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Dynamic simulation of carbon peak pathways in Shandong province of China driven by energy system optimization

Chang Shu[1], Feng Xu[1], Shengnan Li[2], Nan Xiang[2*]

1 School of Economics and Management, Beijing University of Chemical Technology, Beijing 100029, China

2 College of Economics and Management, Beijing University of Technology, Beijing 100124, China
(*Corresponding Author: xiangnan@bjut.edu.cn)

ABSTRACT

As the world's largest energy consumer and carbon emitter, China accounted for 26.5% of global energy consumption and 31% of carbon dioxide (CO_2) emissions in 2021; Shandong province as a heavy industry intensive base in China, confronted with the most imminent task of energy conservation and emission reduction. With pursue on "carbon peak and neutrality", Shandong province need to transfer the high-carbon energy system fundamentally to accomplish the high-quality development. To explore the timetable and roadmap of carbon peak in Shandong province, this research integrates the input-output modelling, system dynamics and multi-objective programming, and innovatively develops the carbon peak model. The model focuses on energy structure transformation and energy efficiency improvement, including incentives for electrification level increase, renewable power (such as wind and solar power) penetration enhancement, and low-carbon technology investment, combined with industrial restructure. A dynamic simulation measure is adopted to predict Shandong province's economy-energy-carbon development from 2020 to 2035. The research can provide a useful reference for formulating operatable energy management and carbon peak schemes in industrially developed regions such as Shandong province.

Keywords: carbon peak, energy system optimization, energy management, input-output model, dynamic simulation

NONMENCLATURE

Abbreviations	
GDP	Gross Domestic Production
CO_2	Carbon dioxide
Symbols	
t	Year
n	Industrial sector
e	Energy
ρ	Social discount rate
v	Value-added rate

1. INTRODUCTION

China, as the world's largest energy consumer and carbon emitter, accounted for 26.5% and 33% of global energy consumption and carbon dioxide (CO_2) emissions in 2021, respectively [1,2]. Therefore, energy conservation and emissions reduction are urgent priorities. As the important contributors to economic growth, characterized of high energy consumption and heavy environmental burdens, the industrially developed regions face the dilemma of achieving coordinated development between the economy and the environment. These regions serve as crucial leverage points for energy conservation and emissions reduction.

Shandong, as a typical heavy industry base in China, contributed 7% of the total Gross domestic production (GDP) in 2021, ranking third [3]. Its total energy consumption and CO_2 accounted for 8.5% and 9.4% of the country, respectively [4], making it a key area for carbon reduction in China [5]. However, the issue of an imbalanced energy structure in Shandong province remains prominent [6], particularly evident in the high proportion of coal consumption and coal-fired power generation, which severely hinder high-quality and low-carbon development.

Under the constraints of "carbon peak and neutrality" target [7], Shandong province urgently needs to optimize its energy system and explore a roadmap for

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achieving the peak of carbon emissions. Such research can provide scientific decision-making references for other industrially developed regions in formulating energy management and carbon peaking plans. that offer opportunities for translation into sustainable solutions.

Currently, studies on carbon peaking in Shandong province have explored the pathway and policy implications from various aspects, including economic transformation [8], energy efficiency improvement [9], and energy structure adjustment [10]. Furthermore, low-carbon pathways for key industries such as steel [11], cement [12], and electricity [13] have been investigated. However, the research on carbon peaking in Shandong province is still insufficient, and the pathway for carbon peaking remains unclear.

In order to explore the timetable and roadmap for carbon peaking, scholars have conducted predictive research on carbon emission trends. The main predictive methods include Stochastic Impacts by Regression on Population, Affluence, and Technology model (STIRPAT) [14], Long-range Energy Alternatives Planning System (LEAP) [15], Kaya model [16], system dynamics model [17], and dynamic scenario analysis [18]. As a complex system, the provincial level involves intricate interactions among the economy, energy, and environment systems (3E). The parameters considered in current research are exogenous settings, often overlooking the internal mechanisms of interactions between elements within the system. Input-output models can systematically reveal the balance and connections between economic sectors, making it an important tool for implementing industrial structure adjustments [19]. Additionally, system dynamic model can be used to study the interactions among multiple subsystems, such as the economy, society, and environment, making it suitable for complex system modeling and dynamic predictions.

Based on the aforementioned research gaps, this study integrates input-output models, system dynamics, and multi-objective programming to simulate and predict the carbon peaking pathway for Shandong province from 2020 to 2035, driven by measures such as energy efficiency improvement, energy structure transformation and industrial structure optimization, and provides decision-making basis for Shandong Province to optimize its energy system.

2. RESEARCH METHODS

This study employs the system dynamics approach to elucidate the coupling mechanisms among the 3E systems in Shandong province. Additionally, based on input-output theory, a predictive model for carbon peaking in Shandong province is constructed. The multi-objective programming is used to simulate various measures to achieve carbon peaking. In this study, in addition to industrial production, carbon emissions from residential activities are also taken into account.

Fig. 1 presents the framework of the research. The simulation is based on the baseline of the current situation in 2017, with the objective function being the maximization of GDP and achieving carbon peaking before 2030. The comprehensive simulation model includes three sub-models: the social-economic model, the energy model, and the environmental model. The social-economic model reflects the industrial structure and economic development trends, while the energy model focuses on the energy production and consumption process under measures such as improving energy consumption efficiency and adjusting renewable energy generation. The environmental model includes constraints on both the total and intensity of carbon dioxide emissions.

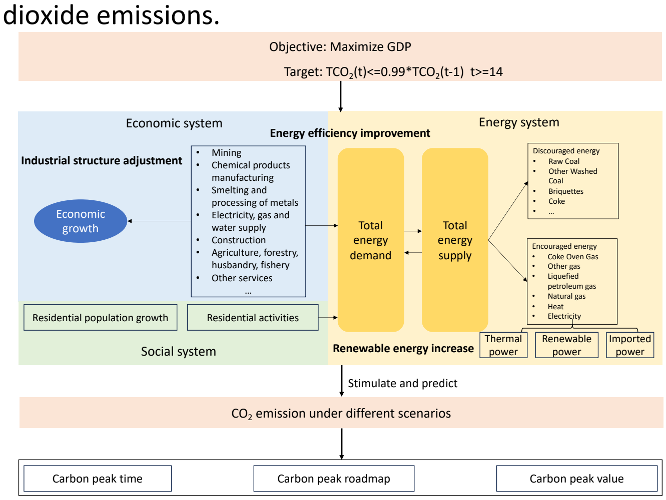

Fig. 1. The framework of the Shandong carbon peak model

2.1 *Model formula*

2.1.1 Objective function and constraints

$$Max \sum_t \frac{1}{(1+\rho)^{t-1}} GDP(t) \quad (1)$$

$$GDP(t) = \sum_{n=1}^{20} v_n * X_n(t) \quad (2)$$

where t is the simulation period, with values from 1(2017) to 19(2035); $GDP(t)$ is the gross domestic production of Shandong in year t, ρ is the social discount rate (5%), $X_n(t)$ is the output of industry n in year t, and v_n is the value-added rate of industry n. The study categorized the industrial sectors into 20 sectors n.

Table 1. Classification of industry sectors in 2017

n=1	Agriculture, forestry, husbandry, fishery
n=2	Mining

n=3	Food and tobacco processing
n=4	Textile industry
n=5	Processing of timber and furniture
n=6	Manufacture of paper, printing and articles for culture, education and sport activity
n=7	Petroleum Processing and Coking
n=8	Chemical products manufacturing
n=9	Nonmetal Mineral Products
n=10	Smelting and processing of metals
n=11	Metal Products
n=12	General and special purpose machinery manufacturing
n=13	Transport equipment and electrical machinery manufacturing
n=14	Electronic and Telecommunications Equipment
n=15	Other Manufacturing Industry
n=16	Electricity, gas and water supply
n=17	Construction
n=18	Transport, Storage, Postal & Telecommunications Services
n=19	Wholesale, Retail Trade and Catering Service
n=20	Other services

The constraints of this model is set to peak before 2030, that is, after 2030, CO_2 will decrease year by year. CO_2 emission calculation can be found in Eq. (17).

$$TCO_2(t) \leq TCO_2(t-1)(t \geq 14) \quad (3)$$

2.1.2 Economic system

Based on input-output theory and considering industrial development and consumer demand, socio-economic models reflect the level of socio-economic development of a country or region, including intersectoral input and output, household and government consumption, net exports and population.

(1) Input-output balance

Simulations are built Input-output models to reveal the relationships between the various industries.

$$a_{ij} = \frac{x_{ij}}{X_j} \quad (4)$$

$$A_{nn} = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix} \quad (5)$$

$$X_n(t) \geq A_{nn} * X_n(t) + C_n(t) + G_n(t) + I_n(t) + E_n(t) - M_n(t)(n = 1, \dots, 20) \quad (6)$$

where A_{nn} is a direct consumption coefficient matrix calculated according to the input-output table of Shandong Province in 2017; $C_n(t)$ is the consumption column vector; $G_n(t)$ is the government expenditure column vector; $I_n(t)$ is the investment column vector; $E_n(t) - M_n(t)$ is the net export column vector.

(2) Population growth model

$$Z(t+1) = (1 + 0.65\%) * Z(t) \quad (7)$$

where *Z(t)* is the population in year *t*; 0.65% is the average natural growth rate of the permanent population of Shandong Province from 2012 to 2017, and the model assumes that the population growth rate will remain at 0.65% in the simulation period.

2.1.3 Energy supply and demand model

(1) Energy supply and demand

Total energy demand consists of 20 industrial sectors and residential consumption, including 16 energy types.

Table 2. Types of energy consumption

e=1	Raw Coal
e=2	Other Washed Coal
e=3	Briquettes
e=4	Coke
e=5	Coke Oven Gas
e=6	Other Gas
e=7	Crude Oil
e=8	Gasoline
e=9	Kerosene
e=10	Diesel Oil
e=11	Fuel Oil
e=12	Liquefied petroleum gas
e=13	Refinery Gas
e=14	Natural Gas
e=15	Heat
e=16	Electricity

$$TES(t) = \sum_{e=1}^{16} ES_e * SCF_e(t) \quad (8)$$

$$TED(t) = \sum_{n=1}^{20} ECI_n(t) * X_n(t) + ECI_z * Z(t) \quad (9)$$

$$TES(t) \geq TED(t) \quad (10)$$

where $TES(t)$ represents the total energy supply in year *t*, $ES_e(t)$ is the physical quantity of energy *e* in year *t*, SCF_e is the standard coal coefficient of energy *e*; $TED(t)$ represents the total energy demand in year t; $ECI_n(t)$ is the energy consumption coefficient of section *n*; ECI_z is the energy consumption coefficient of residents.

(2) Energy structure adjustment

To drive the development of non-fossil energy and optimize the energy structure, in conjunction with the end-consumption situation in Shandong Province, the model classifies energy into two categories. The first category is discouraged energy, which includes Raw Coal, Other Washed Coal, Briquettes, Coke, Crude Oil, Gasoline, Kerosene, Diesel Oil, Fuel Oil, Refinery Gas. The consumption of this category of energy is constrained by physical quantities. The second category is encouraged energy, which includes coke oven gas, other gas, liquefied petroleum gas, natural gas, heat, and electricity. The consumption of this category of energy is linked to the output value of industries.

$$TED(t) = \sum_{e=1}^{20} SCF_e * (EDR_e(t) + EDI_e(t)) \quad (11)$$

$$EDR_e(t) = \sum_{n=1}^{20} EDR_e^n(t) + EDRI_e^z * Z(t), e = 1,2,3,4,7,8,9,10,11,13 \quad (12)$$

$$EDI_e(t) = \sum_{n=1}^{20} EDII_e^n * X_n(t) + EDII_e^z * Z(t), e = 5,6,12,14,15,16 \quad (13)$$

$EDR_e(t)$ is the physical consumption of discouraged energy *e* in year *t*, $EDI_e(t)$ is the physical consumption of encouraged energy *e* in year *t*; $EDR_e^n(t)$ refers to physical consumption of discouraged energy *e* in sector *n* in year t; $EDRI_e^z$ refers to the physical energy consumption intensity of the discouraged energy *e* in residential sector; $EDII_e^n$ is the physical energy consumption intensity of encouraged energy *e* in sector *n*, $EDII_e^z$ is the physical energy consumption intensity of encouraged energy *e* in residential sector.

(3) Electricity supply and demand model

The power structure in Shandong province consists of thermal power generation, renewable energy generation, and electricity imported from other provinces.

$$TELECS(t) = ELEC_{thp}(\mathrm{t}) + ELEC_{reg}(\mathrm{t}) + ELEC_{im}(\mathrm{t}) + LOST(t) \quad (14)$$

$$TELECD(t) = \sum_{n=1}^{20} ELECI_n * X_n(t) + ELECI_z(t) * Z(t) \quad (15)$$

$$TELECS(t) \geq TELECD(t) \quad (16)$$

where $TELECS(t)$ represents the total power supply in year *t*; $ELEC_{thp}$ represents the thermal power generation in year *t*; $ELEC_{reg}(t)$ represents the renewable power generation in year *t*; $ELEC_{im}(t)$ represents the electricity imported from other provinces in year *t*; $TELECD(t)$ represents the total power demand in year *t*; $ELECI_n$ represents the electricity consumption coefficient of the sector *n*; $ELECI_z(t)$ represents the electricity consumption coefficient of residential sector in year *t*; $L(t)$ is the power loss in year *t*.

2.1.4 CO_2 emission model

CO_2 emissions come from industrial production activities and residential energy consumption.

$$TCO_2(t) = \sum_{e=1}^{16} EF_e * (EDR_e(t) + EDI_e(t)) - EF_{16} * ELEC_{reg}(\mathrm{t}) \quad (17)$$

where $TCO_2(t)$ is the total carbon emissions in year *t*, and EF_e is the carbon emission factors of the energy *e*.

2.2 Scenario setting

To analyze the carbon peaking pathway in Shandong province under different measures, three policy scenarios have been established: Policy Scenario (S1), Energy Efficiency Improvement Scenario (S2), and Comprehensive Scenario (S3).

Table 3. Scenario setting

	Industrial structure adjustment	Renewable energy increase	Energy efficiency improvement
S1	+	+	
S2	+	+	+
S3	+	++	+

Table 4. Renewable energy increase

Renewable energy increase: Renewable power proportion increase			
	2025	2030	2035
（+）	Renewable power is developing at an average annual growth rate of no more than 10%		
（++）	0.27-0.3	0.38-0.4	0.47-0.5

In 2017, the chemical industry, metal smelting and processing industry, as well as the production and supply of electricity, heat, gas, and water, collectively contributed 11% to the GDP but consumed 38% of the energy and emitted 39% of the carbon dioxide. Therefore, it is essential to focus on improving efficiency in these three key industries.

Table 5. Energy efficiency improvement setting

Energy efficiency improvement：energy consumption coefficient decrease			
	2025	2030	2035
Chemical products manufacturing	17%	20%	25%
Smelting and processing of metals	17%	20%	25%
Electricity, gas and water supply	17%	20%	25%
Other industries	7%	10%	18%

Sensitivity testing is one of the means to verify the effectiveness of a model. In this study, the deviations between CO_2, total end-consumption and the actual values are within 5%.

3. RESULTS

3.1 Carbon peak time and peak prediction

Under different scenarios, there are differences in economic development and carbon peaking, but all scenarios aim to reach the peak by 2030 (as shown in Fig. 2). In S1, the economy maintains an average annual growth rate of 4.4% between 2020 and 2035, with a peak of 1,275 million tons in 2030. In this scenario, the development of energy-intensive and pollution-intensive industries, such as the chemical industry and metal smelting, is sacrificed (with a 3% and 14% decrease in GDP in 2035 compared to 2020, respectively), resulting in the lowest peak value. In S2, with improved energy efficiency, the vitality of industrial development increases, and the economic growth rate accelerates to 5% per year, resulting in a peak value of 1,354 million tons. The peak value in this scenario is relatively high. In S3, further increasing the proportion of renewable energy, the economic growth rate increases to 5.2%, and the peak value is reduced to 1,348 million tons.

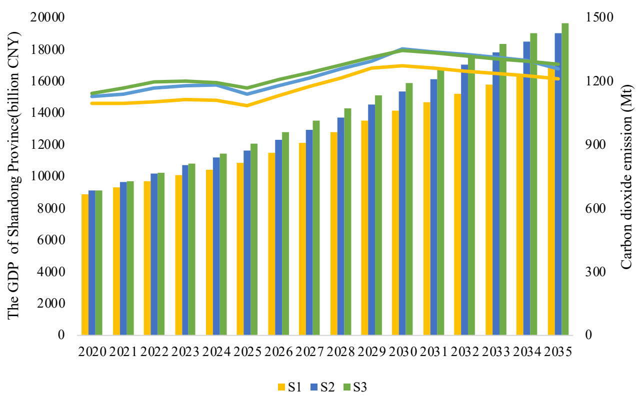

Fig. 2. GDP and CO_2 emissions under three scenarios

3.2 Industrial structure analysis

Fig. 3 illustrates the changes in industrial structure in 2035 under the three scenarios. In all three scenarios, the service sector dominates in Shandong province, accounting for over 60%, with the highest percentage in S1 at 64.3% and 62% in S2 and S3. Improved energy efficiency in industries and further increase in the proportion of renewable energy stimulate the development of the industrial sector. By 2035, the share of the secondary industry increases from 29.1% in S1 to 32.4% in S2 and 32.7% in S3. Among them, the chemical industry undergoes the significant growth, with GDP reaching 680 billion yuan in S1 and up to 1,229 billion yuan in S3, achieving an 81% increase. Compared to 2017, the industry's economic output proportion decreases from 7.3% to 4% in S1 and 6.3% in S3.

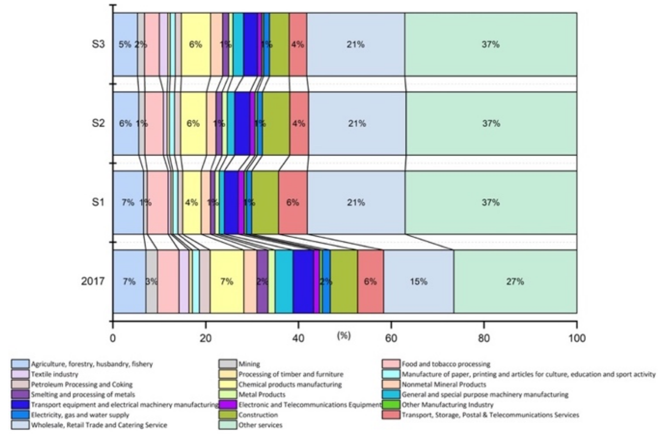

Fig. 3. Industrial structure in 2035 under three scenarios

3.3 Energy structure analysis

In three scenarios, the proportion of end-consumption electricity exceeds 30% in 2035, reaching 37.8% in S3. In S1, the proportion of thermal power generation is 56% in 2025, and the proportion of renewable power generation reaches 19%. By 2035, these proportions change to 24% and 40%, respectively. However, in S2, due to the increasing demand for electricity but a constant speed of renewable power generation, the proportion of renewable power decreases to 33% in 2035. In S3, with faster development of renewable energy, the proportion increases to 50%. As for coal and coke, in S1, their proportions increase from 14.6% and 13.4% in 2017 to 18.6% and 14.7% in 2035, respectively. However, with the improvement of energy efficiency and the development of renewable energy, these proportions decrease to 9.9% and 7.1% in S3, respectively.

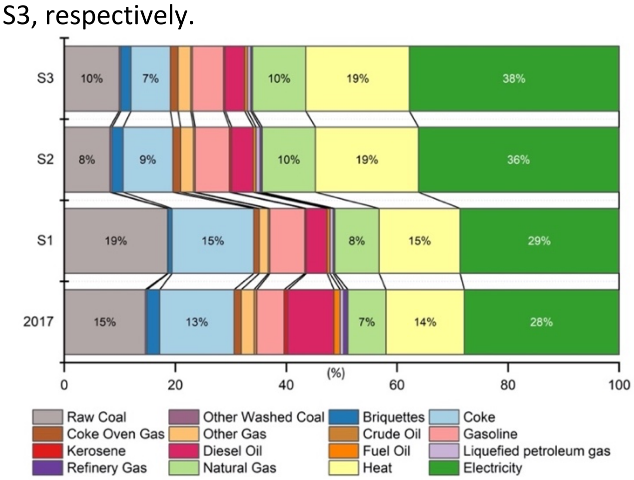

Fig. 4. Energy consumption structure in 2035 under three scenarios

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DECLARATION OF INTEREST STATEMENT

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

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