario, industries will accelerate the promotion of new and clean energy sources, improve energy utilization efficiency, and reduce unnecessary energy consumption;
- The radical substitution scenario (extreme scenario) assumes that industries will take more aggressive measures in the future to replace traditional energy sources as much as possible, aiming to achieve maximum carbon reduction. In this scenario, industries will vigorously promote new and clean energy sources, explore the adoption of advanced technologies, and completely transform their existing energy utilization methods and industrial structures.

2.4. Data Sources

The data samples extracted for this study include historical carbon emission data from 47 end-use energy-consuming industries in Henan Province from 2010 to 2019 [5–8]. Data on Henan Province's total population, urban population, GDP, and secondary industry output were mainly obtained from the Henan Provincial Bureau of Statistics website [37].

Activity level data for the electricity industry, such as electricity generation, electricity consumption, installed capacity of various power sources, and hours of power generation, were sourced from reports such as the Henan Province Energy Development Report and the Henan Province Electricity Industry Research Report [38,39]. Data on crude steel production, cement production, the turnover volume of various transportation modes, coal production, and fixed investment in industries were obtained from the Henan Statistical Yearbook [22]. End-use consumption, average lower heating value, and carbon content per unit of heat for various energy sources were sourced from the China Energy Statistical Yearbook and provincial greenhouse gas inventory preparation guidelines [26,40]. For some missing or differing data, predictions were made within a certain range.

3. Status of Key Industries

3.1. Electricity Industry

With the rapid growth of new energy generation and the absorption of electricity from outside the province, the overall power source structure in Henan Province has been continuously optimized [39]. In 2020, the total installed capacity of power generation in Henan Province reached 101.69 GW, with coal-fired power accounting for 69%, higher than the national average of 57%. The installed capacity of wind and solar power was on par with the national average, while the installed capacity of hydropower was 12.8% lower than the national average. Nuclear power has not yet been developed, as shown in Figure 2. From the perspective of power generation data, coal-fired power still maintains its dominant position in the province, accounting for 68% of the total power generation. Renewable energy generation reached 39.1 billion kWh, accounting for over 11.5% of the total social electricity consumption, and was fully utilized with zero waste via wind, solar, and hydropower generation. However, this coal-dominated power generation structure has led to persistently high carbon emissions from Henan Province's electricity industry.

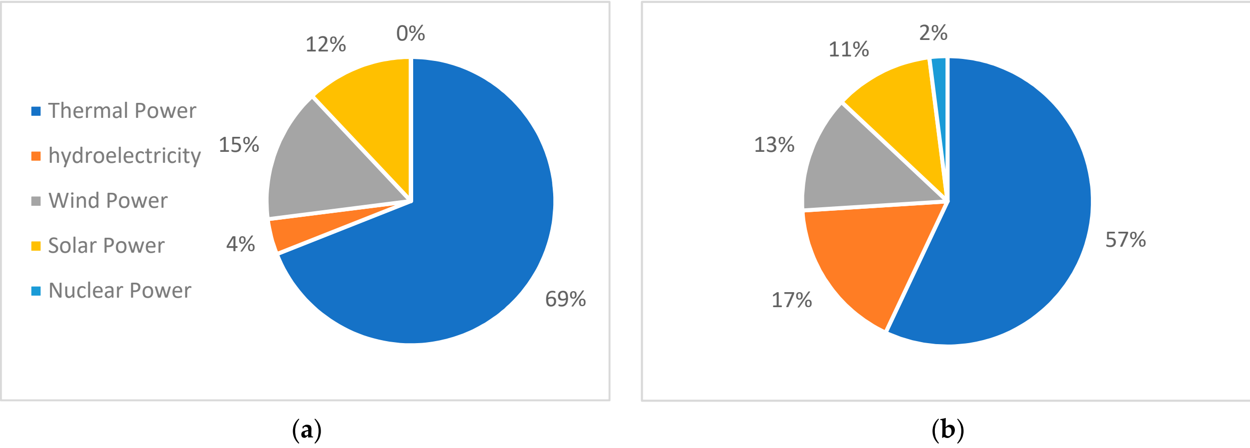


Figure 2. Comparison of the average power supply installation structure in Henan and China. (**a**) Power supply installation structure in Henan Province in 2020; (**b**) average power supply installation structure in China in 2020.

3.2. Steel Industry

As an important industrial province in China, Henan Province has a traditional advantage in the steel industry. Currently, significant transformation projects, such as ultra-low emission and extreme energy efficiency, are continuously advancing in the steel industry of Henan Province [41]. The data show that 47 steel enterprises have completed the entire process of ultra-low emission transformation, involving a steel production capacity of about 243 million tons, and 26 enterprises have completed partial ultra-low emission transformation, involving a steel production capacity of about 157 million tons. In 2021, the annual production of pig iron and steel in Henan Province declined, compared to the previous year. Specifically, steel production was at 33.161 million tons, with a decrease of 6.1%, and pig iron production was at 27.4675 million tons, with a decrease of 0.8%, as shown in Figure 3. Despite the decline in steel demand for the construction industry, the general demand for steel may continue to grow with the development of new energy vehicles, wind and solar power, and other new energy sources.

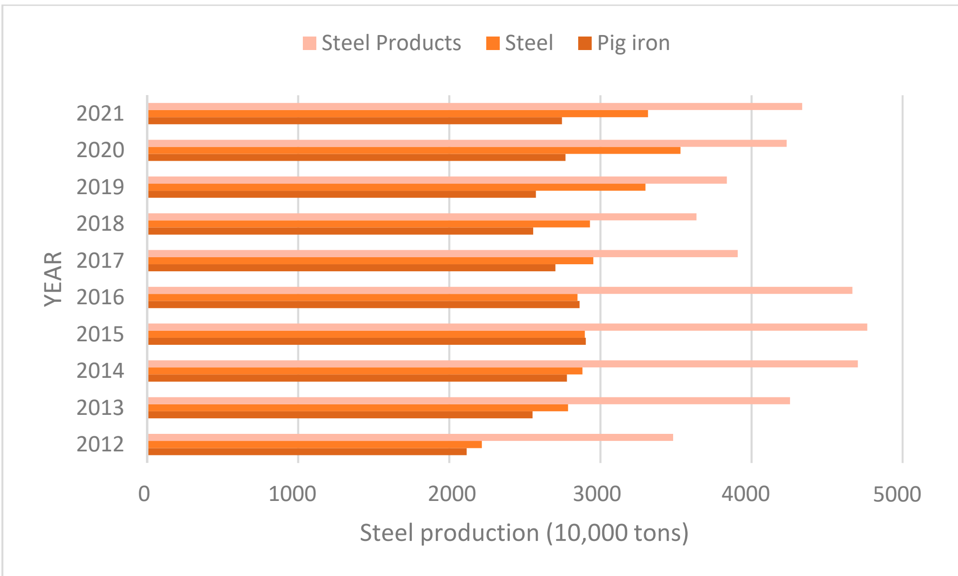


Figure 3. Steel production in Henan Province from 2012 to 2021.

3.3. Cement Industry

Henan Province is one of the major cement production regions in China. As of 2019, the province had a total of 230 cement enterprises, with a combined designed cement production capacity of approximately 300 million tons. However, the actual cement production was less than 150 million tons, resulting in an overcapacity rate exceeding 50%, as shown in Figure 4. On the other hand, the designed clinker production capacity was 93 million tons, but the actual production reached 115 million tons, leading to an excess production rate of 35% in the province. The significant overcapacity in the cement industry poses challenges to the sector, impacting both economic and environmental aspects. Over the years, the cement industry has been a substantial emitter of carbon. In 2010, the carbon emissions from the cement industry were approximately 33.6 million tons, and this figure gradually increased to 50.4 million tons in 2014.

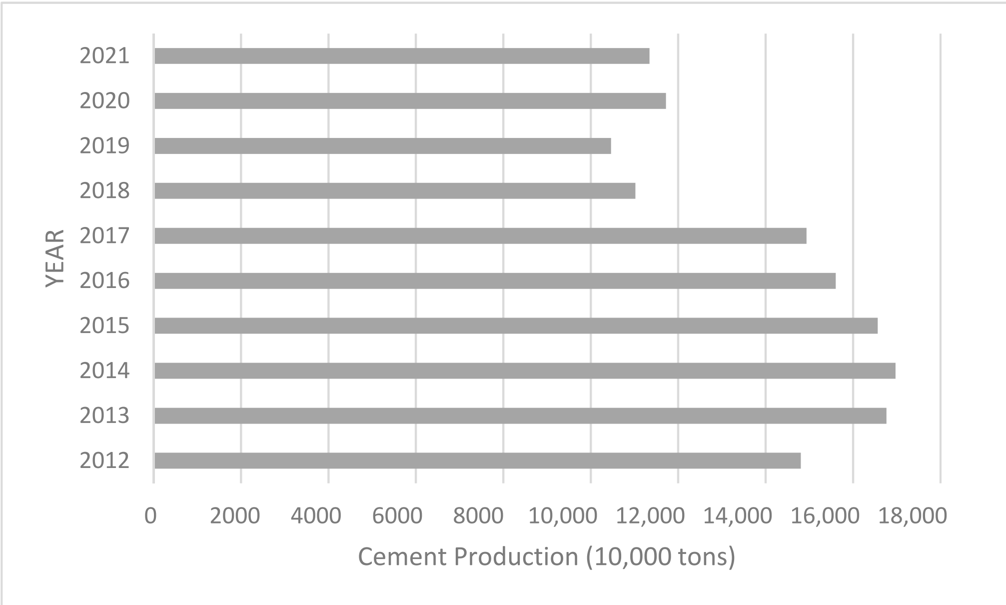


Figure 4. Cement production in Henan Province from 2012 to 2021.

3.4. Transport Industry

Henan Province is located in the Central Plains and serves as a crucial transportation hub in China. In recent years, the province has made significant strides in the construction of highways, railways, and water transportation infrastructure, leading to continuous growth in freight ton kilometers [42], as shown in Figure 5. However, it is worth noting that the transportation industry in the province heavily relies on conventional fuel vehicles. As of 2021, Henan Province had a total of 21,339,098 vehicles, with new energy vehicles accounting for only 3.1% (i.e., 667,255 vehicles).

3.5. Coal Industry

The Henan coal base is one of the 14 major coal bases in China. Currently, Henan Province has accumulated proven coal reserves of 43.856 billion tons and has remaining reserves of 38.907 billion tons. From 2016 to 2020, the number of coal mines in Henan Province decreased from 512 to 218, and the production capacity decreased from 226 million tons to 155 million tons. The data indicate that both coal production and its proportion in the primary energy production in Henan Province have shown a fluctuating downward trend, as shown in Figure 6. In 2011, coal production reached 2.01857 billion tons, accounting for approximately 91.30% of the province's primary energy production. By 2021, coal production had decreased to 0.99948 billion tons, and its proportion of primary energy production significantly dropped to 73.20%.

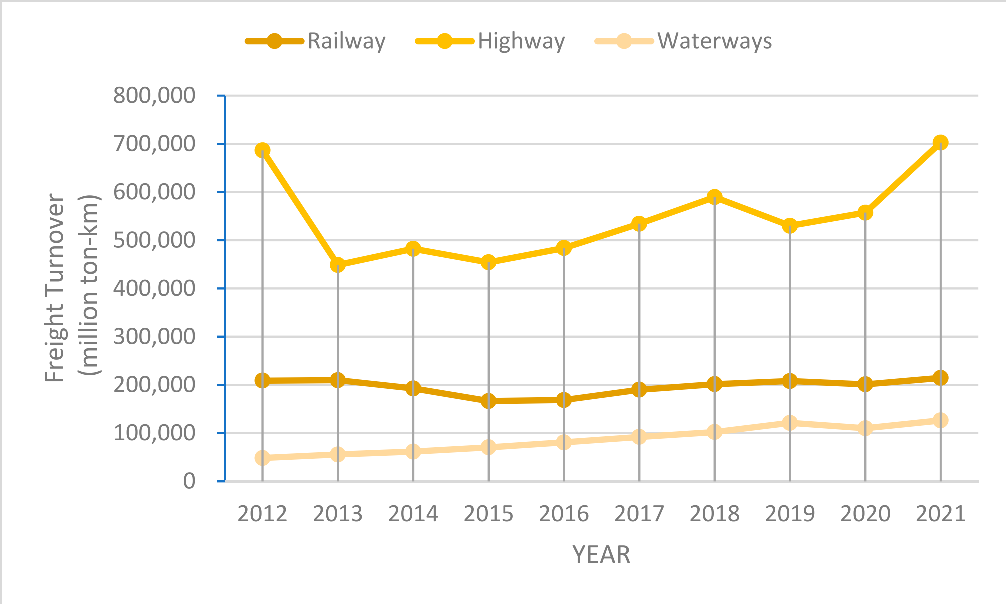


Figure 5. Freight turnover of railways, highways, and waterways in Henan Province from 2012 to 2021.

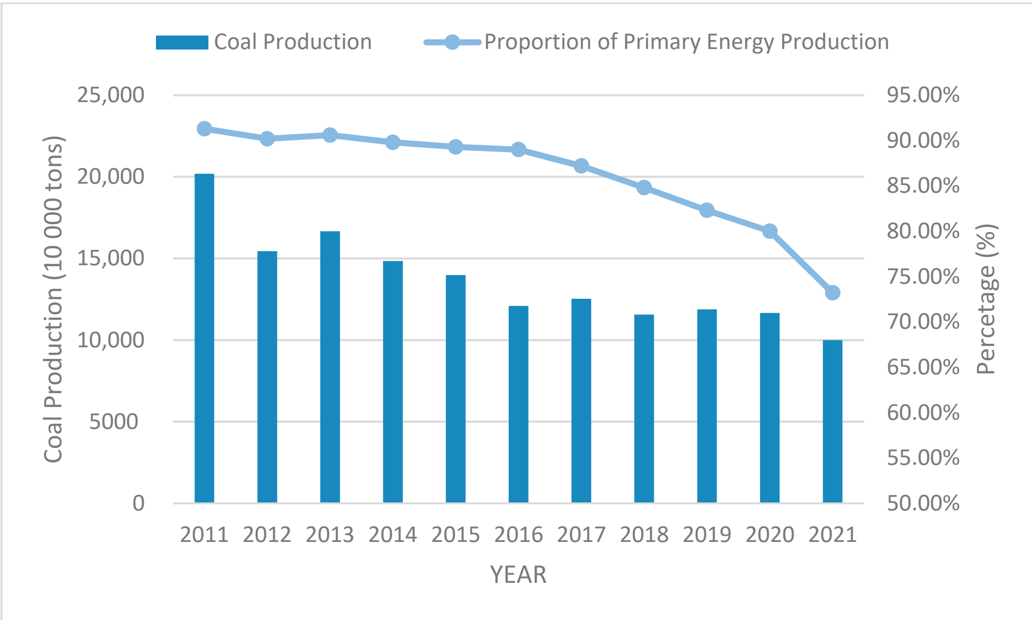


Figure 6. Coal production and proportion in Henan Province from 2012 to 2021.

3.6. Chemical Industry

The chemical industry serves as a vital economic pillar in Henan Province, while also being a high-energy and high-emission sector. As illustrated in Figure 7, total fixed-asset investment in Henan's chemical industry increased from CNY 86.223 billion in 2012 to CNY 169.292 billion in 2021. Currently, due to the upward trend in chemical product prices and the recovery of oil prices, the investment scale in the chemical industry continues to rise, indicating its enormous development potential.

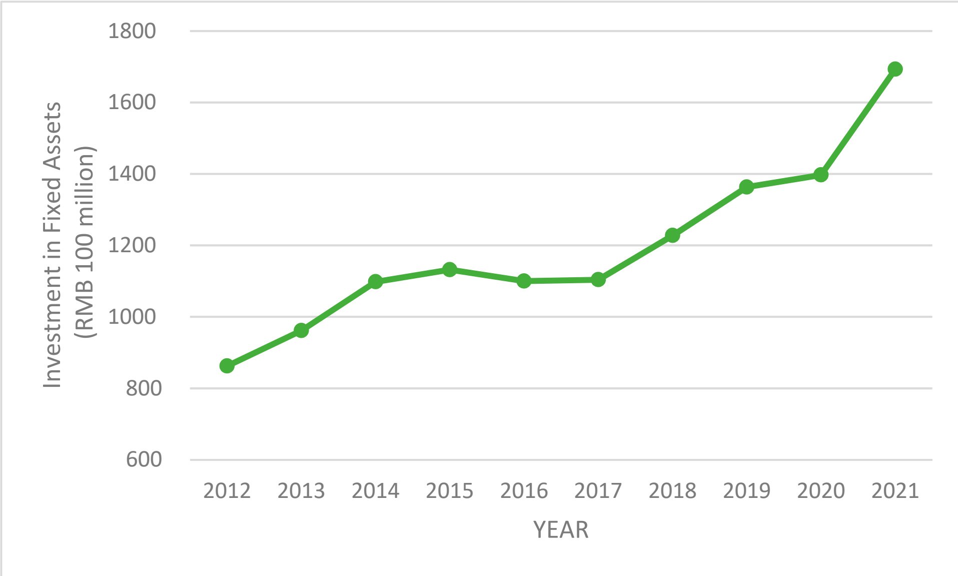


Figure 7. Fixed-asset investment in the chemical industry from 2012 to 2021 in Henan Province.

4. Carbon Emission Forecast Results

4.1. Parameter Setting

4.1.1. Electricity Industry

Electric power demand and various power source capacities in Henan Province have been projected according to the three scenarios defined in Section 2.3, aiming to predict the carbon emissions in the electricity industry. A noticeable slowdown was evident in the total electricity consumption in Henan Province from 2016 to 2020, with an average annual growth of 3.3%, almost 3 percentage points below the national average of 6.2% [22].

Diving deeper into the forecasts presented in Table 4, it is projected that in the period from 2021 to 2035, Henan Province's electricity demand will sustain steady growth, and post-2035, the growth rate of electricity consumption will be accentuated. Under the conservative scenario, the average annual electricity growth rate from 2035 to 2060 is estimated at 2.7%, with the total electricity consumption anticipated to hit 1385.76 billion kWh by 2060, making up 64.3% of the final energy consumption. The energy transition scenario predicts an average annual electricity growth rate of 2.91%, aspiring towards a total electricity consumption of 1457.4 billion kWh by 2060, accounting for 67.4% of the final energy usage. Meanwhile, the extreme scenario, which anticipates an average annual growth rate of 3.12%, projects the total electricity consumption as reaching 1533.8 billion kWh by 2060, contributing 70.1% of the final energy consumption.

Addressing the installed capacity aspect, Table 4 elucidates that in the conservative scenario, the coal-fired power capacity of Henan Province is anticipated to peak around 2025 and be sustained until 2035, later undergoing a gradual decline. By 2060, coal-fired power capacity is projected to maintain 20 million kW, while new energy installations would burgeon, approximately reaching 350 million kW. The energy transition scenario foresees a swift development in gas, biomass, wind, and solar power, inducing a slight dip in coal consumption for use in power generation. Coal-fired power capacity is predicted to peak around 2025 and gently diminish post-2030. By 2060, the coal-fired power capacity will still be 10 million kW, while total wind and solar power installations will ascend to 360 million kW. Conversely, the extreme scenario propels non-fossil energy generation to its zenith, and after its peak around 2025, the older coal-fired power units will be sequentially decommissioned according to their standard retirement years. Henan Province is projected to retain a nominal coal-fired power capacity of approximately 2 million kW for heating and safety backup by 2060, amounting to less than 1% of the total capacity, while total wind and solar power installations are expected to attain 370 million kW.

Table 4. Forecast of electricity demand and the installed capacity of various power sources.

Year			2025	2030	2035	2060
Electricity demand (10^{11} kW·h)		Conservative Scenario	4.63	5.63	6.83	13.86
		Reference Scenario	4.86	5.91	6.98	14.57
		Extreme Scenario	5.12	6.36	7.12	15.33
Installed Capacity (10^5 kW)	Coal Power	Conservative Scenario	7601	7741	7817	2000
		Reference Scenario	7617	7761	7554	1000
		Extreme Scenario	7617	7501	6870	200
	Gas Power	Conservative Scenario	384	524	600	837
		Reference Scenario	400	544	600	814
		Extreme Scenario	400	544	600	814
	Hydroelectric Power	Conservative Scenario	418	429	440	483
		Reference Scenario	431	432	453	497
		Extreme Scenario	457	468	480	527
	Renewable Energy	Conservative Scenario	5113	7195	9506	35,000
		Reference Scenario	5313	7670	10,093	36,000
		Extreme Scenario	5618	7929	10,738	37,000

4.1.2. Other Industries: STIRPAT Model

The variable growth rates of the STIRPAT carbon emission forecasting model for five other key industries in Henan Province (steel, cement, transportation, coal, and chemical industries) under the three scenarios are set as follows:

1. Population. From 2011 to 2020, the average annual population growth rate in Henan Province was 0.55%. According to the current population situation in Henan Province and the China Population Development projections, it is projected that under the established policy scenario, the population of Henan Province will experience slow growth [43]. However, under the energy transition scenario and the aggressive replacement scenario, the population of Henan Province is expected to experience negative growth.
2. Urbanization rate. From 2011 to 2020, the urbanization rate in Henan Province increased at an average annual growth rate of 1.43%. Despite this relatively rapid growth, it still remained below the national average of 65.2% for China [44]. It is projected that with the improvement of the economic situation in Henan Province and industrialization, the urbanization rate will further increase at different rates under the three scenarios.
3. Per capita gross domestic product (GDP). From 2011 to 2020, the per capita GDP in Henan Province achieved an average annual growth rate of 8.6%, surpassing the national average of 6.1% in China [43]. However, the current per capita GDP in Henan Province stands at only CNY 62,000, significantly lower than the national average of CNY 82,000 per capita GDP. It is anticipated that under different scenarios, the per capita GDP in Henan Province will continue to experience robust growth at a relatively high level.
4. Industrial structure. From 2011 to 2020, the proportion of secondary industry in Henan Province decreased at an average annual rate of 1.23%. Currently, the proportion is approaching the national average of 39.4% in China [40]. Based on the predictions of IEA regarding industrial structure in China, estimations for the industrial structure of Henan Province under three different scenarios is estimated [45].
5. Energy structure. The proportion of natural gas and electricity consumption in Henan Province increased from 8% in 2011 to 21% in 2021 [22]. With the optimization of the future industrial energy consumption structure, the consumption proportion of clean energy sources such as natural gas and electricity is expected to increase significantly, leading to a great potential for emission reduction through consumption structure optimization.

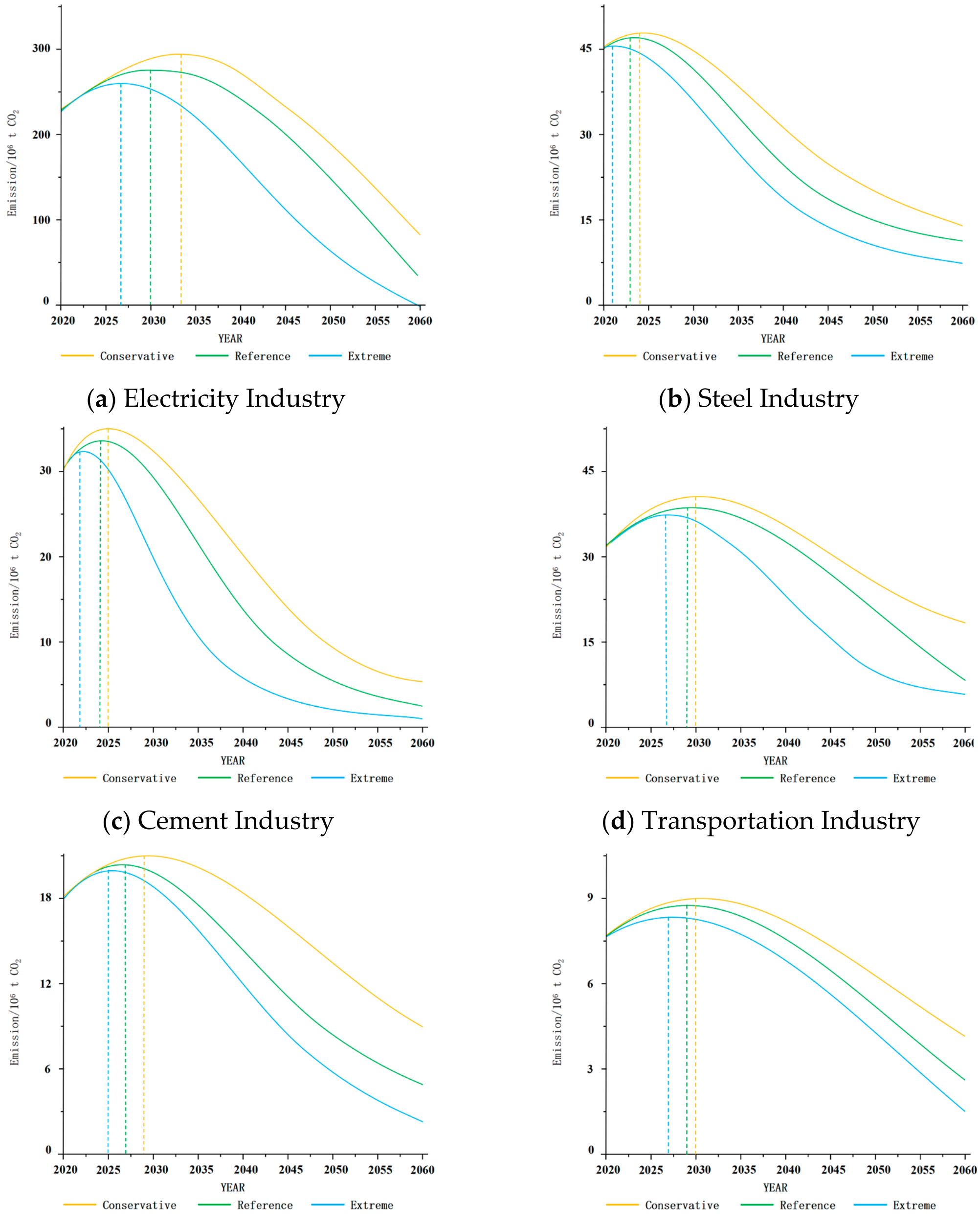
6. Industrial technology level. In the STIRPAT model, the two factors with the greatest impact on carbon emissions in each industry are selected as variables to measure the technological level of the industry. Based on the annual average growth rate of these variables from 2011 to 2020, the growth rates are predicted and set for the three scenarios, as shown in Table 5.

Table 5. Variations in influencing factors across industries in different scenarios.

Year				2020–2025	2026–2030	2031–2035	2036–2060
Population			Conservative Scenario	0.40%	0.20%	0.05%	0.01%
			Reference Scenario	0.50%	0.30%	−0.10%	−0.20%
			Extreme Scenario	0.60%	0.40%	−0.15%	−0.25%
Urbanization Rate			Conservative Scenario	1.20%	0.90%	0.70%	0.50%
			Reference Scenario	1.40%	1.10%	0.90%	0.70%
			Extreme Scenario	1.60%	1.30%	1.10%	0.90%
GDP Per Capita			Conservative Scenario	6.50%	5.50%	4.50%	3.50%
			Reference Scenario	7.50%	6.50%	5.50%	4.50%
			Extreme Scenario	8.50%	7.50%	6.50%	5.50%
Industrial Structure			Conservative Scenario	−0.50%	−0.50%	−0.50%	−0.50%
			Reference Scenario	−0.60%	−0.65%	−0.70%	−0.75%
			Extreme Scenario	−0.70%	−0.75%	−0.80%	−0.85%
Energy Structure			Conservative Scenario	8.00%	7.00%	5.50%	3.00%
			Reference Scenario	10.00%	9.00%	7.50%	5.00%
			Extreme Scenario	12.00%	11.00%	9.50%	7.00%
Industry Technology Level	Steel Industry	Crude steel production	Conservative Scenario	0.50%	−0.10%	−0.30%	−0.50%
			Reference Scenario	−0.50%	−1.00%	−1.30%	−1.50%
			Extreme Scenario	−1.00%	−1.20%	−1.50%	−2.00%
		Energy use per unit of steel produced	Conservative Scenario	−3.50%	−3.00%	−2.50%	−2.00%
			Reference Scenario	−4.50%	−4.00%	−3.50%	−3.00%
			Extreme Scenario	−5.50%	−5.00%	−4.50%	−4.00%
	Cement Industry	Cement production	Conservative Scenario	0.50%	−0.30%	−1.10%	−1.90%
			Reference Scenario	−0.50%	−1.50%	−2.50%	−3.00%
			Extreme Scenario	−1.50%	−3.00%	−4.50%	−6.00%
		Proportion of clinker	Conservative Scenario	−1.50%	−1.80%	−2.00%	−2.20%
			Reference Scenario	−1.80%	−2.00%	−2.30%	−2.50%
			Extreme Scenario	−2.00%	−2.30%	−2.70%	−3.00%
	Transportation Industry	Proportion of road transport turnover volume	Conservative Scenario	−4.50%	−3.00%	−2.00%	−1.00%
			Reference Scenario	−6.50%	−5.00%	−4.00%	−3.00%
			Extreme Scenario	−8.50%	−7.00%	−6.00%	−5.00%
		Transportation intensity	Conservative Scenario	6.00%	4.50%	3.00%	1.50%
			Reference Scenario	7.50%	6.00%	4.50%	3.00%
			Extreme Scenario	8.50%	7.00%	5.00%	4.00%
	Coal Industry	Coal production	Conservative Scenario	1.00%	0.50%	−0.50%	−1.00%
			Reference Scenario	0.50%	−0.50%	−1.00%	−1.50%
			Extreme Scenario	−0.50%	−1.00%	−1.50%	−2.00%
		Energy use per unit of coal produced	Conservative Scenario	−2.50%	−2.00%	−1.50%	−1.00%
			Reference Scenario	−3.50%	−3.00%	−2.50%	−2.00%
			Extreme Scenario	−4.50%	−4.00%	−3.50%	−3.00%
	Chemical Industry	Output per capita	Conservative Scenario	1.00%	1.20%	1.50%	1.80%
			Reference Scenario	2.00%	2.30%	2.50%	2.80%
			Extreme Scenario	2.50%	2.80%	3.20%	3.50%
		Fixed-asset investment	Conservative Scenario	12.00%	12.00%	12.00%	12.00%
			Reference Scenario	10.00%	10.00%	10.00%	10.00%
			Extreme Scenario	8.00%	8.00%	8.00%	8.00%

4.2. Results

Calculated according to the parameter settings, the projected carbon emissions from the electricity, steel, cement, transportation, coal, and chemical industries in Henan Province under the three scenarios are illustrated in Figure 8.



(**a**) Electricity Industry (**b**) Steel Industry

(**c**) Cement Industry (**d**) Transportation Industry

(**e**) Coal Industry (**f**) Chemical Industry

Figure 8. Carbon emission forecast results for key industries in Henan Province.

The forecast results regarding carbon emissions in the electricity industry indicate that under the conservative scenario of maintaining the current level of coal consumption for electricity generation in Henan Province, the power sector will not be able to peak before 2030. The peaking time is expected to be delayed by approximately three years, reaching 273.8×10^6 t in 2033. In the reference and extreme scenarios, characterized by the accelerated development of renewable energy sources and energy efficiency improvements, the total CO_2 emissions from the power industry are projected to peak between 2027 and 2030. The peak emission level is estimated to range between 259.7×10^6 t and 265.4×10^6 t, as illustrated in Figure 8a. In the extreme scenario, the electricity industry of Henan Province is expected to achieve zero emissions by 2060.

The predictive results indicate that the carbon emissions from the steel industry of Henan Province are currently at a peak plateau. It is projected that the CO_2 emissions have reached their peak between the years 2021 and 2024, as shown in Figure 8b, with a peak value ranging from 45.1×10^6 t to 48.3×10^6 t. Specifically, under the conservative scenario, carbon emissions from the steel industry are estimated to reach their peak in the year 2024. In the reference scenario, the peak for carbon emissions from the steel industry is anticipated to occur in 2023. In the extreme scenario, the peak in carbon emissions for the steel industry is projected to have occurred in 2021. It is anticipated that by 2060, the carbon emissions from the steel industry under the conservative, reference, and extreme scenarios will be 15.3×10^6 t, 11.8×10^6 t, and 7.4×10^6 t, respectively, making it challenging to achieve zero emissions for the industry.

Based on the designed emission scenarios, the CO_2 emissions from the cement industry of Henan Province for the years 2020–2060 are depicted in Figure 8c. In the conservative scenario, the cement industry is projected to reach its emissions peak around 2025, with a peak in carbon emissions of approximately 35.1×10^6 t. Under the reference scenario, the carbon emissions of the cement industry are expected to peak in 2024, reaching 33.7×10^6 t. In the extreme scenario, the carbon emissions of the cement industry are forecasted to have peaked in 2022 at 32.3×10^6 t. By the year 2060, it is anticipated that the carbon emissions from the cement industry of Henan Province will reduce to a range of 1.1×10^6–5.9×10^6 t across the three scenarios.

The CO_2 emissions from the transportation industry in Henan Province are projected to peak between 2027 and 2030, as shown in Figure 8d. In the conservative scenario, the carbon emissions from the transportation industry are expected to reach their peak in 2030, with a peak value of 40.2×10^6 t. By 2060, the emissions are anticipated to decrease by 21.7×10^6 t compared to the peak period. In the reference scenario, the carbon emissions of the transportation industry are estimated to peak in 2029 at 38.7×10^6 t. By 2060, the emissions are predicted to decrease by 30.6×10^6 t from the peak level. Under the extreme scenario, the carbon emissions are forecasted to peak in 2027 at 37.5×10^6 t. By 2060, a reduction of 32.1×10^6 t is projected compared to the peak period.

In the conservative scenario, the carbon emissions from the coal industry in Henan Province are projected to reach their peak in 2029, with an estimated peak value of around 24.0×010^6 t. Under the reference scenario, the coal industry is anticipated to achieve its emission peak in 2027, with this peak value being estimated at approximately 38.7×10^6 t. In the extreme scenario, the carbon emissions from the coal industry are expected to reach their peak as early as 2025, with a maximum projected emission of 37.5×10^6 t. By the year 2060, the carbon emissions from the coal industry in Henan Province are anticipated to decrease by 53.9% in the conservative scenario, by 79.1% in the reference scenario, and by 85.6% in the extreme scenario, compared to the peak period, as illustrated in Figure 8e.

Figure 8f visually illustrates the carbon emission projections for the chemical industry in Henan Province from 2020 to 2060. It is projected that the CO_2 emissions from the chemical industry in the province will peak between 2027 and 2030, with a peak range of 9.02×10^6–8.32×10^6 t. Specifically, under the conservative scenario, the carbon emissions from the chemical industry are estimated to peak in 2030. In the reference scenario, the peak is expected to be reached in 2029, with a peak value of 8.84×10^6 t. In the extreme scenario, the peak in the carbon emissions of the chemical industry is projected to occur in 2027. By the year 2060, the carbon emissions from the chemical industry are predicted to decrease to a range of 1.5×10^6–4.1×10^6 t across the three different scenarios.

4.3. Policy Implications

Based on the aforementioned research findings, we believe that, although current policies are comprehensive, they often lack actionable measures and the necessary support systems to achieve rapid industry transition. The existing regulatory environment might also be insufficient to address the unique challenges faced by specific sectors. Hence, we propose the following policy recommendations:

- Electricity Industry: Enhance the generating capacity of wind and solar energy, transitioning toward a predominantly renewable-based power generation system. Formulate and promote incentive mechanisms for renewable energy investments. Allocate provincial and national grants for renewable energy infrastructure. This would lead to a reduced dependency on non-renewable resources, fewer emissions, and job creation in the renewable energy sector;

- Steel and Cement Industry: Implement rigorous regulatory oversight for capacity adjustments and expedite the adoption of deep decarbonization techniques, such as fuel substitution and CCS technology. Achieving sustainable industry practices, reduced emissions, and cost-effective production can be facilitated through industry collaboration, technology transfers, or public–private partnerships and international cooperation;
- Transportation Industry: Emphasize the application of clean energy, especially the rapid adoption of electric vehicles. The government should offer tax incentives for electric vehicle users and invest in a charging infrastructure, thereby reducing emissions, decreasing reliance on fossil fuels, and improving air quality;
- Coal Industry: Advocate for a transition from reducing overall capacity to optimizing it, emphasizing the development of higher-grade coal capacity and progressively phasing out outdated and inefficient capacities. Introduce coal-grading standards and mandatorily phase out inefficient mines. Investment in cleaner coal technology should be made, coupled with retraining programs for displaced workers, aiming toward a more sustainable, efficient, and low-emission coal industry;
- Chemical Industry: Promote the transition to integrated petrochemical refining and a shift toward fine chemicals, prioritizing innovation and product diversification. Collaborate with leading international industry enterprises for technology transfers and research partnerships, fostering R&D funds and industry–academia–research collaboration. This would result in reduced emissions, improved product quality, and enhanced market competitiveness.

5. Conclusions

This in-depth analysis has elucidated the carbon emission trajectories of pivotal industries in Henan Province from 2020 to 2060. The six major sectors, electricity, steel, cement, transportation, coal, and chemicals, account for over 80% of the province's total emissions. Notably, while the steel and cement industries are anticipated to peak by 2025, transportation, coal, and chemicals are projected to peak by around 2030. The electricity sector might experience a delayed peak around 2033. An aggregate assessment predicts a potential reduction of approximately 296.1×10^6 t–387.2×10^6 t in emissions by 2060, relative to peak levels.

Although our research is rigorous, there are potential limitations in the predictive models, especially regarding long-term industrial trends. Given that the geographical focus of the study is on Henan Province, the findings might not be directly generalizable to other provinces or at the national level. We did not deeply account for external factors, such as global economic shifts, which might influence future development trajectories.

Thus, we propose several avenues for further research in the future. For instance, enhancing the predictive models by incorporating a broader range of variables, including factors such as global economic shifts, will help to improve prediction accuracy. As technological advancements emerge and industries evolve, it is imperative to periodically reassess the framework utilized in this study to ensure its sustained relevance. Integrating socio-economic indicators offers a more holistic approach for assessing the societal implications of industrial transitions. Additionally, as the economy progresses, new industries will emerge. Future research should take these sectors into account to provide a dynamic and evolving analysis.

In conclusion, while this research serves as a foundational exploration, it represents merely the onset of an extensive journey. It not only provides a solid foundation for further inquiry but also underscores the need for continuous refinement and adaptability.

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References

1. Abbass, K.; Qasim, M.Z.; Song, H.; Murshed, M.; Mahmood, H.; Younis, I. A Review of the Global Climate Change Impacts, Adaptation, and Sustainable Mitigation Measures. *Environ. Sci. Pollut. Res.* **2022**, *29*, 42539–42559. [CrossRef]
2. Wang, Q.; Li, S.; Pisarenko, Z. Modeling Carbon Emission Trajectory of China, US and India. *J. Clean. Prod.* **2020**, *258*, 120723. [CrossRef]
3. Dong, J.; Li, C.; Wang, Q. Decomposition of Carbon Emission and Its Decoupling Analysis and Prediction with Economic Development: A Case Study of Industrial Sectors in Henan Province. *J. Clean. Prod.* **2021**, *321*, 129019. [CrossRef]
4. Zhang, Y.; Li, S.; Luo, T.; Gao, J. The Effect of Emission Trading Policy on Carbon Emission Reduction: Evidence from an Integrated Study of Pilot Regions in China. *J. Clean. Prod.* **2020**, *265*, 121843. [CrossRef]
5. Guan, Y.; Shan, Y.; Huang, Q.; Chen, H.; Wang, D.; Hubacek, K. Assessment to China's Recent Emission Pattern Shifts. *Earth's Future* **2021**, *9*, e2021EF002241. [CrossRef]
6. Shan, Y.; Guan, D.; Zheng, H.; Ou, J.; Li, Y.; Meng, J.; Mi, Z.; Liu, Z.; Zhang, Q. China CO_2 Emission Accounts 1997–2015. *Sci Data* **2018**, *5*, 170201. [CrossRef]
7. Shan, Y.; Huang, Q.; Guan, D.; Hubacek, K. China CO_2 Emission Accounts 2016–2017. *Sci. Data* **2020**, *7*, 54. [CrossRef]
8. Shan, Y.; Liu, J.; Liu, Z.; Xu, X.; Shao, S.; Wang, P.; Guan, D. New Provincial CO_2 Emission Inventories in China Based on Apparent Energy Consumption Data and Updated Emission Factors. *Appl. Energy* **2016**, *184*, 742–750. [CrossRef]
9. Zhou, N.; Fridley, D.; Khanna, N.Z.; Ke, J.; McNeil, M.; Levine, M. China's Energy and Emissions Outlook to 2050: Perspectives from Bottom-up Energy End-Use Model. *Energy Policy* **2013**, *53*, 51–62. [CrossRef]
10. Wu, J.; Tang, G.; Wang, R.; Yanwei, S. Multi-Objective Optimization for China's Power Carbon Emission Reduction by 2035. *J. Therm. Sci.* **2019**, *28*, 184–194. [CrossRef]
11. Li, W.; Zhang, S.; Lu, C. Research on the Driving Factors and Carbon Emission Reduction Pathways of China's Iron and Steel Industry under the Vision of Carbon Neutrality. *J. Clean. Prod.* **2022**, *361*, 132237. [CrossRef]
12. Ofosu-Adarkwa, J.; Xie, N.; Javed, S.A. Forecasting CO_2 Emissions of China's Cement Industry Using a Hybrid Verhulst-GM(1,N) Model and Emissions' Technical Conversion. *Renew. Sustain. Energy Rev.* **2020**, *130*, 109945. [CrossRef]
13. Lin, B.; Xie, C. Reduction Potential of CO_2 Emissions in China's Transport Industry. *Renew. Sustain. Energy Rev.* **2014**, *33*, 689–700. [CrossRef]
14. Wang, D.; Nie, R.; Long, R.; Shi, R.; Zhao, Y. Scenario Prediction of China's Coal Production Capacity Based on System Dynamics Model. *Resour. Conserv. Recycl.* **2018**, *129*, 432–442. [CrossRef]
15. Geng, Z.; Zhang, Y.; Li, C.; Han, Y.; Cui, Y.; Yu, B. Energy Optimization and Prediction Modeling of Petrochemical Industries: An Improved Convolutional Neural Network Based on Cross-Feature. *Energy* **2020**, *194*, 116851. [CrossRef]
16. York, R.; Rosa, E.A.; Dietz, T. STIRPAT, IPAT and ImPACT: Analytic Tools for Unpacking the Driving Forces of Environmental Impacts. *Ecol. Econ.* **2003**, *46*, 351–365. [CrossRef]
17. Shi, A. The Impact of Population Pressure on Global Carbon Dioxide Emissions, 1975–1996: Evidence from Pooled Cross-Country Data. *Ecol. Econ.* **2003**, *44*, 29–42. [CrossRef]
18. Liddle, B. Demographic Dynamics and Per Capita Environmental Impact: Using Panel Regressions and Household Decompositions to Examine Population and Transport. *Popul. Environ.* **2004**, *26*, 23–39. [CrossRef]
19. Wang, P.; Wu, W.; Zhu, B.; Wei, Y. Examining the Impact Factors of Energy-Related CO_2 Emissions Using the STIRPAT Model in Guangdong Province, China. *Appl. Energy* **2013**, *106*, 65–71. [CrossRef]
20. Martínez-Zarzoso, I.; Maruotti, A. The Impact of Urbanization on CO_2 Emissions: Evidence from Developing Countries. *Ecol. Econ.* **2011**, *70*, 1344–1353. [CrossRef]
21. Industrial Classification for National Economic Activities. Available online: https://www.mca.gov.cn/images3/www/file/201711/1509495881341.pdf (accessed on 26 August 2023).
22. Henan Statistical Yearbook. Available online: https://tjj.henan.gov.cn/tjfw/tjcbw/tjnj/ (accessed on 26 August 2023).
23. Requirements of the Greenhouse Gas Emission Accounting and Reporting—Part 1: Power Generation Enterprise. Available online: https://www.chinesestandard.net/PDF/English.aspx/GBT32151.1-2015 (accessed on 26 August 2023).
24. Requirements of the Greenhouse Gas Emission Accounting and Reporting—Part 5: Iron and Steel Production Enterprise. Available online: https://www.chinesestandard.net/PDF/English.aspx/GBT32151.5-2015 (accessed on 26 August 2023).
25. Requirements of the Greenhouse Gas Emission Accounting and Reporting—Part 8: Cement Enterprise. Available online: https://www.chinesestandard.net/PDF/English.aspx/GBT32151.8-2015 (accessed on 26 August 2023).

26. The Provincial Greenhouse Gas Inventories. Available online: http://www.cbcsd.org.cn/sjk/nengyuan/standard/home/20140113/download/shengjiwenshiqiti.pdf (accessed on 26 August 2023).
27. Greenhouse Gas Emission Accounting Methodology and Reporting Guidelines for Coal Producers in China (Trial). Available online: https://www.ndrc.gov.cn/xxgk/zcfb/tz/201502/W020190905507324625877.pdf (accessed on 26 August 2023).
28. Mohajan, H. Dangerous Effects of Methane Gas in Atmosphere. Available online: https://mpra.ub.uni-muenchen.de/50844/ (accessed on 1 October 2023).
29. Greenhouse Gas Emission Accounting Methodology and Reporting Guidelines for Chemical Manufacturing Enterprises in China (Trial). Available online: https://www.ndrc.gov.cn/xxgk/zcfb/tz/201311/W020190905508184972266.pdf (accessed on 26 August 2023).
30. Wang, K.; Wang, S.; Liu, L.; Yue, H.; Zhang, R.; Tang, X. Environmental Co-Benefits of Energy Efficiency Improvement in Coal-Fired Power Sector: A Case Study of Henan Province, China. *Appl. Energy* **2016**, *184*, 810–819. [CrossRef]
31. Wang, Q.; Li, S.; Jiang, F. Uncovering the Impact of the COVID-19 Pandemic on Energy Consumption: New Insight from Difference between Pandemic-Free Scenario and Actual Electricity Consumption in China. *J. Clean. Prod.* **2021**, *313*, 127897. [CrossRef] [PubMed]
32. Dietz, T.; Rosa, E.A. Rethinking the Environmental Impacts of Population, Affluence and Technology. *Hum. Ecol. Rev.* **1994**, *1*, 277–300. Available online: https://www.jstor.org/stable/24706840 (accessed on 26 August 2023).
33. Shan, B.; Zhang, C.; Wang, X.; Yao, L.; Liu, Q.; Tan, X. Relationship between Electricity Elasticity Coefficient and Industrialization Stage in China. *Electr. Power* **2020**, *53*, 7.
34. Dong, Z.; Cheng, C. Analysis of variety status of electricity consumption elasticity coefficient in Henan. *Power Syst. Prot. Control* **2010**, *38*, 60–63. [CrossRef]
35. Burke, P.J.; Abayasekara, A. The Price Elasticity of Electricity Demand in the United States: A Three-Dimensional Analysis. *Energy J.* **2018**, *39*, 2. [CrossRef]
36. Wang, Q.; Li, S.; Li, R.; Jiang, F. Underestimated Impact of the COVID-19 on Carbon Emission Reduction in Developing Countries—A Novel Assessment Based on Scenario Analysis. *Environ. Res.* **2022**, *204*, 111990. [CrossRef]
37. Henan Provincial Bureau of Statistics. Available online: https://tjj.henan.gov.cn (accessed on 26 August 2023).
38. Henan Province Energy Development Report. Available online: https://www.pishu.com.cn/skwx_ps/bookdetail?SiteID=14&ID=13591186 (accessed on 26 August 2023).
39. Henan Province Electricity Industry Research Report. Available online: http://www.nrdc.cn/information/informationinfo?id=313&cook=2 (accessed on 26 August 2023).
40. China Energy Statistical Yearbook. Available online: http://www.stats.gov.cn/sj/ndsj/ (accessed on 26 August 2023).
41. Decomposition of Energy-Related CO_2 Emissions in China's Iron and Steel Industry: A Comprehensive Decomposition Framework. Available online: https://ideas.repec.org/a/eee/jrpoli/v59y2018icp103-116.html (accessed on 1 October 2023).
42. Li, R.; Li, L.; Wang, Q. The Impact of Energy Efficiency on Carbon Emissions: Evidence from the Transportation Sector in Chinese 30 Provinces. *Sustain. Cities Soc.* **2022**, *82*, 103880. [CrossRef]
43. Zhang, X.; Zhai, Z.; Tao, T. Trends and Patterns of Negative Population Growth in China. *Popul. Res.* **2020**, *44*, 3. Available online: https://rkyj.ruc.edu.cn/CN/Y2020/V44/I3/3 (accessed on 26 August 2023).
44. Yu, B. Ecological Effects of New-Type Urbanization in China. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110239. [CrossRef]
45. International Energy Agency-2020 World Energy Outlook. Available online: https://iea.blob.core.windows.net/assets/a72d8abf-de08-4385-8711-b8a062d6124a/WEO2020.pdf (accessed on 26 August 2023).