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*Original Research*

# Research on Public Building Carbon Emission Peak Paths in Mid-Latitude Inland Areas Based on LEAP Model: Case of Shanxi Province

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## Abstract

There is an emphasis on urban carbon peaking in the building industry, and public buildings (PB) are the major source of building industry carbon emissions. This research develops a model for forecasting PB's carbon emissions in Shanxi Province by using the LEAP model to analyze the carbon peaking time and carbon emission level under various scenarios for PB in Shanxi Province in 2021–2050. The findings indicate that: (1) The baseline scenario and the control area scenario do not reach the peak during the forecast period; the energy-saving scenario is synchronized with China's peak carbon target to peak in 2030; the green scenario is the optimal scenario set in this research and reaches the peak in 2025. (2) Controlling the public building area moderately can decrease carbon emissions and energy consumption to a great extent. (3) Carbon emissions can be reduced and peak times brought forward by reducing energy intensity, adjusting the energy structure, cleaning the heat network, and cleaning the grid. Finally, according to the prediction results, the carbon peak path of PB in Shanxi Province provides useful references for public building carbon emission reduction in the mid-latitude inland areas.

**Keywords:** carbon emissions, LEAP model, public buildings, scenario analysis

## Introduction

Scientific research observations have shown that global climate change has been significant in the past century as a result of accelerated industrialization and excessive human activities and that climate change has brought about a series of harms that have seriously damaged the human living environment and natural ecosystems. As the country with the highest GHG emissions and energy consumption in the world, China, in response to the current state of climate change and energy shortages, has committed to aim for carbon peaking by 2030 and carbon neutrality by 2060 [1, 2].

Buildings are one of the three main fields of energy consumption. The energy consumption of building operations is 30% of the world's total end-use energy consumption, as reported by the International Energy Agency (IEA), and buildings account for 40% of global carbon emissions [3], but due to the differences in the stages of development of each country, there is a large difference

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between the share of carbon emissions and energy consumption of buildings in various countries. In 2020, the share of China's total building and construction energy consumption in the national total energy consumption was 45.5%, and the total carbon emissions of the operating stage of China's buildings were about 21.7% of China's total societal emissions. Currently, a huge portion of China's building energy consumption is accounted for by PB [4]. In the last few years, the fast development of the tertiary sector has caused quick growth in public building areas, energy demand, and carbon emissions in urban areas [5, 6]. The public building area accounted for 21.68% of the overall building area in Chinese cities in 2021, while the total energy consumption of PB had reached 34.8% of China's overall city building energy consumption, with PB's total carbon emissions accounting for 32.7% of the total building carbon emissions [7]. As economic and social development and urbanization rates continue to increase, the share of PB in new buildings is rising every year, and the PB's carbon emissions and energy consumption will further increase [8, 9]. The PB in China has low energy conversion efficiency, high carbon emissions, multiple functions, and high energy consumption [4, 10]. The large volume of PB is an essential part of the building industry for energy savings and emission reduction. There is enormous potential for the building industry to reduce emissions [11, 12], and in addition, it is simpler to carry out the promotion of measures for energy conservation and abatement because a majority of PB are constructed with the government's participation [4].

As the environment, energy use, and level of socio-economic development vary among China's provinces, coupled with differences in construction scale and energy efficiency, it adds to the uncertainty of national carbon emission forecasts [13]. Thus, exploring provincial peak carbon paths in the construction sector becomes imperative for facilitating the accuracy of national forecasts and the fulfillment of targets.

Shanxi Province is located in North China, landlocked in a mid-latitude zone between longitude 110°14′–114°33′E and latitude 34°34′–40°44′N, covering 156,700 $Km^2$ with a temperate continental climate. As a typical resource-based, energy and high-carbon economy province in northern China, Shanxi Province is the richest in coal resources and more reliant on fossil energy for urban development. With large total carbon emissions and high carbon emission intensity, it is an arduous task and of enormous meaning to realize the dual-carbon target. Building energy consumption in Shanxi province now occupies over 18% of the province's energy consumption, and it will still be on the rise with economic and social development, so it is especially important to realize GHG emission reduction in Shanxi province and to explore a carbon peak path in line with the characteristics of the development of the region.

As a pilot of the energy revolution comprehensive reform during the 13th Five-Year Plan period, Shanxi Province has made significant progress in continuously popularizing green buildings, assembly-type buildings, and standardized construction, upgrading the building energy consumption. As a key energy-using sector, the building industry still faces challenges in energy savings and emission reduction. Shanxi Province has issued several plans and programs since the 14th Five-Year Plan, which are designed to ensure peak carbon performance in urban and rural construction, including low-carbon construction of PB.

The analysis of carbon emission reduction in PB in Shanxi Province can offer a theoretical basis and reasonable suggestions to inland regions in the same mid-latitude, which can help the government make effective emission reduction policies. It complies with the policy objectives and has a sound demonstration effect on promoting carbon peak throughout the building industry, which is meaningful to China's early realization of carbon peak. The results of this research complement the regional target of peak carbon forecasting in China. Although there are many existing peak carbon studies, there is no peak carbon research on PB based on regional climate and other characteristics. Shanxi, as a province with large carbon emissions and energy consumption, finds it of great practical significance to study the peak time and realization path. In addition to this, its findings can also provide a model for other similar regions, not only to provide a reference for similar provinces and cities such as Hebei, Tianjin, and Inner Mongolia to formulate policies to reduce emissions from PB, but also for similar provinces and cities in other developing countries to facilitate the sustainable development of human and natural environments.

## Literature Review

The building industry has gained wide concern from scholars in China and overseas because of its high carbon emissions and energy consumption, resulting in in-depth research on the building industry. Taking the core database resources of the Web of Science as the basis, this research sets the search keywords, article types, etc., and manually screens the acquired literature. Choosing the documentation metrics software, VOSviewer, to construct and visualize the analysis, a keyword contribution network diagram is generated so as to find the research hot spots and development trends in the field of architecture. The current state of research in architecture is visualized graphically as shown in Fig. 1, where circles and labels form an element, the size of the element depends on the strength of the nodes and connecting lines, etc., and various colors indicate various clusters. The research hot spots in architecture at home and abroad at this stage mainly focus on two aspects, as shown in Fig. 1.

Firstly, there is research related to energy consumption in buildings that focuses on the different energy-saving measures to be taken, including active, passive, and renewable energy applications, assessment methods, and energy-saving optimization. This is specifically reflected in the optimization of lighting [14], HVAC [15], envelope retrofitting [16], application of ground-source heat pumps [17], solar photovoltaic systems, etc. [18], life-cycle assessment [19], performance simulation [20], etc. the study on energy efficiency in buildings in foreign countries has an early origin, and this concept can be traced

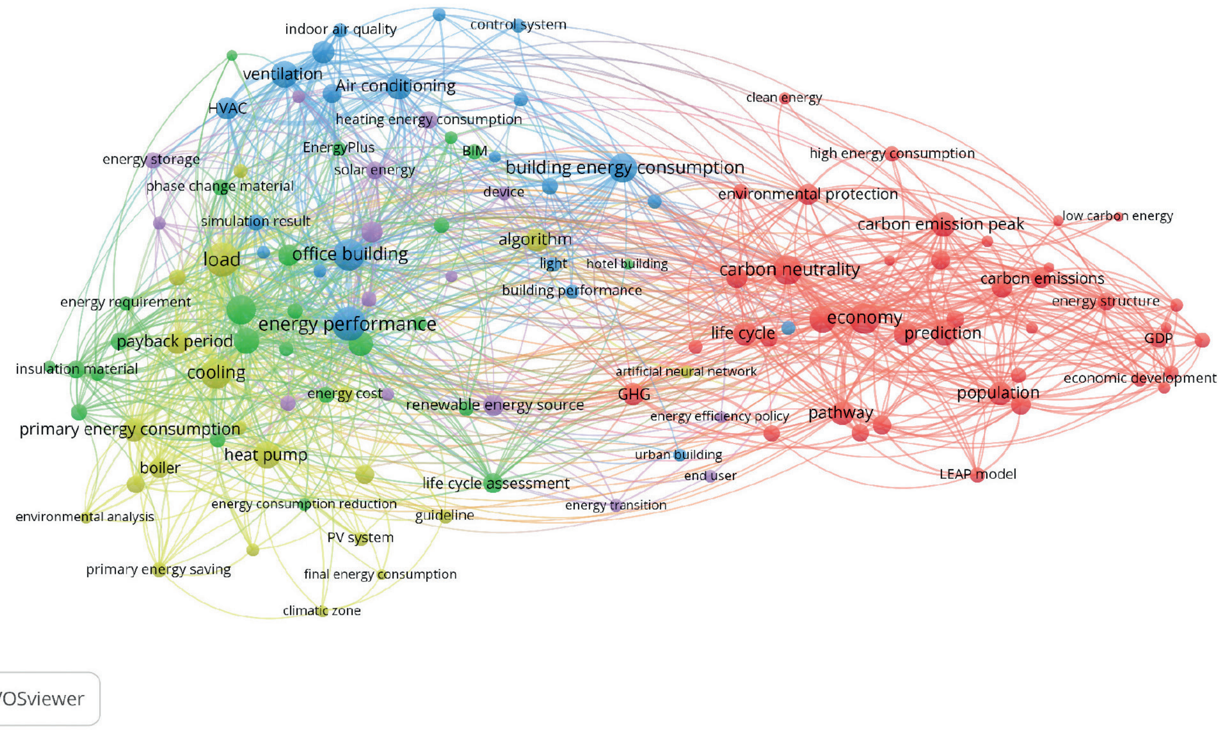


Fig. 1. Carbon emission visualization of the research status.

back to the 1970s. Bhatt et al. [21] used a sample of 8 typical residential buildings in Bangalore and 5 commercial buildings in New Delhi and found that the commercial buildings consume more energy than the office buildings. Mo et al. [22] developed a load model for hotels, hospitals, and office buildings, as well as compared the energy demand characteristics of each type of building. Franco et al. [23] investigated occupant-centered control strategies to improve the control of chillers and heat pumps to reduce energy demand in large non-residential buildings. China's low-carbon building concept started relatively late compared to foreign countries, beginning in the 1980s, mainly focusing on building energy efficiency. Numerous scholars have begun to conduct research on the building sector's energy use as energy-saving measures are vigorously implemented in buildings. Xue et al. [24], based on energy consumption field measurement data, discussed and analyzed the use and characteristics of energy and the energy conservation potential of large PB in Beijing. Wu et al. [25] proposed a synergistic optimization approach combining passive and active energy savings for renewable energy generation systems and building energy systems. Qiu et al. [26] developed a dynamic model of a photovoltaic/thermal system and ground source heat pump system (PVT-GSHP) for building energy supply based on TRNSYS and formulated a corresponding control strategy.

Secondly, studies related to building carbon emissions. The main research is on carbon emission forecasting, including influencing factors, forecasting methods, emission reduction pathways, and so on. In the background of global environmental issues, different models have been used in China and abroad by scholars to research the building industry's future emission trends and abatement paths. Forecasting models for GHG emissions can be categorized into three main types: top-down, bottom-up, and hybrid models [27, 28]. Among them, the top-down model is mainly applicable to macroeconomic analyses and energy policy planning research, which cannot predict the specific path of carbon peaking [29, 30]. Top-down models include the CGE model, the Kaya constant, the STIRPAT model, the EKC hypothesis, and the LMDI model [31]. Zhu et al. [32] explore the effects of implied carbon emissions of various energy-saving technology scenarios on the Chinese building industry by using the CGE model and show that the building industry's implied carbon emission reductions rely heavily on energy-saving technologies across the whole industry. Cong et al. [33] researched the drivers of $CO_2$ emissions from buildings in different regions of China under different climatic conditions by using the STIRPAT model. Mavromatidis et al. [34] analyzed carbon emissions from energy use at three separate sizes: the whole energy system, the building sector, and the small-scale community energy system in Switzerland, by applying the Kaya constant equation and evaluating various energy strategies. Zhang et al. [35] analyzed the factors influencing carbon emission in Xi'an from 2006 to 2020 by adopting the LMDI method

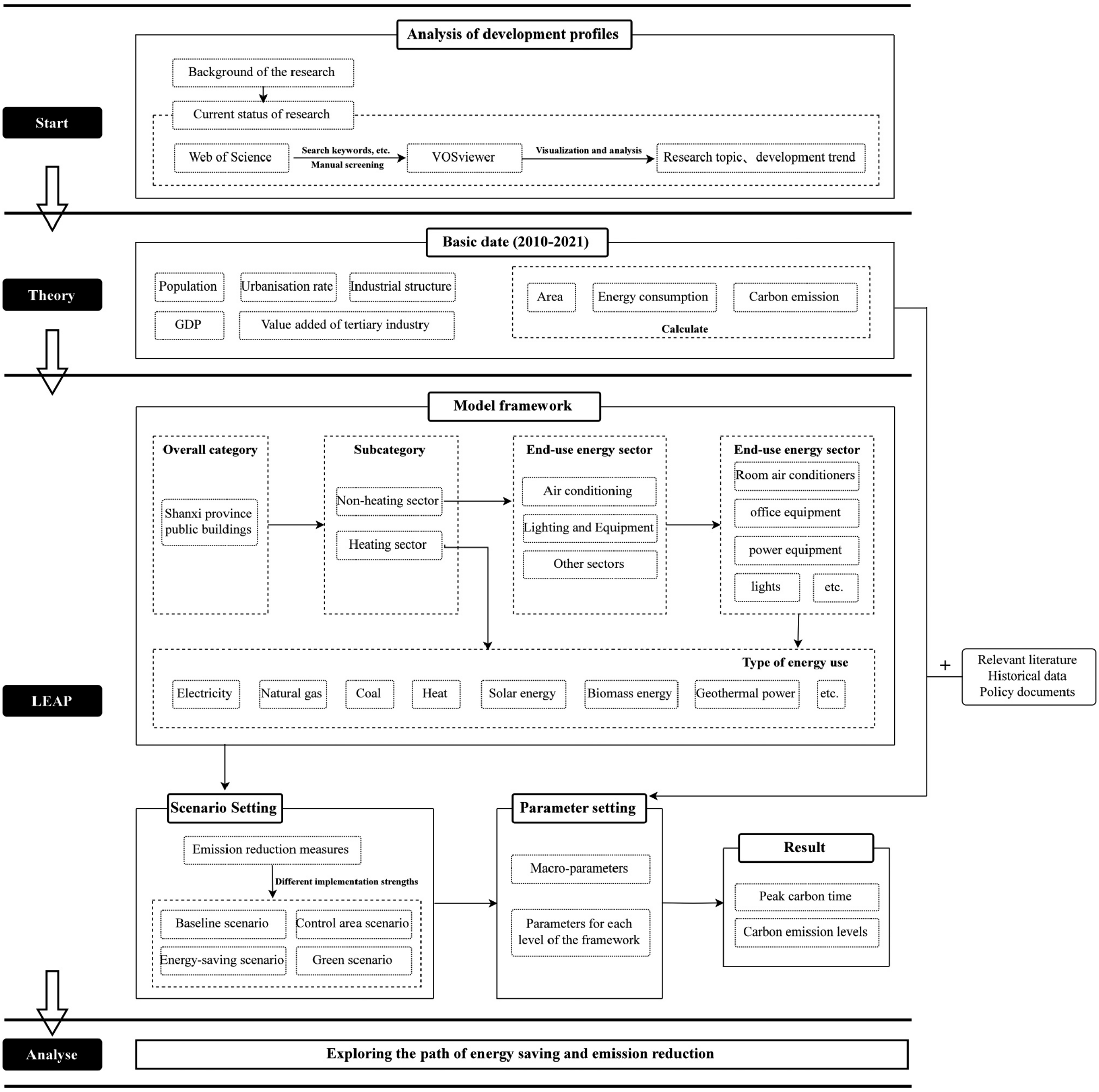


Fig. 2. Research framework.

and applying the STIRPAT model to simulate the carbon emissions under seven PB scenarios in the operation stage. The bottom-up model is an engineering and technical model as a starting point for describing and simulating energy efficiency measures, coupled with scenario analysis, to analyze the environmental impacts and identify appropriate abatement measures [36]. The bottom-up models consist of the MARKAL model, the EFOM model, the LEAP model, and so on. Among them, the LEAP model, as a quantitative energy, economic, and environmental analysis model, has been broadly used in energy demand forecasting recently [31, 37]. Subramanyam et al. [38] took Alberta, a western province of Canada, as an example and applied the LEAP model to set up 23 energy efficiency improvement scenarios for the commercial and office sectors, setting up a fast period and a slow period as the prediction cycle to simulate the reduction potential of different technologies and the amount of carbon reduction. Kusumadewi V. T. and Limmeechokchai B. [39] applied LEAP modeling to analyze the reduction potential of energy efficiency and renewable energy in Indonesian and Thai residential buildings. As for China, predicting national, provincial, and municipal carbon emissions and peak emissions in the building industry has become an important area of concern for researchers and scholars [40, 41]. Based on the LEAP model, various researchers and scholars have simulated and predicted the time to peak and carbon emissions under various scenarios in the building industry in China [4, 42], Heilongjiang [43], Chongqing [29, 44], Shenzhen [45], Shanghai [46], and so on, and derived the potential for emission reductions from each measure, as well as carried out the analysis of emission reduction pathways and policy recommendations. However, there is still a lack of research in this area in Shanxi Province, which is China's major energy province with high carbon emissions. Especially, there is no research on PB in Shanxi Province as an entry point, and this research can fill this gap. The LEAP model has been criticized for its subjectivity in scenario setting and weak focus on key parameters, despite its proven effectiveness as a tool for forecasting carbon emission trends. Thus, to enhance the simulations' accuracy, more attention to scenario setting and parameter assignment is needed. However, hybrid models are complex and multidisciplinary in structure, which is not favorable for decision-making [28]. Hybrid models include the NEWS model, etc.

The above summary shows that despite the groundwork laid by the vast amount of available research on building carbon emissions, there are still deficiencies: 1) Among the available studies on carbon emissions in the building industry, most focus on the whole sector, especially residential and commercial buildings, while PB is still lacking in research. 2) The regional targets of building carbon emission prediction studies mostly focus on the national level and southern Chinese cities, while resource-based cities like Shanxi Province receive less attention. The research aims to simulate and predict the peak level of carbon emissions under various scenarios by using the LEAP model for PB in Shanxi Province as a research target. Then, we discuss the carbon emission peak paths and countermeasure suggestions for PB in Shanxi Province, depending on the forecasting results. It is shown in Fig. 2 as the research framework.

## Experimental

### Research Subject Definition

According to the property of usage, China's buildings can be classified into civil, industrial, and agricultural buildings. Of these, industrial buildings include plants (machine shops, workshops), warehouses, auxiliary ancillary facilities, etc., due to the functional nature of the building compared to other building types with greater energy consumption. Agricultural buildings are those that carry out agricultural and livestock production and processing, which are characterized by small-scale and low energy consumption, which are generally ignored. Civil buildings are the major source of building energy consumption; as per their use, they can be categorized into residential buildings and PB. PB are classified into office buildings, commercial and service buildings (department stores, hotels, restaurants, and other service buildings), scientific research and education buildings (research institutes, teaching buildings, libraries, etc.), culture, sports, and recreation buildings (cultural centers, gymnasiums, theaters, etc.), health and medical care buildings (all types of medical institutions, wards, medical buildings, outpatient clinics, health clinics, pharmacies, and other houses), and other buildings (transportation buildings, communication buildings, post and telecommunications buildings, etc.).

When accounting for building carbon emissions, the life cycle assessment methods and social emission inventory methods for the whole building sector are generally used, both of which account for the total amount of $CO_2$ emissions during the manufacturing of building materials, constructing, operating, and using of buildings, as well as dismantling and disposing of buildings, with the difference that the life cycle assessment focuses on the cumulative carbon emissions from a single building during its life cycle, while the inventory method is primarily used to make a macro analysis of the whole field of buildings, a certain region, and a country's building-related carbon emissions [7]. The operational stage of the building is the major part of the contribution to carbon emissions from the building industry as a whole [35, 47]. As of 2021, the ratio of the building operation phase to China's total social energy consumption was 21%, and to China's total $CO_2$ emissions from energy activities, it was about 21% [7], and this ratio will continue to increase with China's development of society and economy and urbanization rate increase. Hence, the inventory method is used in this study to account for the operational-phase carbon emissions of PB.

Operational energy consumption during building use, including energy input from the outside and used to maintain the building environment (e.g., lighting, ventilation, cooling, heating, etc.) and various types of activities in the building (e.g., office, cooking, etc.).

### Calculation Method

The year-by-year recursive method is used to calculate the public building area in Shanxi Province [48, 49], and the calculation method is based on the energy balance sheet put forward by Huo et al. [50] to calculate the buildings and PB energy consumption in Shanxi Province in 2010–2021. It is calculated that the public building area in 2021 accounted for approximately 21.7%, while it already took up 36.7% of the total building energy consumption.

Building operational carbon emissions consist mainly of carbon emissions generated by the direct burning of fossil fuels and the indirect use of non-fossil energy sources (e.g., heat, electricity) during the operational process of buildings. To calculate carbon emissions by using the emission factor method (IPCC inventory method), the basic rule of calculation is the multiplication of the carbon emission factor and the energy consumption. The Equation is as follows:

$$E_{emissions} = E_d + E_{id} \tag{1}$$

$$E_d = \sum_{i=1}^{n} AD_i \times EF_i \tag{2}$$

$$E_{id} = E_{el} + E_H \tag{3}$$

$$E_{el} = AD_{el} \times EF_{el} \tag{4}$$

$$E_H = AD_H \times EF_H \tag{5}$$

Where $E_{emissions}$ is PB's total $CO_2$ emissions ($tCO_2$). $E_d$ is PB's direct carbon emissions due to fossil fuels ($tCO_2$). $E_{id}$ is the indirect carbon emissions of PB due to purchased heat and electricity ($tCO_2$). $AD_i$ is the i$^{th}$ fossil fuel amount consumed in PB (tce). $EF_i$ is the i$^{th}$ fossil fuel's $CO_2$ emission factor ($tCO_2$/tce). $E_{el}$ is the indirect carbon emissions of PB due to purchased electricity ($tCO_2$). $AD_{el}$ is the purchased electricity of the public building (MWh). $EF_{el}$ is the $CO_2$ emission factor for electricity ($tCO_2$/MWh). $E_H$ is the indirect carbon emissions of PB due to purchased heat ($tCO_2$). $AD_H$ is the purchased heat of PB (GJ). $EF_H$ is the $CO_2$ emission factor for heat ($tCO_2$/GJ).

## Scenario Analysis

Scenario analysis (SA) is mainly based on generating future scenarios based on assumptions and analyzing their impacts on objectives through forecasting and simulation. SA is capable of describing a wide range of possible future outcomes, which has the advantage of enabling managers to avoid overestimating or underestimating future trends and impacts by analyzing long-term uncertainty scenarios in the absence of data and quantitative factors. From a macro perspective, the SA is more applicable to the fields of climate change, energy planning, and carbon emission projections due to its ability to effectively depict the process of future changes [44].

## LEAP Model

LEAP is an integrated modeling tool in the energy systems analysis model that is mainly used in the middle and long-range energy outlook of countries and cities. It can foresee pollutant emissions, GHG emissions, and energy demand under the effects of different drivers and can be used to conduct GHG emissions reduction analyses and integrate resource utilization planning [51]. A flexible data structure and convenience of operation are the advantages of the LEAP model [27, 52]. Users can construct their own data structure according to the type of study, purpose, and data availability and give the environmental impacts, costs, and technical characteristics of the environmental technologies, which is conducive to decision-making for policy analysis.

## Data Sources

With 2021 as the baseline year, historical data from 2010–2021, and a projection period from 2022–2050. The data on population, buildings, and other related data of Shanxi Province in the past years were obtained from the National Development and Reform Commission, the China Energy Statistical Yearbook, the China Statistical Yearbook, the Shanxi Provincial Statistical Yearbook, and related literature and research.

## Scenario Setting

### *Influencing Factors*

Considering the situation of Shanxi Province, this research selects population, urbanization rate, GDP, industrial structure, public building area, per capita public building area, energy intensity, and energy structure as key driving factors. The connection between the driving factors and carbon emissions and energy consumption is shown in Fig. 3.

### *Social Factor*

As the scale of China's PB continues to grow, carbon emissions also continue to grow. Among them, social factors also play a large role, including population, urbanization rate, GDP, industrial structure, etc.

Population is one of the central drivers of the building industry's carbon emissions [53]. In particular, changing resident populations will affect changes in demand for PB and subsequently changes in public building energy consumption. The population of Shanxi Province in 2022 was 34.8135 million people, according to the latest data, which is a rebound from the population in 2021. The population forecast in this research adopts the Leslie population model established by Liu et al. [54]. The population of Shanxi Province is realistically estimated to peak around 2025, with a subsequent slow decline, based on available data and considering the trend of population growth in Shanxi Province under the three-child policy. The urbanization process leads to the rise in the urban population and is accompanied by the construction of large-scale public infrastructure and the expansion of urban building areas [55]. The urbanization rate in Shanxi Province has been increasing, and the urbanization rate was 63.42% in 2021, which is in the medium-term acceleration stage. GDP is an essential factor in measuring the status and level of development of a country or region's economy, and it also determines the industrial structure of the city [23]. Among them, there is a strong relationship between the tertiary industry's economic activities and the PB's carbon emissions [56], and due to the rapidly developing tertiary sector, the PB is increasing in scope.

To sum up, macro-social factors directly affect public building areas, which in turn affect carbon emissions and energy consumption.

### *Per Capita Public Building Area*

Per capita public building area is the major factor influencing carbon emissions. The per capita public building area in Shanxi province was below 11 $m^2$/person in 2021

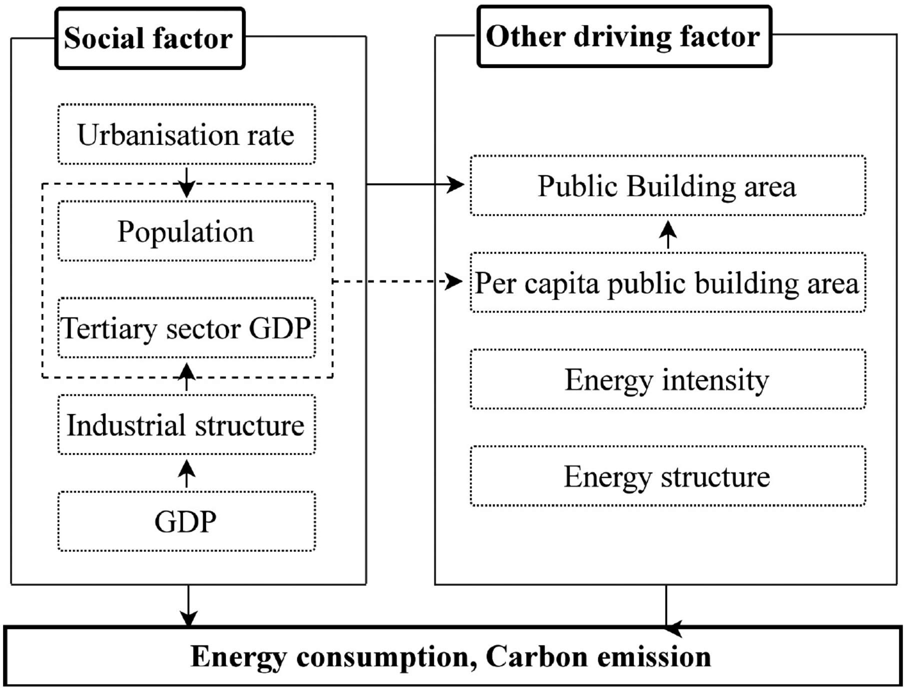


Fig. 3. Driving factor links and impacts.

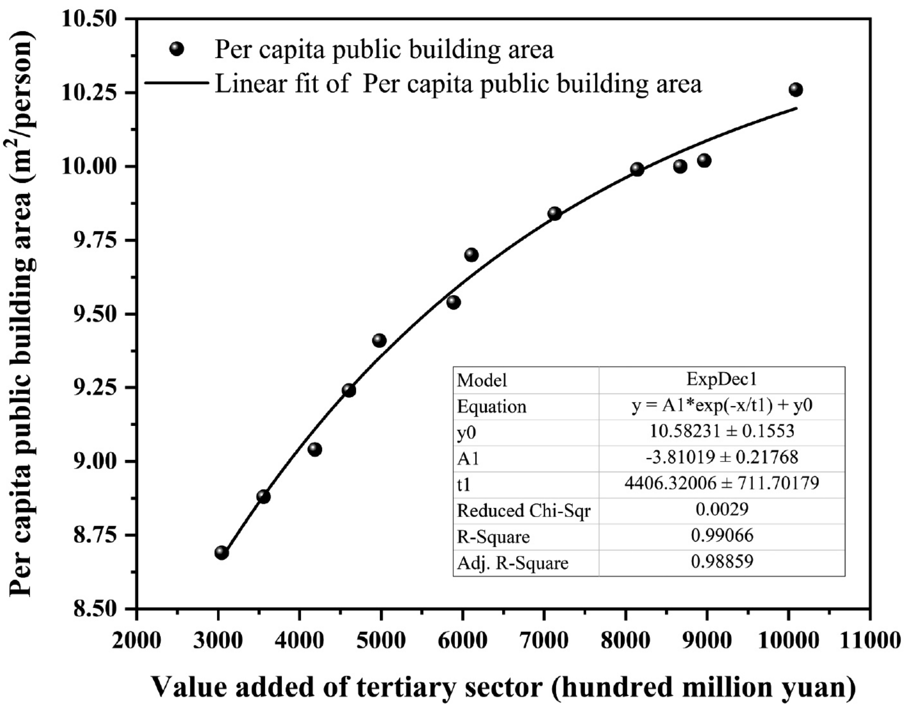


Fig. 4. Linear fit between the value added of the tertiary sector and per capita public building area.

and will continue to grow as the economy and society continue to develop. According to relevant literature and research, the tertiary sector has a greater influence on per capita public building areas with no policy guidance [44, 57]. Taking the value added of the tertiary sector and per capita public building area from 2010 to 2021 as historical data, the functional relationship between the two is constructed, as shown in Fig. 4, to predict the future public building area.

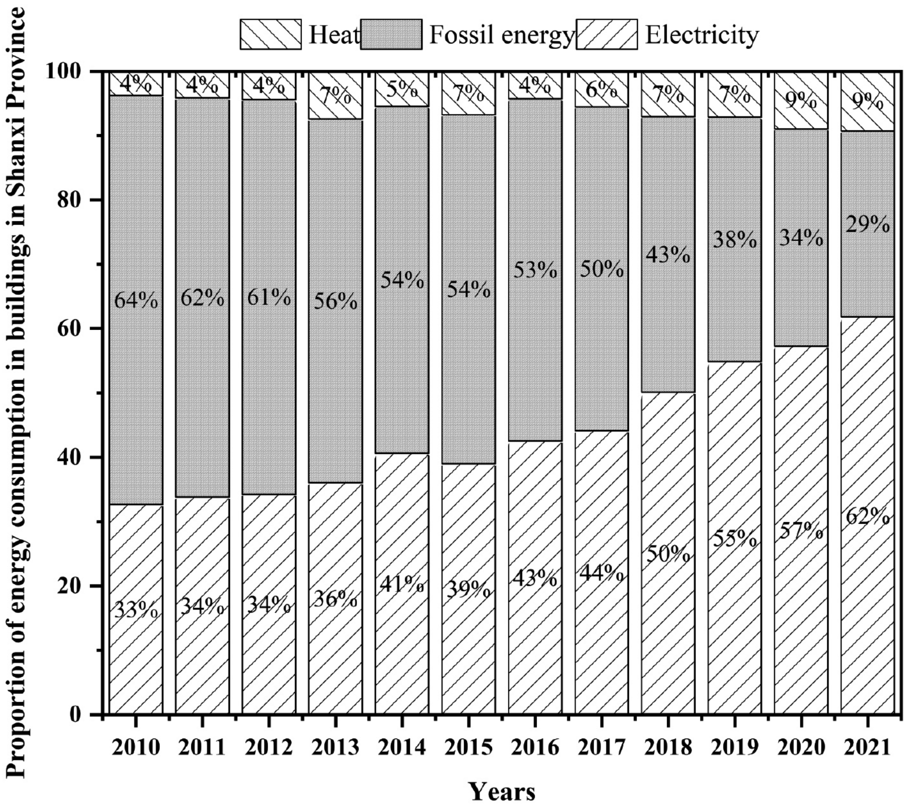


Fig. 5. Energy consumption share of PB in Shanxi Province, 2010–2021.

*Energy Intensity*

PB has raised the unit area energy consumption from 17 kgce/m$^2$ in 2001 to over 24.7 kgce/m$^2$ in 2020 in China, which is about three times the annual energy consumed by residential buildings [58]. This research is summarized based on literature and research data. The average unit area electricity consumption of PB of each type in Shanxi Province is 50–130 kWh/m$^2$, with commercial and service buildings being the highest, and the unit area power consumption of large PB can even reach more than 300 kWh/m$^2$. At the same time as the growth of PB in recent years, large-volume buildings are also growing significantly; their unit building area power consumption is above 100 kWh/m$^2$. This part, because of the building volume and form constraints on energy intensity, is much more than ordinary PB, which is also a major cause of the continuous growth of PB's energy intensity [58].

*Energy Structure*

Optimization of the energy structure is essential for achieving carbon peaks [59]. The major energy sources consumed by buildings are coal, gasoline, diesel, natural gas, heat, and electricity. Among them, electricity is used for air conditioning, office equipment, lighting, power equipment, etc. Fossil energy sources are used for household hot water, cooking, building heating, etc. Heat is used to provide domestic hot water and heating. As shown in Fig. 5, in the last decade, the share of electricity in buildings has gradually grown to 62%, while the fossil energy ratio is gradually declining to 29%, and the share of centralized heating has remained basically stable.

## Historical Data Simulation

The raw data on carbon emissions for PB in Shanxi Province in 2010–2021 were calculated from Eqs. (1)–(5), and the carbon emissions in this phase were simulated using the LEAP model. The relative error is within 3%, which is good for simulation, and the results are shown in Table 1. Hence, it is feasible to use the LEAP model to forecast future carbon emissions from PB in Shanxi Province.

## Scenario Setting and Parameter Setting

According to the carbon emission and energy consumption of PB and the implemented policies, technologies, and measures for energy savings and emission reduction in buildings in Shanxi Province, considering the target planning for carbon peaking in Shanxi Province, four carbon peak prediction scenarios are developed: the baseline scenario (BAS), the control area scenario (CON), the energy-saving scenario (ENE),

Table 1. Results of carbon emission simulation for PB in Shanxi Province, 2010–2021.

| Years | Original data (Million $tCO_2$) | Simulation data (Million $tCO_2$) | Relative error (%) |
|---|---|---|---|
| 2010 | 20.05 | 20.30 | 1.27 |
| 2011 | 22.21 | 22.05 | -0.73 |
| 2012 | 23.54 | 22.86 | -2.86 |
| 2013 | 24.13 | 23.96 | -0.68 |
| 2014 | 22.49 | 21.99 | -2.21 |
| 2015 | 23.86 | 23.59 | -1.14 |
| 2016 | 24.22 | 23.52 | -2.89 |
| 2017 | 26.45 | 27.23 | 2.97 |
| 2018 | 28.69 | 28.97 | 0.99 |
| 2019 | 27.77 | 28.07 | 1.08 |
| 2020 | 27.49 | 27.91 | 1.55 |
| 2021 | 28.13 | 28.05 | -0.28 |

Table 2. Emission reduction measures.

| Measures | Specific measures |
|---|---|
| Energy conservation retrofits of existing buildings | Strengthening energy-use systems and enclosure structure renovation, enhancing heating and air-conditioning system efficiency, accelerating the popularization of LED lighting fixtures, and so on. |
| Energy-efficiency upgrading of new buildings | Raising energy efficiency standards, improving envelope performance, and adopting energy-efficient technologies. |
| Electrification rate | Actively promoting the substitution of electricity for gas and oil and promoting the electrification of cooking, heating, and other building energy. |
| Application of renewable energy | Promoting the construction and application of solar thermal and photovoltaic integration, carrying out shallow geothermal energy applications in accordance with local conditions, and increasing the share of renewable energy used in cooking, domestic hot water, cooling, and heating. |
| Cleaning the heat network | Adjusting the structure of heat supply systems, popularizing and applying geothermal energy, air thermal energy, biomass energy, industrial waste heat, etc., in accordance with local conditions, to address the demand for heat supply in buildings, and reducing the indirect carbon emissions from purchased heat. |
| Cleaning the grid | Reducing the use of fossil energy, vigorously promoting solar, wind, and other renewable energy generation, and decreasing electricity carbon emission factors. |

and the green scenario (GRE). The main ways to control carbon emissions are: reducing energy intensity (RED), including energy conservation retrofits of existing buildings and energy efficiency upgrades of new buildings; adjusting the energy structure (ADJ), including electrification rates and the application of renewable energy; cleaning the heat network (HEA); and cleaning the grid (GRI). As shown in Table 2, for a specific description of the different measures. The structure of the scenario setting is shown in Fig. 6, where CON, ENE, and GRE have the same area, as described below.

BAS: the reference scenario, this research uses 2021 as the baseline year, and scenarios are planned according to the document in accordance with the policies, measures, and technical means currently adopted; no scenarios are set at times outside the documented planning. Under this scenario, the building area grows at the average annual growth rate; by 2025, the energy conservation retrofit area of existing buildings will reach 2.801 million $m^2$, and the retrofit will achieve an overall energy efficiency improvement of more than 20%; by 2025, the new PB will implement 72% of the local standards, and the level of energy efficiency will increase by 20% compared to 2020; by 2025, the renewable energy replacement rate will reach 8%; and other settings will maintain the present situation.

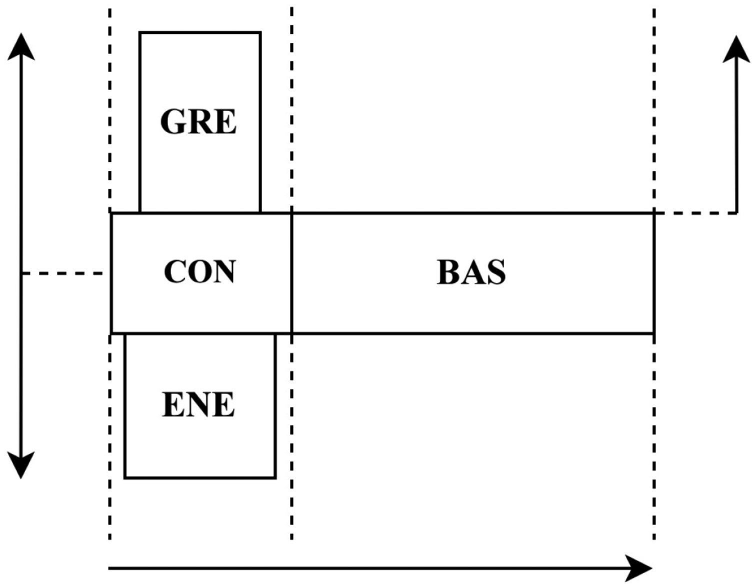


Fig. 6. Scenario Setting.

Table 3. End-use energy sector parameter settings.

| | | Non-heating sector (kWh/m$^2$) | | | Heating sector (GJ/m$^2$) |
|---|---|---|---|---|---|
| | | Air conditioning | Lighting and equipment | Other sectors | |
| Base Year | 2021 | 34.42 | 24.58 | 15.66 | 0.40 |
| BAS | 2025 | 34.36 | 24.42 | 15.60 | 0.395 |
| CON | 2025 | 34.29 | 24.36 | 15.57 | 0.394 |
| ENE | 2030 | 34.08 | 24.14 | 15.43 | 0.391 |
| | 2040 | 31.48 | 22.07 | 14.16 | 0.36 |
| | 2050 | 28.50 | 19.75 | 12.67 | 0.34 |
| GRE | 2030 | 33.97 | 24.07 | 15.39 | 0.389 |
| | 2040 | 29.74 | 20.79 | 13.37 | 0.34 |
| | 2050 | 25.72 | 17.68 | 11.45 | 0.30 |

CON: the area is controlled according to the projections of population and public building area per capita based on the BAS, and the other settings remain unchanged.

ENE: based on the CON in accordance with the improved rhythm of the BAS, the energy conservation retrofit area of existing buildings will reach 2.801 million m$^2$ every five years; by 2030, new PB will be 10% more energy efficient than they were in 2025 and then 30% more energy efficient every 10 years thereafter; renewable energy utilization; the heat sector maintaining BAS settings; increasing the ratio of clean energy generation with decreasing power grid carbon emission factors.

GRE: setting up on the basis of the CON. Before 2030, the energy conservation retrofit area of existing buildings will reach 2.801 million m$^2$ every five years, and after 2030, the energy conservation retrofit area of existing buildings will reach 5.602 million m$^2$ every five years; the level of energy-efficiency upgrading of new buildings will be improved by 20% every five years; increasing the electrification rate; increasing the utilization rate of renewable energy; adjusting the structure of heat supply to limit coal-fired boiler use, increasing the proportion of heat supplied by renewable energy sources with decreasing heat carbon emission factors; further increasing the ratio of power generation by clean energy sources with decreasing power grid carbon emission factors.

As per the settings and descriptions of various scenarios, the end-use energy sector's parameters are set in Table 3.

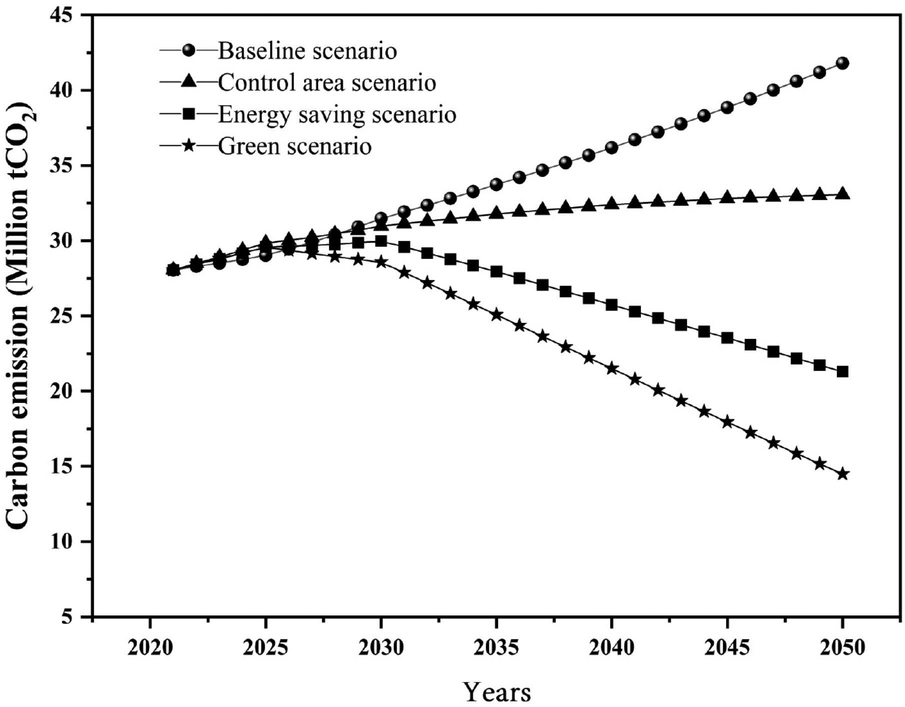


Fig. 7. Forecasts of total carbon emissions for various scenarios, 2021–2050.

## Results and Discussion

According to the constructed LEAP model for PB in Shanxi Province, the set parameters in the four scenarios are inputted to simulate and predict the trend of PB's total carbon emissions and energy consumption in Shanxi Province.

### Carbon Emission Forecasting Results and Analysis

The tendency of carbon emissions from PB in Shanxi Province in 2021–2050 is shown in Fig. 7. The public building area in the BAS grows at an average annual rate. Although carbon emissions grow slowly in 2021–2025 due to energy savings and emission reduction measures, they grow with the rapid expansion of PB throughout the forecast period and do not peak. Although the CON has an obvious impact on reducing carbon emissions due to controlling the size of PB, it still falls short of the peak over the forecast period. Under the BAS and CON, even with the implementation of existing measures and policies and reasonable control of the size of PB, it is still not possible to fulfill the target of peaking in 2030, which requires further measures to save energy and reduce emissions. The ENE builds on the CON, vigorously promotes energy conservation transformation technologies, reduces the overall carbon emission level of PB, and achieves peak carbon emissions in 2030, synchronizing with China's carbon peaking target. The peak is 29.99 million $tCO_2$, and the carbon emissions in 2050 will be 21.29 million $tCO_2$. The ENE's carbon emissions are lower than the CON's as a whole. For the optimal scenario proposed in this research, the GRE continues to promote energy-saving transformation technologies, ADJ, vigorously develop clean energy and renewable energy, and optimize energy use so as to achieve peak carbon emissions in 2025. The peak is 29.59 million $tCO_2$, and the carbon emission in 2050 will be 14.49 million $tCO_2$. Hence, through implementing carbon reduction measures, it is entirely feasible for PB to achieve a carbon peak by 2030.

### Analyze the Contribution of Carbon Reduction Measures

Fig. 8a) shows the breakdown of carbon emissions with various carbon reduction measures superimposed. It is evident that various carbon reduction measures can reduce carbon emissions. Among them, ADJ is an effective way to control the rise in carbon emissions, which could reach its peak in 2035. The reduction in energy intensity peaks in 2030, substantially reducing carbon emissions in the forecast period. Therefore, the government needs to further strengthen the energy-saving retrofits of existing buildings and continuously improve the energy-saving requirements for new buildings. The strong promotion of clean energy for heat and power generation and reducing the fossil energy use ratio will be critical to achieving the peak carbon targets, which will peak in 2030 for heat source cleaning and in 2025 for grid cleaning.

The contribution of superimposed measures to carbon reduction in 2050 is shown in Fig. 8b). The contributions are, in descending order, GRI, RED, HEA, and ADJ. It

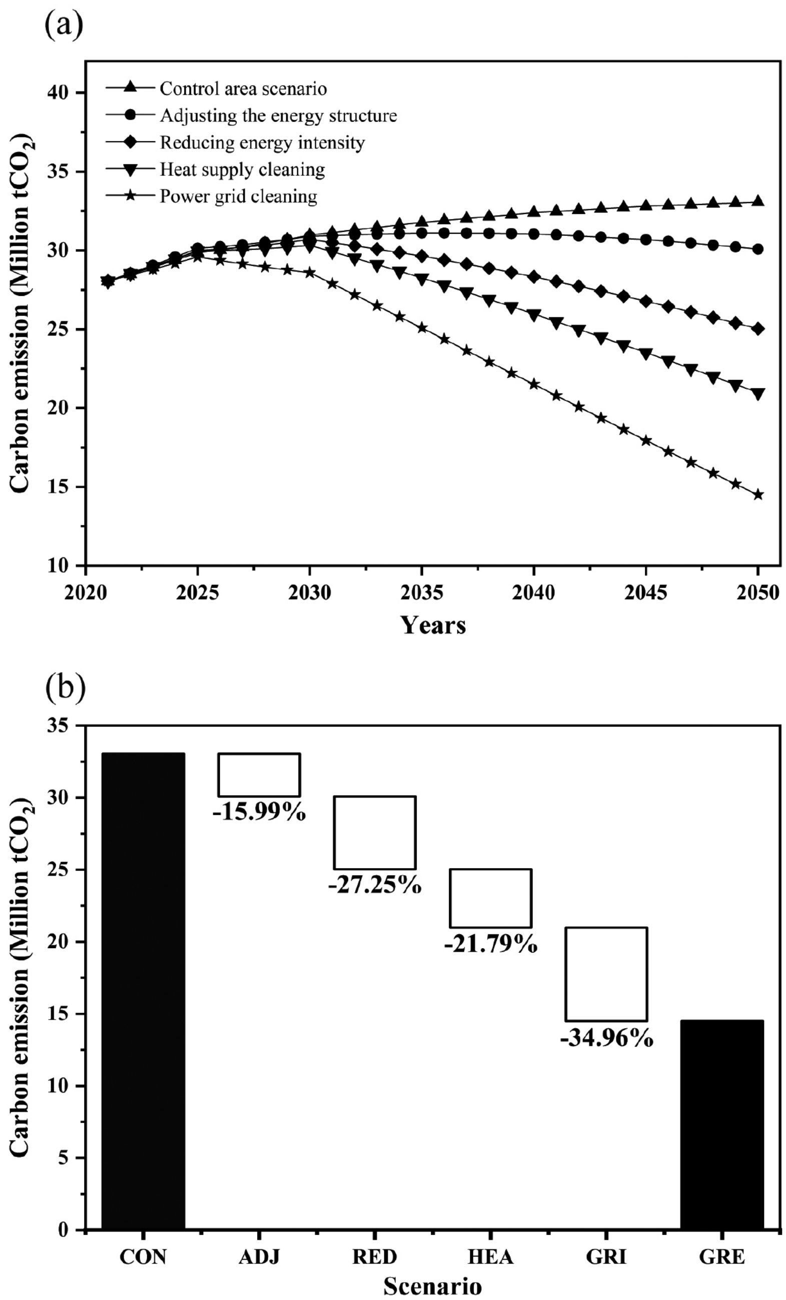


Fig. 8. Stacking various carbon reduction measures (a) Carbon emissions (b) Contribution in 2050.

is clear that achieving carbon peaking in PB requires the cooperation of various sectors. The implementation of two autonomous energy-saving methods for PB, namely ADJ and RED, could reach its peak in 2030. PB should fully open up the implementation of energy-saving methods under the current mode of development. Adopting building energy-saving technologies, strengthening energy-use system renovation, and improving maintenance structure performance and energy-saving standards. Optimizing energy use and increasing the ratio of electrical use in PB, including heat pumps, electric kitchens, etc. The electrification of buildings is a necessary way to boost renewable electrical energy use in buildings. Increasing the use of geothermal energy, photovoltaic, and other renewable energy sources in PB. The government should also formulate appropriate policies to promote the implementation of energy-saving technologies and the enforcement of energy-saving standards. On this basis, HEA and GRI are indispensable external measures to reduce carbon emissions and accelerate the fulfillment of carbon peaking. The heating method in Shanxi Province is based on a centralized heat supply, which mainly includes cogeneration and coal-fired boilers. The government should attach importance to adjusting the structure of the heat supply system and adopting geothermal energy and air thermal energy to solve the heat supply demand in accordance with local conditions, so as to achieve HEA. The ratio of renewable energy power generation has reached 17.75% in Shanxi Province in 2021, mainly based on wind power and solar power. In order to promote a deep low-carbon transformation of the power sector, the policy should be formulated by the government to raise the proportion of electricity generated by renewable energy sources and gradually build a new type of power system.

## Conclusions

Under the background of global energy shortages, climate issues, environmental issues, and China's dual-carbon target, this research constructs a LEAP model relating total carbon emissions and energy consumption of PB in Shanxi Province on the basis of the development situation of PB in Shanxi Province, combining with the SA method to put forward four scenarios: the BAS, the CON, the ENE, and the GRE, in order to simulate and predict the peak time and peak level of PB in Shanxi Province. The major findings are as follows:

(1) The building area and energy consumption of PB were estimated. Combined with relevant literature and research data, it is known that commercial and service buildings have the highest energy consumption and great potential for energy savings.

(2) In all four scenarios, the BAS and CON do not reach their peak, but controlling the growth of public building areas can significantly reduce carbon emissions. Both the ENE and GRE can reach the peak carbon target, with carbon emissions from PB peaking under the ENE in 2030 and under the GRE in 2025.

(3) The largest to smallest carbon reduction contributions of each measure in 2050 are GRI, RED, HEA, and ADJ, of which ADJ will peak in 2035, RED and HEA will both peak in 2030, and GRI will peak in 2025.

By researching the carbon emission status and reduction potential of PB in Shanxi Province, this research can not only make up for the shortcomings of the existing literature but also provide a theoretical basis and reasonable suggestions for PB's energy savings and emission reduction in Shanxi Province.

### Carbon Emission Reduction Pathway Proposal

(1) Reasonable control of the development of PB. Relevant policies should be launched by the government to control the scope of developments in PB, reduce the strength of exploitation in the real estate industry and PB, decrease the vacancy rate of PB, and alleviate the current situation of supply exceeding demand.

(2) Reducing energy consumption in PB. Increase the energy-saving renovation of existing PB, including mainly the energy conservation retrofit of the envelope and energy-consuming equipment; improve the standard of energy conservation in new buildings; promote green buildings; increase the proportion of assembled buildings in the total building area; and comprehensively promote green building materials. Relevant departments should ensure the implementation of energy conservation standards and energy conservation retrofits.

(3) Increase the use of clean energy in PB. Continuously advance the construction and use of solar thermal and photovoltaic integration, and according to local conditions, popularize the application of geothermal energy, air thermal energy, biomass energy, industrial waste heat, etc., to address building heating, domestic hot water, and other energy demands. Establishing a system of building energy consumption centered on electricity consumption and vigorously promoting solar, wind, and other renewable energy generation. Promote the green, efficient, and clean utilization of coal and reduce coal and other fossil energy use proportions.

Establishing a comprehensive platform for monitoring building energy consumption. Proactively carry out energy audits, improve the energy-saving statistical system, and statistically summarize the energy consumption situation of energy equipment at PB. Enhancing the oversight and tracking management of energy-using units and establishing an energy consumption monitoring platform to provide data support for energy conservation and carbon reduction in PB.

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## Conflict of Interest

The authors declare no conflict of interest.

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