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Unveiling the Energy Transition Process of Xinjiang: A Hybrid Approach Integrating Energy Allocation Analysis and a System Dynamics Model

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Abstract: The Xinjiang Uygur Autonomous Region (Xinjiang), being a rapidly developing region and a comprehensive energy base, plays an important role in China's low-carbon energy transition. This paper attempts to develop a hybrid approach integrating energy allocation analysis, Logarithmic Mean Divisia Index (LMDI) decomposition, and a system dynamics (SD) model to identify the driving factors of the energy system's changes during 2005–2020, and to analyze future scenarios of the energy system from 2020 to 2060. The results indicate that in 2005–2020, coal and electricity consumption increased sharply, due to the expansion of the chemical and non-ferrous metal industries. Meanwhile, the natural gas flow also expanded greatly because of the construction of the Central Asia pipeline and the increase in local production. In the baseline scenario, energy-related carbon emissions (ERCE) will peak in 2046 at 628 Mt and decrease to 552 Mt in 2060. With a controlled GDP growth rate and an adjusted industrial structure, ERCE will peak in 2041 at 565 Mt and decrease to 438 Mt in 2060. With a controlled energy intensity and an adjusted energy structure, ERCE will peak in 2039 at 526 Mt and decrease to 364 Mt in 2060. If all policy measures are adopted, ERCE will peak in 2035 at 491 Mt and decrease to 298 Mt in 2060.

Keywords: low-carbon energy transition; energy allocation analysis; LMDI; system dynamics model

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1. Introduction

The rapid low-carbon transition of the energy system is identified as an important measure in addressing the increasingly severe global climate change [1]. China emerges as a significant influencing factor in this measure, given its substantial contributions over the past decade to the global increase in coal and oil consumption, alongside a nearly one-third contribution to the global growth in natural gas consumption [2]. Among the main energy-supplying regions in China, Xinjiang plays an important role in the overall process of China's low-carbon energy transition. From the perspective of resource endowment, Xinjiang is an important supply base for both fossil and renewable energy in China, having 30%, 15%, 19%, and 20% of the resource reserves of coal, oil, natural gas, and wind in the national total [3]. From the perspective of geological location, Xinjiang serves as a bridge, linking Central Asia, Russia, and Eastern China [4]. Therefore, Xinjiang is regarded as the national "Three Bases and One Corridor", namely, an oil and gas production and processing base; a coal production, coal power and coal chemical base; a wind power base; and a national energy and resource corridor [5]. Moreover, due to the rapid expansion of its economy and energy utilization, Xinjiang receives widespread attention from the

country and society. From 2005 to 2015, the annual average growth rate of energy consumption and ERCE in Xinjiang was 12.40% and 13.09%, respectively. Meanwhile, the carbon emissions per GDP and carbon emissions per capita of Xinjiang ranked second and third place in China [6]. Given its fragile ecological environment, Xinjiang currently faces extra challenges with its energy development. In summary, Xinjiang's low-carbon energy transition significantly influences not only its own but also the nation's low-carbon transition progress. This makes Xinjiang's energy transition a highly debated research topic for China's climate progress and national energy security.

However, the low-carbon energy transition of Xinjiang still lacks policy support, in particular in the form of long-term planning. Currently, there are only short-term targets towards 2025, including constraints on total energy consumption, energy intensity, carbon emission intensity, and the proportion of non-fossil energy used, together with a brief outlook on these targets for 2035. These political targets are part of the "Fourteenth Five-Year Plan for National Economic Development of Xinjiang Uygur Autonomous Region" [7]. In addition to this, there are some sector-specific implementation plans aiming at a carbon peak before 2030, such as the "Implementation Plan for Carbon Peak in the Industrial Field of Xinjiang Uygur Autonomous Region" [8], and the "Implementation Plan for Carbon Peak in the Urban and Rural Construction Field of Xinjiang Uygur Autonomous Region" [9]. To guide the low-carbon energy transition of Xinjiang, long-term plans towards 2060 still need to be further developed and enacted, in order to achieve the vision of carbon neutrality. On this transition pathway, controlling accumulated carbon emissions is essential for the mitigation of climate change.

To some extent, the lack of long-term plans for Xinjiang's low-carbon energy transition is attributed to insufficient academic studies in this field. Although the low-carbon energy transition of Xinjiang receives more and more attention, previous studies have not yet presented a complete picture of this transition process (referring to Section 2.1). These studies contribute to improving our understanding of the low-carbon energy development in Xinjiang, especially the historical trends and driving factors of energy consumption. However, there is a notable lack of comprehensive research with higher-resolution views that consider the structural changes of the various stages and sectors of Xinjiang's energy system. Moreover, studies on long-term energy scenarios considering various options for the low-carbon energy transition are rare. The research concerning the low-carbon energy transition of Xinjiang could still be improved with the simultaneous consideration of the resolution of the energy system and algorithmic modeling for long-term energy scenarios.

SD models can provide a methodological approach to show changes over time that can be used to establish long-term energy scenarios. The SD model serves as an effective scenario simulation method employed for forecasting and analyzing future energy demands and carbon emissions [10]. Due to the discerning role of LMDI decomposition in identifying driving factors, researchers integrate it with the SD model for enhanced analytical capabilities (referring to Section 2.2). However, the current combination of the two methods can only address the external driving factors of ERCE, and so neglect the internal driving factors within the energy system, especially the process from primary energy consumption to final energy consumption. The internal driving factors need to be based on a high-resolution view of the energy system analysis, and the energy allocation analysis will be one of the methodological options. To reveal a more comprehensive set of driving factors in the past, the authors of this paper have developed a research framework combining energy allocation analysis with LMDI decomposition to examine changes in energy consumption over time (referring to Section 2.3). Therefore, to address both the problem of long-term energy scenarios and a high-resolution view of the energy system, it is worth exploring the possibilities of combining the SD mode, energy allocation analysis, and LMDI decomposition into a whole framework. In this framework, energy allocation analysis can be applied to enhance the resolution of energy systems in the past, the SD model can be employed for long-term energy scenarios, and LMDI decompositions can be a

bridge linking energy allocation analysis and the SD model. Then, we can tell a continuous story of the energy transition from the past to the future.

Therefore, this paper aims to develop a hybrid approach integrating energy allocation analysis, LMDI decomposition, and SD modeling, and apply it to the case of Xinjiang's low-carbon energy transition to present a complete picture of the energy system's evolution from the past to the long-term future. In this approach, energy allocation analysis and LMDI decomposition are firstly applied to reveal historical trends in Xinjiang's energy systems. The former can observe the energy system's structure to reveal internal driving factors, and the latter can identify external driving factors of energy consumption growth. Secondly, an SD model of long-term energy scenarios is built to calculate future energy consumption and ERCE under various settings of economic and energy policy choices. The scenario settings are referring to principles of the driving factors identified by the first step, so that a hybrid approach combining energy allocation analysis and SD modeling is realized. We applied this approach on Xinjiang from 2005–2060 to derive the policy implications for low-carbon energy transition. The year 2060 is referring to the timeline of the national carbon neutrality target, and 2005–2020 is a period of Xinjiang's rapid development.

The main contributions of this work include the following: (1) a hybrid approach to reveal the historical and future trends of energy systems based on an integration of energy allocation analysis, LMDI decomposition, and SD modeling, which both enables a high-resolution understanding of energy systems, a quantitative analysis of the driving factors, and a comprehensive analysis of strategic choices for low-carbon energy transition; (2) an application of this approach on the case of Xinjiang's low-carbon energy transition, which unveils a complete picture of the evolution of Xinjiang's energy system, including its current status, its historical trends, the driving factors of its energy consumption, and future policy measures to control its ERCE; (3) policy recommendations based on analyzing future energy scenarios of Xinjiang, which can enlighten the long-term planning for Xinjiang's low-carbon energy transition.

This paper is organized as follows: Section 2 introduces the literature review, Section 3 introduces the methodology, Section 4 discusses the results, and finally Section 5 presents conclusions.

2. Literature Review

2.1. Previous Studies on Xinjiang's Energy Development

Most studies include Xinjiang's energy development as part of a national-level energy analysis, often missing out on specific details unique to the province. On a provincial level, the availability of studies is quite limited. In these studies, the driving factors of energy development are normally general, such as population, economic growth rate, and resource endowment. There are only a few studies tailored specifically to Xinjiang, and they can be divided into two categories: macro-level analyses focusing on the total energy consumption and ERCE, and micro-level analyses including the evaluation of key elements within the energy system.

In the macro-level studies, there are three categories. The first category focuses on Xinjiang's impact on national carbon emissions. Studies conducted by Xu et al. [11] and Lu et al. [12] compared the contribution of various provinces to China's overall ERCE. They indicate that Xinjiang's increasing trend in carbon emissions is attributed to its energy utilization structure dominated by fossil fuels and lower levels of energy efficiency. The main reasons are the rapidly increasing energy consumption due to a rapid development of energy-intensive and low value-added industries. The two studies both concluded that national energy conservation and emission reduction efforts should particularly address provinces with prominent contradictions, especially Xinjiang. The second category decomposes and analyzes ERCE in Xinjiang, quantifying the contributions of various driving factors to emission growth. Huo et al. [13] conducted a quantitative historical analysis of the relationship between carbon emissions and economic and social factors, finding that population growth and economic structural transformations play a significant role

in driving carbon emissions. Wang et al. [14] further refined the driving factors, utilizing the STIRPAT model to analyze the driving forces of emissions in Xinjiang over a long period (1952–2014). Economic growth emerges as a primary driving force for the increase in carbon emissions, while carbon emission intensity exerts a certain inhibitory effect. The third category discussed Xinjiang's energy consumption and ERCE from other perspectives. Yin et al. [15] explored the spatial distribution characteristics of energy consumption intensity and ERCE in fifteen prefectures of Xinjiang. The former explicitly delineated a spatially uneven pattern in energy consumption intensity in Xinjiang, while the latter, employing spatial geographic statistical methods, concluded that there is a significant spatial differentiation in ERCE among different prefectures in Xinjiang.

The micro-level research focuses more on specific sectors or industries. Zhang et al. [16] emphasized that the carbon emissions from industrial sectors in Xinjiang account for over 80% of the total ERCE. They conducted an index decomposition and attribution analysis to discuss the impact of each industrial sub-sector on the overall industrial carbon intensity. The results indicated that the rapid growth of energy-intensive industries such as fuel processing, metal smelting, and textiles has been a significant factor contributing to the increase in industrial carbon intensity since 2009. Xu et al. [17] conducted an analysis of the energy industry, with a specific focus on the wind energy sector in Xinjiang. By examining the allocation of sustainable resources in the region, the study identified several challenges that hinder the development of sustainable energy in Xinjiang. These challenges include an inadequate understanding of the structure of new energy resources, such as wind and solar energy, weak technical capabilities, ineffective government guidance and supervision, and the fragile ecological environment. This study also evaluated the energy development of some cities in Xinjiang. Meanwhile, Xia et al. [18] investigated the carbon emissions associated with the industrial sector in Xinjiang. The authors identified key industries responsible for high levels of ERCE and evaluated the potential for energy conservation and emissions reduction in these industries.

In summary, the studies reviewed above normally cannot provide a high-resolution overview of the whole energy system of Xinjiang, which is composed of various stages, energy types, and technologies. The main reason is that they are either focusing on the macro-level or the micro-level, while the perspective of energy systems is a meso-level between both of them.

2.2. The Development of the SD Model and LMDI Decomposition in Energy Scenario Analysis

It is also noticeable that studies forecasting the long-term future of Xinjiang's energy systems are rare. Although there are many models that can be applied to calculate future energy scenarios, a simple one should firstly be applied considering the weak research foundation of Xinjiang's energy future. The SD model can be a good option for this purpose, because it is a tool employed to analyze complex real-world systems through causal chains and other methods. Many studies have applied the SD model to estimate the carbon emissions trends of cities or regions [19,20]. Some studies on China constructed SD models based on factor decomposition. For example, Hao et al. [21] utilized carbon emissions data from the past 40 years and employed factor decomposition to develop a system dynamics model, predicting the carbon emissions trends in China from 2020 to 2060. Additionally, Zhan et al. [10] applied the Kaya identity to decompose carbon emissions into distinct factors and constructed an SD model comprising four sub-models—population, economy, energy, and carbon emissions—and forecasted the carbon emissions trends in the Beijing–Tianjin–Hebei region from 2020 to 2060.

It is interesting that some studies attempted a combination of the SD model and LMDI decomposition. LMDI decomposition is a powerful tool to analyze the driving forces of carbon emissions based on the Kaya identity. For example, Gu et al. [22] and Luo et al. [23] built a research framework based on LMDI decomposition and the SD model to estimate the CO_2 emissions of Shanghai and the Guangdong–Hong Kong–Macao Greater Bay Area and surrounding cities, respectively. This research framework utilized LMDI decomposition to

identify the driving factors of CO_2 emissions growth. Subsequently, based on these factors, the SD model was constructed, and scenarios were designed. However, this approach solely addresses external driving factors beyond the energy system, neglecting internal driving factors within the energy system during the process from primary energy consumption to final energy consumption. If the combination of the SD model and LMDI decomposition can be further integrated with methods having a high-resolution overview of energy systems, such as energy allocation analysis, its capability can possibly become stronger.

2.3. Energy Allocation Analysis and LMDI Decomposition in Historical Analysis of Energy Development

The energy allocation analysis for an energy system refers to the comprehensive description of the entire process by which primary energy is distributed to various end-use sectors within the energy system. This process encompasses at least three basic stages: the supply of primary energy, the intermediate conversion, and the end-use sectors. Cullen et al. [24] contend that previous analyses of energy systems have often been confined to assessing the energy utilization efficiency of end-use sectors, and they propose the incorporation of energy losses during the intermediate conversion processes into the energy consumption responsibilities of various end-use sectors. This approach allows for the determination of the share of primary energy consumption that each sector should bear. Additionally, they advocate for the use of Sankey diagrams to visually represent this energy distribution process, known as the Energy Allocation Sankey Diagram. Building upon this theoretical framework, researchers traced the entire process of primary energy, from extraction to intermediate conversion and finally to terminal consumption, and applied it to the world, China, the United Kingdom, and other regions [25,26].

Our research group has extensively employed energy allocation analysis methods in the study of regional energy systems. Chong et al. [27] simplified the approach of compensating for energy losses in the energy conversion process to final energy consumption sectors. They introduced the concept of a primary energy conversion coefficient to mathematically describe the relationship between the calorific value of a secondary energy source and the amount of primary energy required to produce that portion of secondary energy. Subsequently, this new calculation method for allocation analysis was applied to studies on energy systems in regions. In this study, we utilized this method to describe the overall energy flow characteristics in Xinjiang from energy supply to intermediate conversion and ultimately to end-use consumption. By comparing transitions at different historical points, we deepen our understanding of the development trends in the Xinjiang energy system. Chong et al. [28] further integrated energy allocation analysis with the LMDI decomposition method. They incorporated the primary energy conversion coefficient as a driving factor representing energy conversion efficiency into the LMDI decomposition formula. This integration resulted in an LMDI decomposition method based on energy allocation analysis. The combination of these two methods constitutes a comprehensive analytical framework that systematically captures the distribution characteristics of primary energy in the energy system and the driving factors behind consumption growth.

3. Methodology

Based on the above literature review, we design a hybrid approach integrating three methods, including the energy allocation analysis, LMDI decomposition, and the SD model. The energy allocation analysis and LMDI decomposition can be applied to enhance the resolution of the energy system in the identification of the driving factors of energy consumption and ERCE, while the SD model can be employed to analyze future energy scenarios based on those factors. This contemplation can encompass a more comprehensive understanding of the energy system and its driving factors, and unveil the whole process of the energy transition from the past to the long-term future.

3.1. Research Framework

The framework of the hybrid approach is illustrated in Figure 1. The overall process is divided into two steps. The first step is the historical analysis based on the energy allocation analysis and LMDI decomposition, and the second step is the future scenario analysis based on the SD model. In the first step, we initially constructed an energy input–output table reflecting energy consumption responsibilities based on the energy balance sheet. Energy losses were compensated within end-use consumption, and the primary energy consumption responsibility coefficient is computed. Subsequently, utilizing this coefficient, we allocated the primary energy consumption responsibilities across three stages—energy extraction, energy conversion intermediaries, and end-use energy consumption—within a Sankey diagram framework for the years 2005, 2010, 2015, and 2020. Through comparative analysis and synthesis, the internal driving factors influencing the development of energy in Xinjiang were revealed. Building upon the Kaya identity and the primary energy consumption responsibility coefficient, the LMDI decomposition method was utilized to analyze external factors driving the growth of energy consumption during three periods: 2005–2010, 2010–2015, and 2015–2020. In the second step, based on the decomposition calculation formula, an SD model to forecast energy consumption and ERCE in Xinjiang was constructed. This model provided insights into the baseline scenario of energy consumption and ERCE in Xinjiang. On this basis, we conducted a sensitivity analysis and combined the internal and external drivers to identify critical factors affecting energy consumption and ERCE. Finally, considering the identified driving factors, three scenarios were established: a low-carbon economy scenario (LCE), an energy structure optimization scenario (ESO), and a comprehensive optimization scenario (CO). Through a comprehensive analysis of these scenarios and the current status of Xinjiang's energy system, emissions reduction strategies and policy recommendations for Xinjiang were proposed.

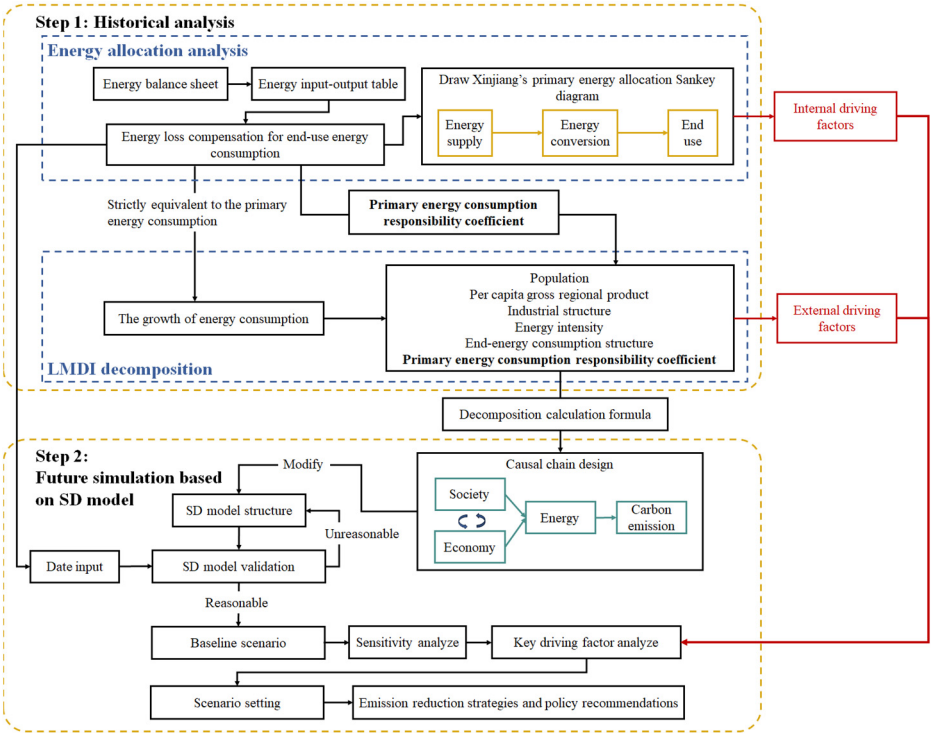


Figure 1. The research framework of the hybrid approach integrating three methods.

3.2. Energy Allocation Analysis

The energy allocation analysis reveals the flow of primary energy from the supply to the intermediate conversion to the final consumption sectors, without accounting for energy losses in the process. Therefore, it is essential to compensate for the final consumption

of various energy sources in the energy balance sheet through the use of primary energy conversion coefficients. This allows for the presentation of energy allocation results in a unified form that does not reflect energy losses. In this study, utilizing the "China Energy Statistical Yearbook" [29–32] and the "Xinjiang Statistical Yearbook" [33–36], specifically the "Energy Balance Sheet for Xinjiang" and the "Table of Total Energy Consumption and Major Energy Consumption by Industry in Xinjiang", respectively, we constructed a Sankey diagram illustrating energy allocation in Xinjiang. The data processed through this method were subsequently input to the SD model. Further details of this method can be found in the literature [37].

3.3. LMDI Decomposition

In the usual LMDI decomposition, the energy consumption (E_{SQ}) of economic sectors is decomposed as shown in Formula (1), in which the drivers considered include population (P), per capita GDP (Q), industrial structure (S_i), energy intensity (I_i), and energy consumption structure (M_{ij}) [28]:

$$E_{SQ} = \sum_{i,j} P \cdot \frac{GDP}{P} \cdot \frac{GDP_i}{GDP} \cdot \frac{E_{SQ,i}}{GDP_i} \cdot \frac{E_{SQ,ij}}{E_{SQ,i}} \quad (1)$$

where GDP_i is the gross product of industry i, $E_{SQ,i}$ is the energy consumption of industry i, and $E_{SQ,ij}$ is the energy consumption of energy j in industry i.

In this study, the growth of energy consumption from time 0 to time T (ΔE_{tot}, not including residential living energy consumption) in Xinjiang was decomposed into the following six factors: population (*pop*), per capita gross regional product (*aff*), industrial structure (*str*), energy intensity (*int*), end-energy consumption structure (*mix*), and primary energy consumption responsibility coefficient (K, used to characterize the structure of energy processing and transformation). The increase in energy consumption caused by these drivers is decomposed into the following:

$$\Delta E_{tot} = E^T - E^0 = \Delta E_{pop} + \Delta E_{aff} + \Delta E_{str} + \Delta E_{Int} + \Delta E_{mix} + \Delta E_K \quad (2)$$

The decomposition of the above driving factors is shown in Table 1.

Table 1. Energy consumption of each factor with the decomposition calculation formula.

Factor	Meaning	Equations
P	Population	$\Delta E_{pop} = \sum_{ij} \frac{E_{ij}^T - E_{ij}^0}{lnE_{ij}^T - lnE_{ij}^0} ln\frac{P^T}{P^0}$
$Q = \frac{GDP}{P}$	GDP per capita	$\Delta E_{aff} = \sum_{ij} \frac{E_{ij}^T - E_{ij}^0}{lnE_{ij}^T - lnE_{ij}^0} ln\frac{Q^T}{Q^0}$
$S_i = \frac{GDP_i}{GDP}$	Industrial structure	$\Delta E_{str} = \sum_{ij} \frac{E_{ij}^T - E_{ij}^0}{lnE_{ij}^T - lnE_{ij}^0} ln\frac{S_i^T}{S_i^0}$
$I_i = \frac{E_{SQ,i}}{GDP_i}$	Energy intensity	$\Delta E_{int} = \sum_{ij} \frac{E_{ij}^T - E_{ij}^0}{lnE_{ij}^T - lnE_{ij}^0} ln\frac{I_i^T}{I_i^0}$
$M_{ij} = \frac{E_{SQ,ij}}{E_{SQ,i}}$	Final energy utilization structure	$\Delta E_{mix} = \sum_{ij} \frac{E_{ij}^T - E_{ij}^0}{lnE_{ij}^T - lnE_{ij}^0} ln\frac{M_{ij}^T}{M_{ij}^0}$
K_j	Primary energy consumption responsibility coefficient	$\Delta E_K = \sum_{ij} \frac{E_{ij}^T - E_{ij}^0}{lnE_{ij}^T - lnE_{ij}^0} ln\frac{K_j^T}{K_j^0}$

3.4. SD Model

3.4.1. Basic Mathematical Model

In 1989, Toichi Kaya first introduced the Kaya identity to decompose the carbon emissions of various countries [38], as represented by Equation (3), aimed at elucidating the relationships among CO_2 emissions (C), total population (P), per capita GDP (GP), energy intensity (EI), and the carbon emissions coefficient (η). In prior research by the research team [37], carbon emissions were categorically delineated into productive (C_I) and residential living emissions (C_L), employed to unveil the interconnections between China's carbon emissions and various economic and social factors, as illustrated by Equations (4)–(6):

$$C = P \cdot \frac{GDP}{P} \cdot \frac{E}{GDP} \cdot \frac{C}{E} = P{\cdot}GP{\cdot}EI{\cdot}\eta \tag{3}$$

$$C = C_I + C_L \tag{4}$$

$$C_I = \Sigma_i\Sigma_j GDP \cdot \frac{GDP_i}{GDP} \cdot \frac{E_i}{GDP_i} \cdot \frac{E_{ij}}{E_i} \cdot \eta_j = \Sigma_i\Sigma_j GDP{\cdot}IS_i{\cdot}EI_i{\cdot}ES_{ij}{\cdot}\eta_j \tag{5}$$

$$C_L = \Sigma_k\Sigma_j P \cdot \frac{P_k}{P} \cdot \frac{E_k}{P_k} \cdot \frac{E_{kj}}{E_k} \cdot \eta_j = \Sigma_i\Sigma_j P{\cdot}PS_k{\cdot}EP_k{\cdot}ES_{kj}{\cdot}\eta_j \tag{6}$$

The meaning of the variables in above equations is shown in Table 2.

Table 2. Meaning of variables in the mathematical model.

Variable	Meaning
i	Categories of industries, including the primary, secondary, and tertiary sector
j	Energy sources, including coal, oil, gas, and non-fossil fuels
k	Resident types, including urban residents and rural residents
IS	Industrial structure, the proportion of a certain industry's GDP in the total GDP
ES	Energy structure, the proportion of a certain type of energy consumption in the total energy consumption
PS	Population structure, the proportion of urban or rural population to total population
EP	Residential living energy consumption per capita

3.4.2. Model Building

Based on the above-mentioned mathematical model, a causal chain among the key driving factors can be established within the SD model. This allows for the estimation of future trends in energy consumption and ERCE in Xinjiang by considering the interactive mechanisms among the various factors in the system (Figure 2). In this study, Xinjiang's carbon emissions are divided into four subsystems within the model: the social, economic, and energy subsystem, as well as carbon emissions. The social subsystem encompasses factors related to residential carbon emissions, such as population, natural population growth rate (PGrowthRate), urban population (UrbanP), and rural population (RuralP). The economic subsystem includes factors related to industrial carbon emissions, such as GDP, GDP growth rate, and industrial structure (PriStructure, SecStructure, TerStructure). The driving factors in the energy subsystem primarily involve energy structure (CoalStructure, OilStructure, GasStructure, NFossilStructure). This study assumes that total carbon emissions resulting from coal, oil, and gas, and secondary energy are converted into these three primary energy sources through the energy allocation analysis method mentioned earlier. The social and economic subsystems are linked through per capita GDP, with the former and latter connecting to the energy subsystem through residential living energy consumption (EL) and productive consumption (EI), respectively. The energy subsystem is connected to carbon emissions through the carbon emissions coefficients (CCoalFactor, COilFactor, CGasFactor). The SD model comprises a total of 47 variables and constants, and computations are conducted using Anylogic software (Personal Learning Edition

8.8.4). The formulas or values for the main factors in the model are shown in Table A1 (Appendix A).

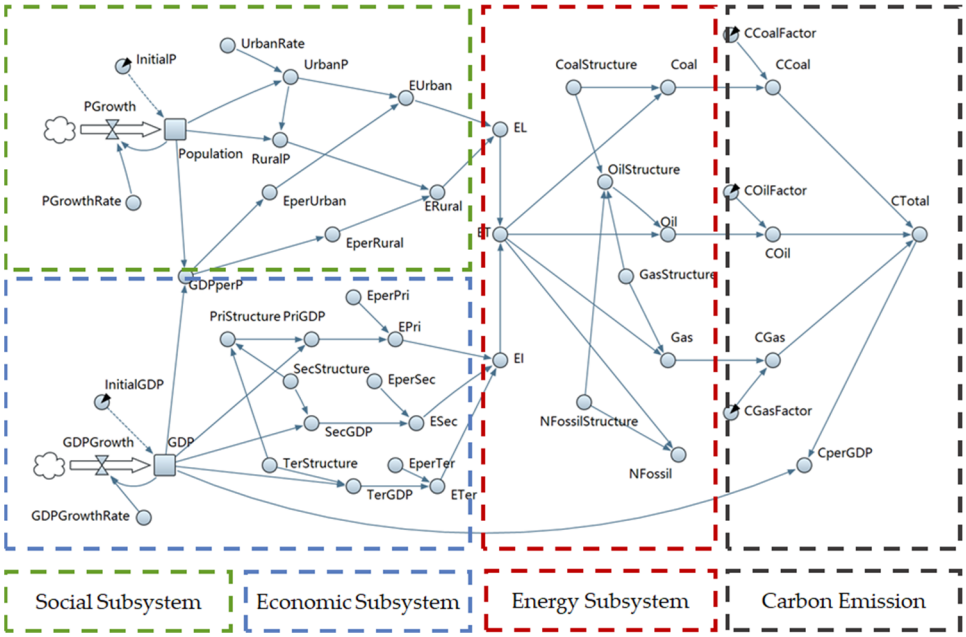


Figure 2. SD model of Xinjiang's energy consumption and ERCE.

The fundamental settings of the model are outlined as follows:

(1) The simulation timeframe spans from 2021 to 2060, with economic indicators such as GDP computed at constant 2005 prices.

(2) The numerical values of key indicators in the model are assigned through table functions, i.e., functions that vary with time. These include population growth rate, GDP growth rate, urbanization rate, industrial structure (percentage of secondary and tertiary sectors), energy intensity (energy intensity of primary, secondary, and tertiary sectors), and energy structure (percentage of coal, natural gas, and non-fossil energy). Initial population, initial GDP, and carbon dioxide emissions coefficients for coal, oil, and gas are assigned as constants, with emissions coefficient values set at 2.459 tCO_2/tce, 2.148 tCO_2/tce, and 1.643 tCO_2/tce, respectively [39].

(3) Many studies discussed the complex relationship between energy, economy, and society, and found that energy consumption, economic growth, population, and other factors are interactional and non-linear [40–43]. However, after China introduced a strong energy intensity policy, total energy consumption was controlled, and China's per capita GDP and per capita energy consumption showed an orderly linear relationship; we believe that future policies will continue this trend. Therefore, a fitting calculation based on historical data from 2005 to 2020 is employed to establish the relationship between per capita urban energy consumption (EperUrban, tce/person), per capita rural energy consumption (EperRural, tce/person), and the indicator reflecting residents' living standards, and the per capita GDP (GDPperP, ten thousand CNY/person), as depicted in Equations (7) and (8). Other main relevant data and sources can be seen in Table A1.

$$EperUrban = 0.1623GDPper + 0.4028 \quad (7)$$

$$EperRural = 0.1123GDPper - 0.0641 \quad (8)$$

3.4.3. Model Validation

Upon establishing the SD model, it is imperative to validate the model to ensure the reliability of the results. In this study, historical data from the years 2005 to 2020 were input into the model, and a simulation was conducted for this timeframe. The simulated values generated by the model were then compared with the actual values to assess the effectiveness of the SD model. In this research, our SD model is divided into four subsystems, namely, the economic system, social system, energy system, and carbon emission system. The primary variables of these four subsystems are GDP, population, energy consumption, and carbon emissions. However, because there is no official statistical value for carbon emissions in Xinjiang, and the amount of carbon emissions is related to energy consumption, we compared the model values of three primary variables, namely, GDP, population, and energy consumption, with the actual values to check the validation of the SD model. The results indicate a high degree of similarity between the simulated and actual values, with a relative error not exceeding 3% (maximum deviation of −2.64%), as shown in the Table 3.

Table 3. Validity check of the SD model.

Variable		2005	2010	2015	2020
Population (million people)	Real value	20.10	21.82	23.85	25.90
	Model value	20.10	21.83	23.89	25.96
	Relative error	0%	−0.07%	−0.16%	−0.23%
Total Energy (Mtce)	Real value	52.55	78.94	156.94	204.57
	Model value	51.13	81.03	159.41	201.57
	Relative error	2.71%	−2.64%	−1.58%	1.46%
GDP [1] (MCNY)	Real value	25.20	42.19	71.65	101.61
	Model value	25.20	42.78	73.48	99.98
	Relative error	0%	−1.40%	−2.55%	1.60%

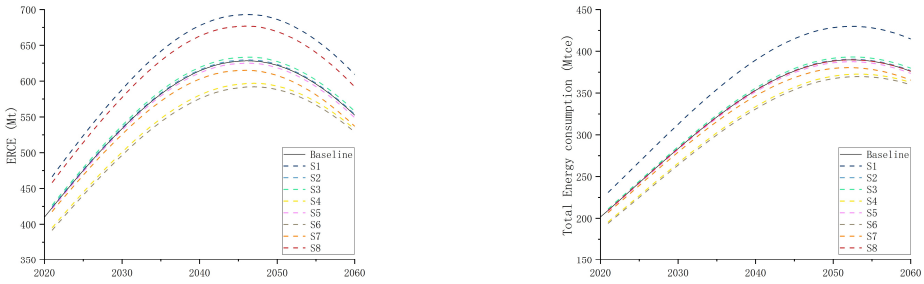
[1] In terms of constant prices from the year 2005.

3.4.4. Sensitivity Analysis

In order to ascertain which indicators may exert significant prospective influences on the carbon emissions associated with energy in Xinjiang, thus serving as reference benchmarks for subsequent scenario settings, we conducted a sensitivity analysis. Previous research involved modifying a particular parameter at a consistent rate while keeping other factors constant, thereby discerning critical driving factors through a comparison of future carbon emissions variations [37]. In this study, eight scenarios were established based on the baseline scenario, each comprising a variation in certain parameters to assess their potential impact on the future trajectory of carbon emissions in the region, namely, +10% GDP (S1), +10% population (S2), +10% urban population (S3), −10% secondary industry share (reduction replaced by tertiary industry, S4), −10% primary industry energy intensity (S5), −10% secondary industry energy intensity (S6), −10% tertiary industry energy intensity (S7), and +10% coal consumption (reduction replaced by non-fossil energy, S8).

As shown in Figure 3, the variations in GDP exhibit the most pronounced impact on both CO_2 emissions and energy consumption levels. A 10% increase in GDP corresponds to a 10.30% rise in the peak of CO_2 emissions and a simultaneous 10.31% increase in the peak of energy consumption. The influences of the secondary industry share and secondary industry energy intensity are also notably significant. A 10% decrease in the secondary industry share results in a 4.98% decrease in the peak of CO_2 emissions, accompanied by a 4.37% decrease in the peak of energy consumption. Similarly, a 10% decrease in secondary industry energy intensity leads to a 5.77% decrease in the peak of CO_2 emissions, coupled with a 5.13% decrease in the peak of energy consumption. Furthermore, the variation in coal consumption has no impact on the total energy consumption, but it significantly

influences CO_2 emissions. A 10% increase in coal consumption results in a 7.73% increase in the peak of CO_2 emissions.



(**a**) (**b**)

Figure 3. Sensitivity analysis results, (**a**) ERCE, (**b**) Total energy consumption.

3.4.5. Scenario Setting

In accordance with historical trends and existing policy objectives, the following assumptions are made for the future changes (2021–2060) in various indicators within the baseline scenario:

(1) Referring to the "Population Development Strategic Research Report 2010–2011" [44], which forecasts future population development in Xinjiang, it is anticipated that Xinjiang will enter a phase of negative population growth after 2030. This study assumes a declining trend in the population growth rate over the analysis period, setting the annual change rate at −0.8‰. The urbanization rate is expected to continue to increase annually, with a growth rate of 0.5% per year.

(2) Drawing on estimates of future economic development in the northwest region of China from the "China Long-Term Low-Carbon Development Strategy and Transformation Path Research Protect" [45], the annual changes in Xinjiang's GDP growth rate, the percentage of the secondary sector, and the percentage of the tertiary sector are set at −0.1%, −0.4%, and 0.5%, respectively.

(3) Based on existing policy objectives to reduce energy intensity, the annual changes in energy intensity for the primary, secondary, and tertiary sectors are set at −0.1 tce/million CNY GDP, −6.8 tce/million CNY GDP, and −0.5 tce/million CNY GDP, respectively. In line with the restrictive targets on the energy consumption structure in the national energy development goals, the annual changes in the proportion of natural gas are set to increase by 0.48% from 2020 to 2030 and to decrease by 0.3% annually after 2030. The annual change in the proportion of non-fossil energy is set at 0.5%. Given the increasing proportions of natural gas and non-fossil energy, the annual change in the coal proportion is set at −0.65%.

Compared to the baseline scenario, the low-carbon economic scenario (LCE) primarily alters economic growth rates and industrial structures. In this scenario, it is assumed that Xinjiang's economic development policy places greater emphasis on future low-carbon development, actively transforming the economic development model and accelerating the optimization of industrial structure. Under such policy objectives, Xinjiang's economic growth rate is anticipated to be more moderate, with industries rapidly transitioning towards the lower energy-intensive tertiary sector.

Compared to the baseline scenario, the energy structure optimization scenario (ESO) mainly adjusts the rate of decline in energy intensity in the secondary sector and the proportion of non-fossil energy in the energy consumption structure. In this scenario, it is assumed that Xinjiang's energy development policy places greater emphasis on future low-carbon development, accelerating the reduction in energy intensity in the secondary sector through the application of energy-saving technologies and the upgrading of energy-intensive indus-

tries. Additionally, it leverages the advantages of local wind and solar renewable energy resources to increase the share of non-fossil energy in the energy consumption structure.

In the comprehensive optimization scenario (CO), combining the settings from both LCE and ESO involves aligning the economic development goals with those of the LCE and aligning the energy development goals with those of the ESO. The CO embodies a synthesis of policy objectives, encompassing the harmonization of economic development patterns and the optimization of energy utilization in both directions.

4. Results and Discussions

4.1. The Energy Allocation Diagrams of Xinjiang's Energy System

Based on the calculations of energy balance, this paper presents the Sankey diagrams illustrating the allocation of energy in Xinjiang for the years 2005, 2010, 2015, and 2020, shown in Figures 4–7. These diagrams depict the flow of energy from left to right, representing the energy supply links, energy intermediate conversion links, and terminal consumption links. The Sankey diagrams demonstrate that the energy entering the system is equal to the energy leaving the system, thereby establishing the principle of energy conservation.

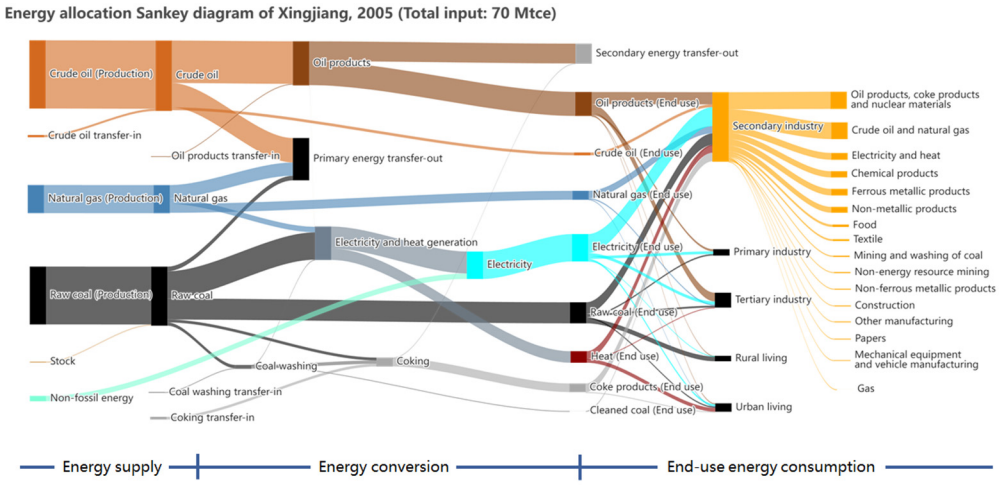


Figure 4. Xinjiang's primary energy allocation Sankey diagram in 2005 (The sectors of the secondary industry in the figure have been consolidated. The corresponding relationships with the sector classification in the "Xinjiang Statistical Yearbook" are shown in Table A1).

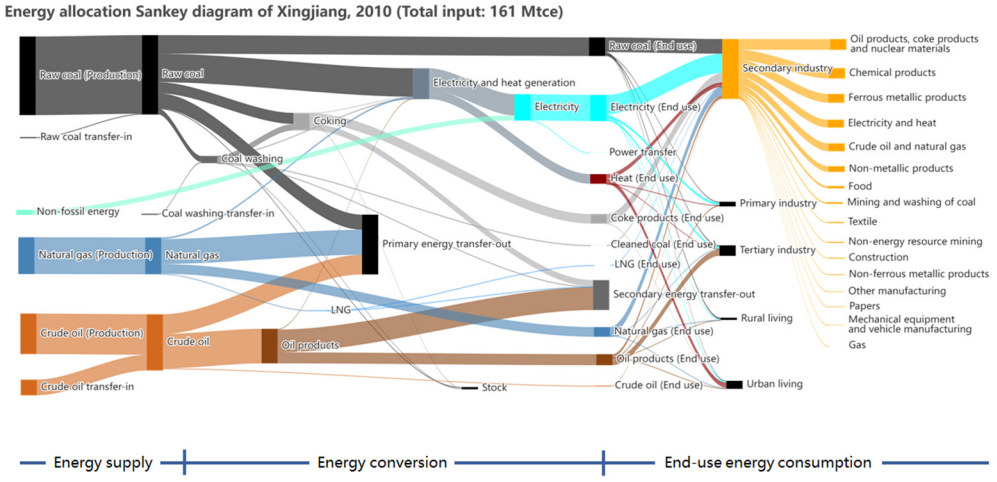


Figure 5. Xinjiang's primary energy allocation Sankey diagram in 2010.

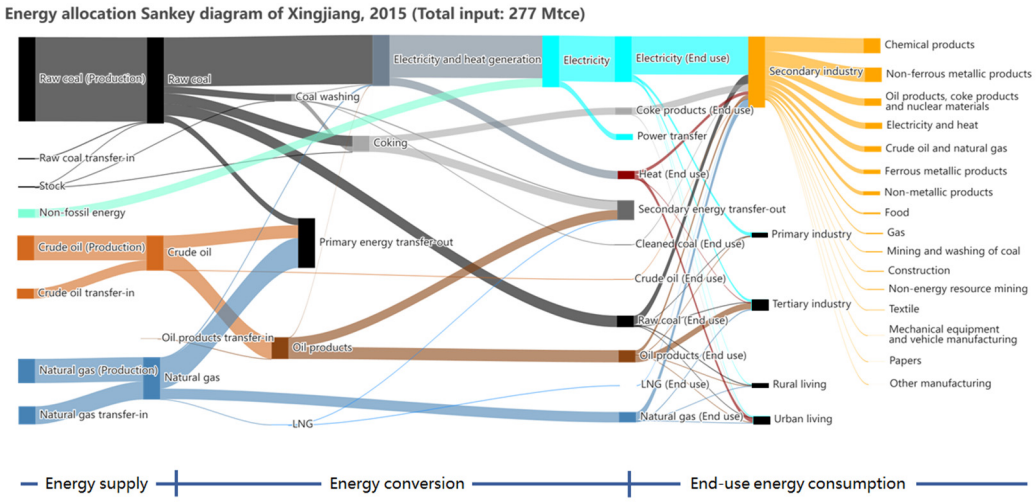


Figure 6. Xinjiang's primary energy allocation Sankey diagram in 2015.

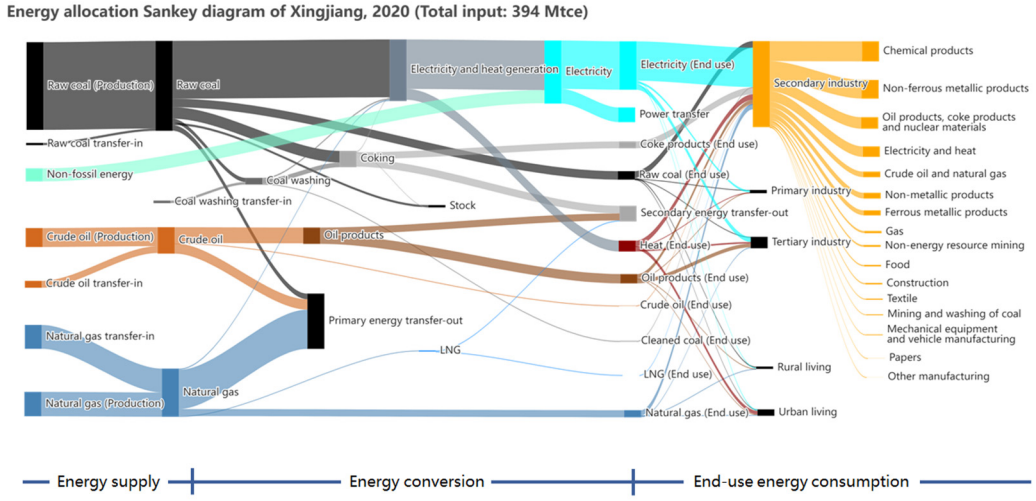


Figure 7. Xinjiang's primary energy allocation Sankey diagram in 2020.

Xinjiang's energy supply primarily relies on local production, encompassing raw coal, crude oil, and natural gas, which experienced substantial growth from 2005 to 2020. Notably, raw coal production exhibited the most prominent growth, increasing from 29.16 Mtce in 2005 to 192.62 Mtce in 2020, indicating an average annual growth rate of 13.41%. Conversely, the production of crude oil and natural gas witnessed only slight increments. Simultaneously, Xinjiang's transit energy sources, characterized by their advanced nature and exportability, demonstrated rapid growth, with natural gas serving as the dominant energy source. This trend signifies the region's increasingly significant role as an energy transit route. The accelerated growth can be attributed to Xinjiang's strengthened collaboration with Central Asia regarding natural gas imports and the ongoing construction of energy transmission infrastructure towards the eastern region during this period.

The intermediate conversion process in Xinjiang has undergone a significant transformation, primarily characterized by a substantial expansion in thermoelectric production. Particularly noteworthy is the surge in power production, rising from 13.82 Mtce in 2005 to 138.50 Mtce in 2020, reflecting an average annual growth rate of 16.61%. Consequently, this growth has driven a corresponding increase in coal consumption as the primary energy source for thermoelectric production. The utilization of raw coal in thermoelectric production surged from 13.79 Mtce in 2005 to 127.00 Mtce in 2020, with an average annual growth rate of 15.95%. In 2020, raw coal accounted for 78.56% of Xinjiang's thermoelectric production sources, while non-fossil energy sources constituted 20.79%. These figures

strongly contrast to the nationwide figures of 61.97% and 28.91%, respectively, thereby indicating an unfavorable situation for achieving low-carbon development in the region.

The end-use energy consumption in Xinjiang experienced a rapid increase from 52.74 Mtce to 204.57 Mtce, reflecting an average annual growth rate of 9.46%. Notably, the period from 2010 to 2020 witnessed even more substantial growth, with an average annual growth rate of 10.27%. Among the various energy sources, electricity consumption showed the most prominent growth, with its share of end-use consumption rising from 26.21% in 2005 to 30.73% in 2010 and further to 51.98% in 2020. This significant increase can be attributed to Xinjiang's energy policy shift towards promoting rapid electrification after 2010. Analyzing the end-use consumption sector, it is evident that energy consumption in the industrial-oriented secondary industry surged from 35.05 Mtce to 153.06 Mtce. The majority of the increase in total end-use consumption over the decade was directed towards the industrial sector, particularly the non-ferrous metal industry and the chemical industry. This trend highlights Xinjiang's substantial undertaking in transferring large-scale energy-intensive industries to the central and eastern regions within the province during this period.

4.2. The Driving Factors of Xinjiang's Energy Consumption in the Past

Over the 15-year period, the two most influential factors affecting the growth of energy consumption in Xinjiang are identified as per capita GDP and energy intensity. The stimulating impact of per capita GDP growth on energy consumption has strengthened along with Xinjiang's development. Energy intensity exhibited an initial ascent followed by a subsequent decline during the 2005–2020 period. The decomposition results manifest a sequential pattern of promoting, restraining, and once again promoting energy consumption, attributed to the influence of the shift in high-energy-consuming industries and Xinjiang's subsequent emphasis on a cleaner and more efficient transformation of the energy system. The slow changes in energy structure and the primary energy consumption responsibility coefficient made the impact of these two factors on the growth of energy consumption weak over the 15-year period. The industrial structure demonstrates a promoting effect followed by a restraining effect, reflecting the positive outcomes of recent years' industrial restructuring efforts in Xinjiang. The detailed decomposition outcomes and analysis of key factors are as follows.

During the period from 2005 to 2010, Xinjiang's economic sector experienced a significant increase in primary energy consumption, rising from 45.56 Mtce to 67.70 Mtce, representing a change of 22.15 Mtce. The results of the LMDI analysis indicate that some factors have contributed to the observed growth, including population (4.49 Mtce), per capita regional GDP (36.95 Mtce), industrial structure (1.38 Mtce), and final energy consumption structure (3.09 Mtce). Simultaneously, some factors have exerted inhibitory effects on the aforementioned growth, including energy intensity (−21.08 Mtce), and energy processing and transformation structure (−2.68 Mtce) (Figure 8).

During the period from 2010 to 2015, the primary energy consumption of Xinjiang's economic sector showed a substantial increase, soaring from 67.70 Mtce to 139.74 Mtce, resulting in a change of 72.04 Mtce. The results of the LMDI analysis indicate that some factors have contributed to the observed growth, including population (8.70 Mtce), per capita regional GDP (45.16 Mtce), energy intensity (31.53 Mtce), and final energy consumption structure (2.82 Mtce). Simultaneously, some factors have exerted inhibitory effects on the aforementioned growth, including industrial structure (−14.68 Mtce), and energy processing and transformation structure (−1.50 Mtce) (Figure 9).

During the period from 2015 to 2020, the primary energy consumption of Xinjiang's economic sector showed a substantial increase, soaring from 139.74 Mtce to 182.11 Mtce, resulting in a change of 42.36 Mtce. The results of the LMDI analysis indicate that some factors have contributed to the observed growth, including population (13.05 Mtce), per capita regional GDP (49.28 Mtce), and final energy consumption structure (0.67 Mtce). Simultaneously, some factors have exerted inhibitory effects on the aforementioned growth,

including industrial structure (−8.68 Mtce), energy intensity (−11.80 Mtce), and energy processing and transformation structure (−0.16 Mtce) (Figure 10).

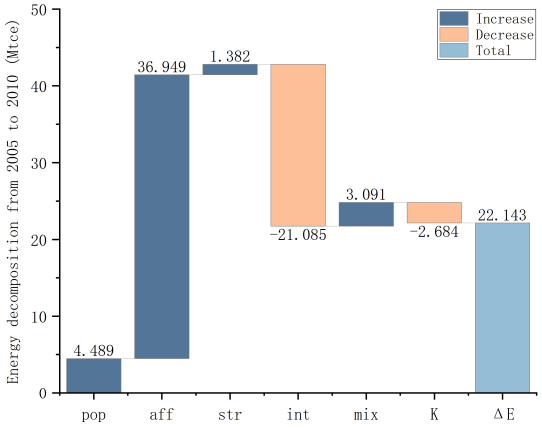


Figure 8. LMDI decomposition from 2005 to 2010 (Decomposition factors: population (pop), per capita gross regional product (aff), industrial structure (str), energy intensity (int), end-energy consumption structure (mix), primary energy consumption responsibility coefficient (K)).

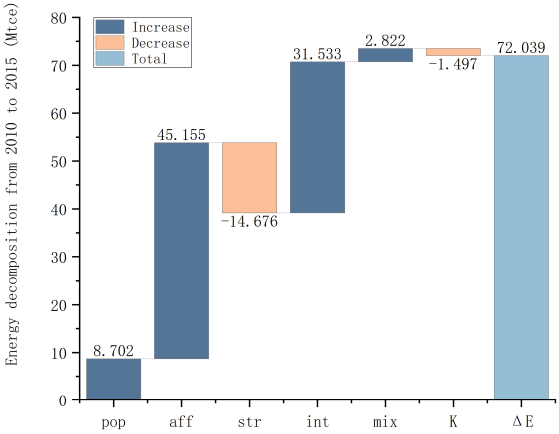


Figure 9. LMDI decomposition from 2010 to 2015 (Decomposition factors: population (pop), per capita gross regional product (aff), industrial structure (str), energy intensity (int), end-energy consumption structure (mix), primary energy consumption responsibility coefficient (K)).

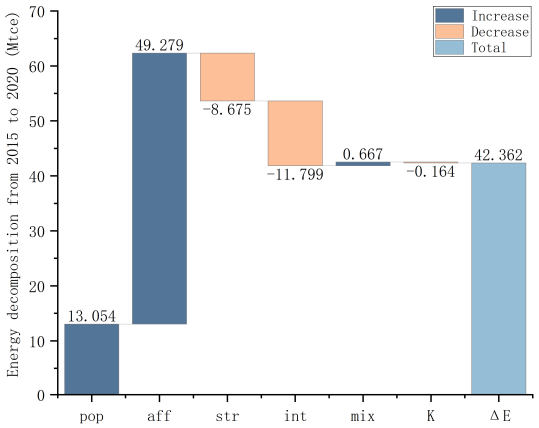


Figure 10. LMDI decomposition from 2015 to 2020 (Decomposition factors: population (pop), per capita gross regional product (aff), industrial structure (str), energy intensity (int), end-energy consumption structure (mix), primary energy consumption responsibility coefficient (K)).

4.2.1. GDP

During the past 15 years, Xinjiang's GDP experienced an average annual growth rate of 9.74% (based on 2005 comparable prices), which was the primary driver behind the rapid increase in primary energy consumption in the region. This period witnessed Xinjiang undergoing a rapid process of industrialization and urbanization, where economic growth fueled a surge in energy consumption. This increase was primarily attributable to the massive energy demand arising from the rapid expansion of energy-intensive industries and the significant investment and construction of fixed assets. Notably, the industrial added value in Xinjiang rose from 96.23 billion CNY to 363.33 billion CNY (measured at current prices), and the proportion of value-added industrial output in the six major high-energy-consuming industries to the total value-added industrial output of enterprises with a designated scale increased from 41.8% to 63.6%. Compared with the more developed provinces in the east, Xinjiang's economic development is relatively lagging behind, and its infrastructure is not fully developed. Consequently, current economic growth is primarily driven by fixed-asset investment and construction focused on infrastructure, which generates significant energy demand.

4.2.2. Energy Intensity

The rapid growth of primary energy consumption in Xinjiang between 2005 and 2020 was driven, in part, by the growth of energy intensity. The changes in energy intensity were analyzed in Xinjiang's primary, secondary, and tertiary industries over this period. The analysis reveals that while the energy intensity of the primary and tertiary industries remained relatively stable, the energy intensity of the secondary industry exhibited a notable upward trend, especially from 2010 to 2015. Given the significant proportion of the secondary industry in Xinjiang's economic structure and its high energy consumption, the overall energy intensity of the region increased significantly. With the gradual economic transformation, China's overall energy intensity has been decreasing annually. According to previous research on the driving factors of China's energy consumption growth [12], the decreasing trend in energy intensity during this period curbed the growth of energy consumption. However, Xinjiang's energy intensity during the same period was much higher than the national average and continued to rise, which contributed significantly to the rapid growth of energy consumption in the region. In the subsequent 2015–2020 period, Xinjiang began to focus on energy conservation in the industrial sector, so changes in energy intensity suppressed Xinjiang's energy consumption growth during this period.

4.2.3. End-Use Energy Consumption Structure

Between 2005 and 2020, the shift in end-use energy consumption structure initially impeded energy consumption growth, but subsequently produced a stimulating effect. The changes in energy consumption attributable to each energy type in the end-use energy consumption structure during the two periods before and after 2010 can be observed. The data reveal that from 2005 to 2010, the decrease in the proportion of oil (including crude oil and oil products) in the end-use energy consumption structure hindered the growth of energy consumption, while the rise in the proportion of electricity in the end-use energy consumption structure significantly contributed to energy consumption growth from 2010 to 2020.

4.3. Future Scenarios of Xinjiang's Low-Carbon Energy Transition

Based on the previously described methodology, we constructed the SD model. The specific settings are shown in Table 4. The results of the four scenarios specified are presented as follows.

Table 4. Comparison of different scenarios.

Feature		Baseline	LCE	ESO	CO
		According to Existing Policy Trends	**Stronger Low-Carbon Economic Policies**	**Stronger Low-Carbon Energy Policies**	**Combination of Economic and Energy Policy**
Parameter in 2060	GDP growth rate (%)	2.1	1.5	2.1	1.5
	The proportion of secondary industry (%)	18.4	12.4	18.4	12.4
	The proportion of tertiary industry (%)	71.2	77.2	71.2	77.2
	Energy intensity of secondary industry (tce/kCNY)	21.69	21.69	15.88	15.88
	The proportion of non-fossil energy (%)	33.7	33.7	50.7	50.7
Result	Peak time of energy consumption	2053	2047	2049	2045
	Energy consumption in peak time (Mtce)	390	336	356	315
	Peak time of ERCE	2046	2041	2039	2035
	ERCE in peak time (Mt)	628	565	526	491
	Energy consumption in 2060 (Mtce)	376	298	330	270
	ERCE in 2060 (Mt)	552	438	364	298

4.3.1. Baseline Scenario

The results indicate that, based on historical trends and current socio-economic and energy development goals, the total energy consumption growth in Xinjiang is expected to continue. The peak time for ERCE is projected to occur in 2046, reaching a peak of 628 Mt. This peak significantly lags behind the national carbon-peaking target. And under this trend, Xinjiang's carbon emissions will be about 552 Mt by 2060, as shown in Figure 11a. It is evident that under current policy objectives, Xinjiang's ERCE are likely to persist in a growing trend for an extended period, posing challenges to effectively support the nation's low-carbon development goals. Economic growth emerges as a primary driver of carbon emission increase, with research suggesting that carbon intensity plays a certain inhibitory role, a factor closely associated with technological innovation [14]. As shown in Figure 11b, under the current policy framework, the secondary industry in Xinjiang is poised for stable development. However, by approximately 2045, the growth rate of the secondary industry is anticipated to decelerate due to a decline in regional and domestic demand. Concurrently, per capita GDP is expected to experience a rapid increase after reaching its population peak. As shown in Figure 11c, owing to Xinjiang's resource endowment, a majority of carbon emissions are coal-related, constituting 71.8% of the total carbon emissions by the year 2060. Figure 11d delineates Xinjiang's energy consumption across various energy sources, projecting a peak in energy consumption around the year 2053, with a zenith of 390 Mtce. Among these sources, coal holds the highest proportion, reaching 42.9% by 2060, with its peak occurring slightly earlier than the overall consumption peak, around 2043. Figure 11e presents the total energy consumption across sectors, indicating that the energy consumption of the secondary industry is expected to reach its peak around 2042, influenced by the dual factors of slowing growth rate and decreasing energy intensity. Anticipated by the year 2060, the energy consumption of the secondary industry is projected to decrease to 42.56% of the total energy consumption, constituting 55.23% of the aggregate energy consumption associated with production activities.

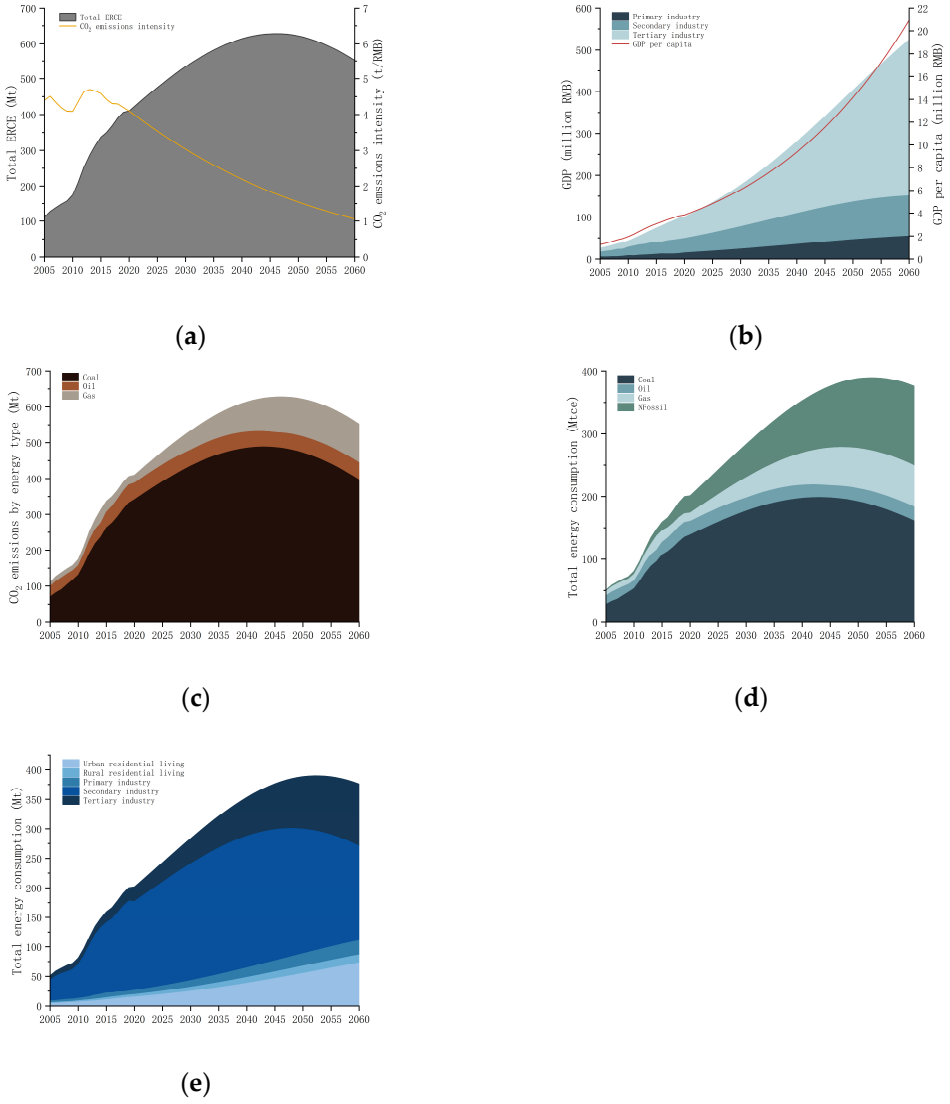
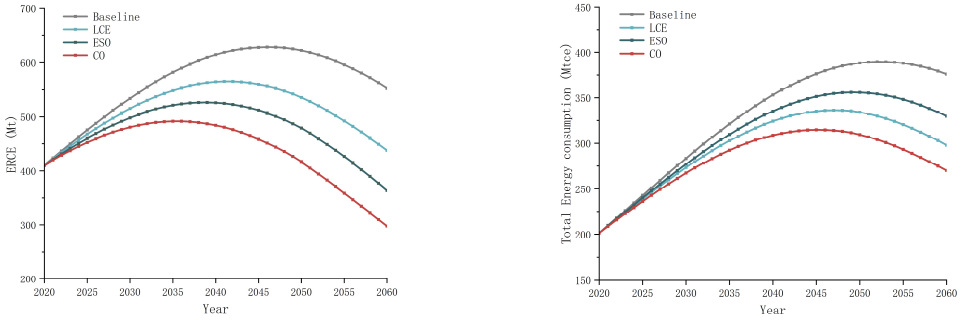


Figure 11. Baseline scenario simulation results. (**a**) Total ERCE and CO_2 emissions intensity. (**b**) GDP structure and GDP per capita. (**c**) CO_2 emissions by energy type. (**d**) Total energy consumption by energy type. (**e**) Total energy consumption by section.

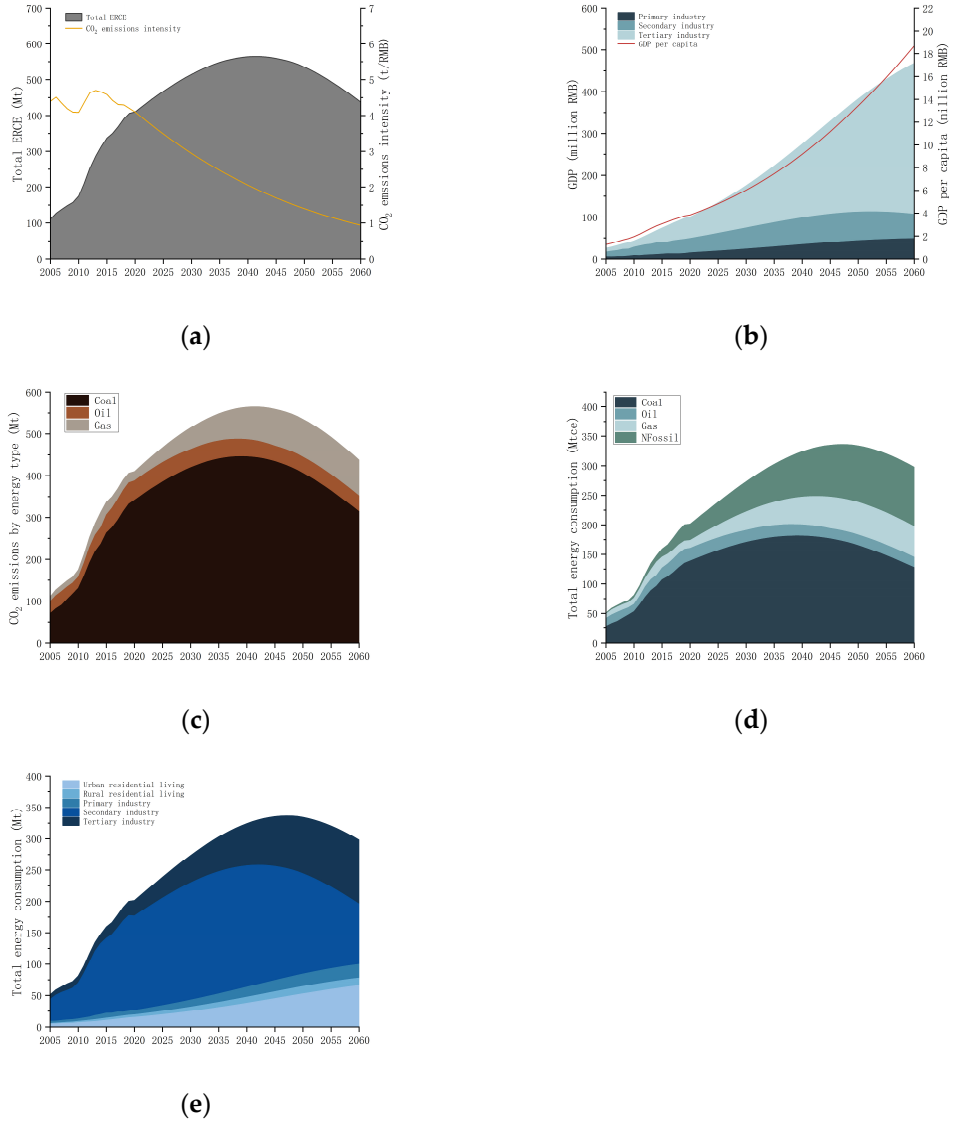
4.3.2. Alternative Scenarios

Total carbon emissions and local energy consumption for LCE, ESO, and CO are shown in Figure 12 (the simulation results of each scenario are shown in Figures 13–15, respectively). The ERCE in 2020 will be about 410 million tons of CO_2. In LCE, Xinjiang is projected to reach its carbon emissions peak in 2041, estimated at 565 million tons of CO_2. Subsequently, in 2047, the region is anticipated to reach the peak of its energy consumption, reaching a value of 336 Mtce. By the year 2060, it is expected that Xinjiang's carbon emissions will decrease to 438 million tons of CO_2, with a corresponding decline in energy consumption to 298 Mtce. In ESO, Xinjiang is projected to reach its carbon emissions peak in 2039, estimated at 526 million tons of CO_2. Subsequently, in 2049, the region is anticipated to reach the peak of its energy consumption, reaching a value of 356 Mtce. By the year 2060, it is expected that Xinjiang's carbon emissions will decrease to 364 million tons of CO_2, with a corresponding decline in energy consumption to 330 Mtce. In contrasting the LCE with ESO, it becomes evident that the former exhibits a more pronounced efficacy in curbing the overall growth of energy consumption, whereas the latter demonstrates more effective control over the escalation of ERCE.



(**a**) (**b**)

Figure 12. ERCE (**a**) and total energy consumption (**b**) under 4 different scenarios during 2020–2060 periods.



(**a**) (**b**)

(**c**) (**d**)

(**e**)

Figure 13. LCE scenario simulation results. (**a**) Total ERCE and CO_2 emissions intensity. (**b**) GDP structure and GDP per capita. (**c**) CO_2 emissions by energy type. (**d**) Total energy consumption by energy type. (**e**) Total energy consumption by section.

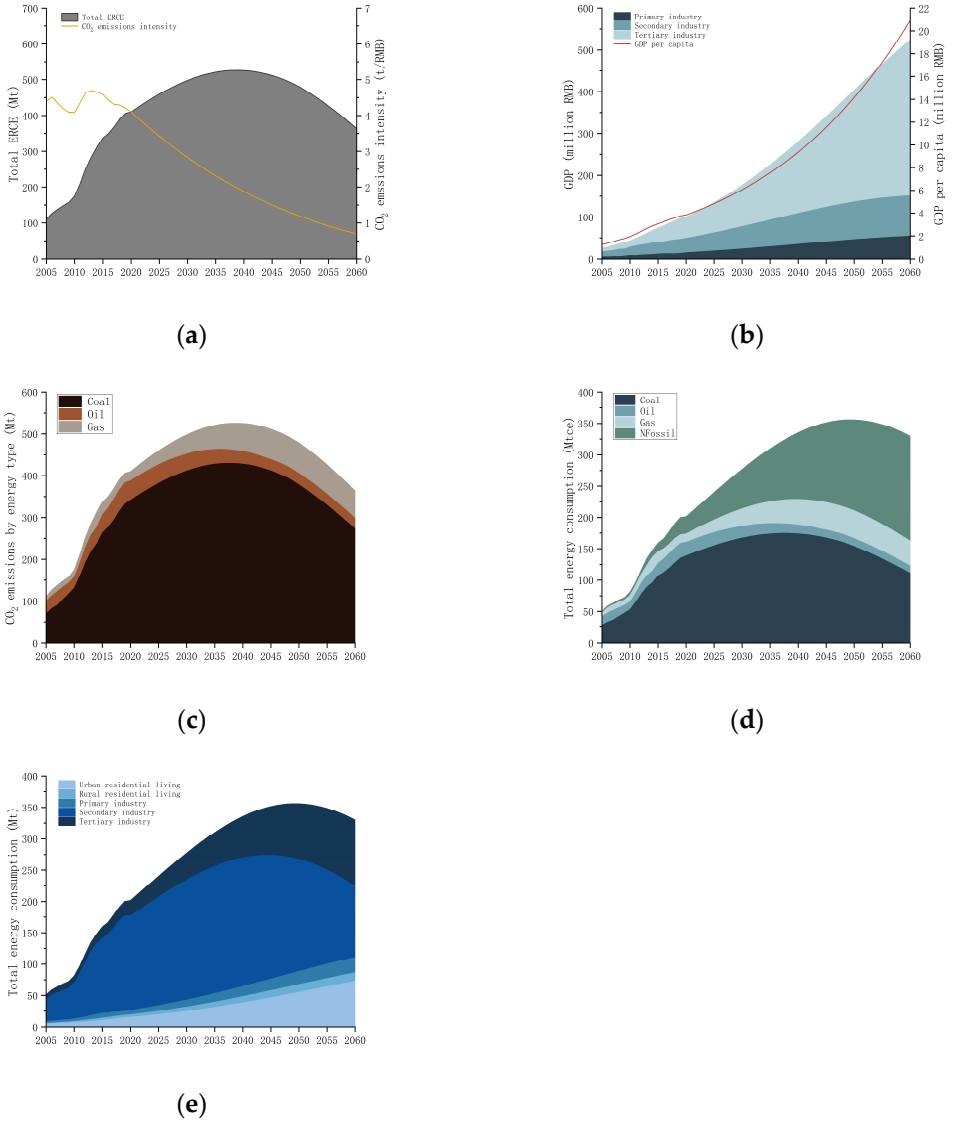


Figure 14. ESO scenario simulation results. (**a**) Total ERCE and CO_2 emissions intensity. (**b**) GDP structure and GDP per capita. (**c**) CO_2 emissions by energy type. (**d**) Total energy consumption by energy type. (**e**) Total energy consumption by section.

The CO incorporates policy parameter settings from the aforementioned LCE and ESO. The results of the model calculations reveal that, through concerted efforts in adjusting both economic development patterns and optimizing energy utilization, effective control over the growth of total energy consumption and ERCE can be achieved. These outcomes also align more closely with China's overarching objectives. In CO, Xinjiang is projected to reach its carbon emissions peak in 2035, estimated at 491 million tons of CO_2. Subsequently, in 2045, the region is anticipated to reach the peak of its energy consumption, reaching a value of 315 Mtce. By the year 2060, it is expected that Xinjiang's carbon emissions will decrease to 298 million tons of CO_2, with a corresponding decline in energy consumption to 270 Mtce.

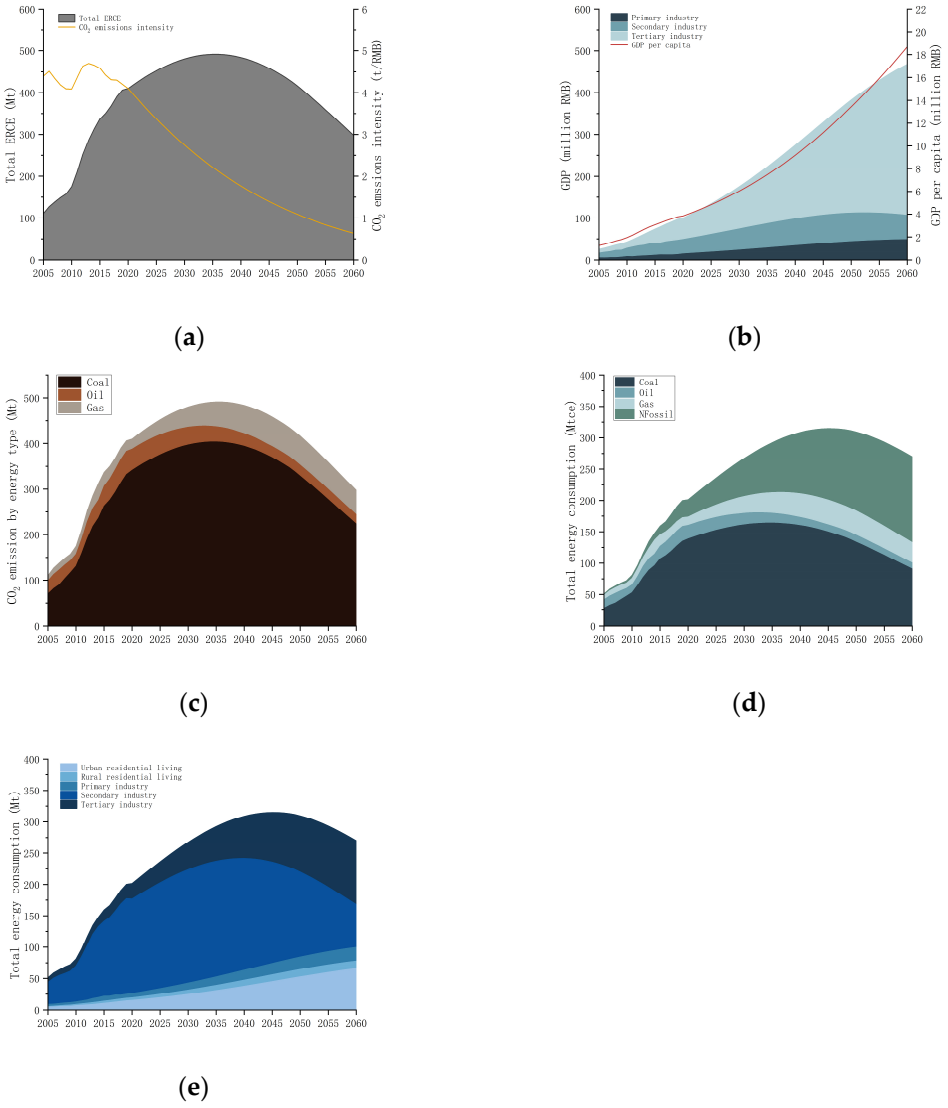


Figure 15. CO scenario simulation results. (**a**) Total ERCE and CO_2 emissions intensity. (**b**) GDP structure and GDP per capita. (**c**) CO_2 emissions by energy type. (**d**) Total energy consumption by energy type. (**e**) Total energy consumption by section.

The results of the scenario analysis indicate that if Xinjiang continues to adhere to its current social, economic, and energy development objectives without promptly undergoing economic transformation and improving energy utilization practices, both the total energy consumption and ERCE will persistently increase for an extended period in the future. The projected peak carbon time significantly lags behind the national overall target, posing challenges to the region's sustainable development. In addition, some new energy policies have little impact on the reduction in carbon emissions in Northwest China [46]. Therefore, Xinjiang's low-carbon transformation should receive more attention from the government. Accelerating the pace of economic transformation, optimizing industrial structures, and pursuing a model of high-quality economic development will be conducive to Xinjiang's low-carbon development. This will be reflected in the effective control of the growth in total energy consumption, with a concurrent earlier attainment of the peak in related carbon emissions. On the other hand, a focused effort on optimizing energy utilization, particularly in expeditiously reducing the energy intensity of the secondary industry and harnessing the advantages of renewable energy resources, will significantly advance Xinjiang's low-carbon development. This is especially pertinent to the effective control of the growth in ERCE, leading to a notable reduction in the time required to reach the

carbon peak compared to the current trend. By integrating measures from both the low-carbon economic and energy optimization perspectives, Xinjiang's trajectory of low-carbon development will be markedly improved, effectively supporting the national overall low-carbon development objectives.

4.4. Policy Recommendations

Based on the analysis and discussion of the results, this paper proposes the following policy implications: (1) Strengthening carbon constraints, particularly with long-term absolute quantity constraints, is of paramount importance in controlling cumulative emissions in Xinjiang, as the current policy targets of Xinjiang are insufficient to support national strategies of carbon peaking and carbon neutrality. (2) It is imperative to accelerate technological innovation in non-fossil energy sources and facilitate the transformation of high-energy-consuming industries, with both efforts synergistically reinforcing each other. For instance, promoting the adoption of non-fossil energy sources in high-energy-consuming industries facilitates the large-scale development of wind and solar energy, thereby contributing to industrial decarbonization. (3) Economic development is paramount. Concurrent with efforts to advance industrial energy conservation and emissions reduction, there must be substantial emphasis placed on the development of high-technology industries and the service sector, alongside the adjustment of economic and energy demand structures. The growth rate of GDP in Xinjiang remains a pivotal driving factor for current carbon emissions, and the rapid urbanization and industrialization in Xinjiang are yet to be completed, necessitating proactive government intervention to steer industrial transformation. However, it is imperative to adhere to the developmental principle of initial construction followed by optimization, recognizing the significance of sequential progress. (4) The efficacy of the aforementioned singular measures is limited, so it is imperative to formulate combined policies integrating these measures. To better align with China's overall energy transition, Xinjiang should integrate various measures, including optimizing industrial structure, adjusting energy composition, and enhancing energy efficiency. For Xinjiang, the capacity-building will require a significant amount of time, which holds considerable importance for policy makers [47].

5. Conclusions

This study developed a hybrid approach integrating energy allocation analysis and LMDI decomposition with SD modeling, which can be used in any region, especially where complex models are difficult to apply due to lack of data. We applied this approach on the case of Xinjiang's low-carbon energy transition to comprehensively analyze the driving factors of energy systems and estimate the future trends in ERCE. In addition, in our previous study, energy allocation analysis and LMDI decomposition were also applied in places like Malaysia [28], and system dynamics models could be further constructed in these countries to estimate their future energy consumption and energy-related carbon emissions.

We conducted a balanced calculation of the energy system in Xinjiang, China, and presented Sankey diagrams depicting energy allocation at four distinct time points—2005, 2010, 2015, and 2020—to illustrate the outcomes of energy allocation analysis. Based on the findings of the energy allocation analysis, this paper revealed the intrinsic driving factors behind the growth in energy consumption in Xinjiang over the 15-year period. The key conclusion is as follows: Between 2005 and 2020, significant transformations occurred in various facets of Xinjiang's energy system, resulting in rapid increases in energy consumption. The primary intrinsic driving factors can be summarized as follows: (1) The rapid development of energy-intensive industries such as non-ferrous metals and chemicals led to a notable increase in end-use energy consumption, particularly in electricity consumption, as the electrification process rapidly advanced. (2) Electricity production continued to rely predominantly on coal, with an increasing proportion of non-fossil electricity, yet thermal electricity production remained coal-dominated. (3) The growth in energy supply primarily manifested in the expansion of local raw coal production, while

non-fossil energy, although experiencing rapid growth, remained relatively small in scale, and natural gas was mainly transited through the region with limited local utilization.

Furthermore, this study decomposed the growth in energy consumption in Xinjiang from 2005 to 2020. The primary conclusions based on the results of the LMDI decomposition are as follows: During this period, energy consumption in Xinjiang experienced rapid growth, with the external driving factors largely consistent. Per capita GDP growth and population growth were identified as the primary factors. Energy intensity initially played a restraining role before transitioning to a driving force, followed by reverting to a restraining role. The industrial structure initially exhibited some driving force before assuming a restraining role, reflecting certain effects generated by the recent green transformation of Xinjiang's industrial structure.

Finally, this research employed a carbon emissions prediction model for Xinjiang's energy system based on SD models. Utilizing a forward-looking quantitative scenario analysis method, this study constructed a baseline scenario for the future trajectory of ERCE in Xinjiang. Building upon this baseline scenario, a sensitivity analysis was conducted on various indicators influencing ERCE. The results revealed that crucial indicators affecting the future trajectory of carbon emissions in Xinjiang include GDP growth rate, economic indicators such as industrial structure, and also energy indicators such as the energy intensity of the secondary industry and the proportion of non-fossil energy. Based on the outcomes of the sensitivity analysis, alternative scenarios were constructed, encompassing a low-carbon economy, energy optimization, and a comprehensive scenario, to explore the impact of different policy objectives on the future trajectory of ERCE.

The results of the scenario analysis indicate that in the baseline scenario, Xinjiang is projected to achieve carbon peaking by the year 2046. However, in comparison to the national low-carbon targets, this peak is relatively delayed and achieving carbon neutrality appears unrealistic within this century. In light of this challenging scenario, Xinjiang must strive for special policies and vigorously promote industrial and technological innovation. The outcomes of the LCE suggest that optimizing industrial structure and pursuing a model of high-quality economic development will expedite the achievement of the carbon peak in Xinjiang. Additionally, the ESO illustrates that efforts to optimize energy utilization methods will significantly promote Xinjiang's transition towards a low-carbon economy. Considering both aspects of the objectives, carbon emissions in Xinjiang will be better controlled, providing enhanced support for the overall development goals of China.

Due to the weak foundation of relevant policies and academic research on low-carbon energy transition of Xinjiang, this study represents a preliminary investigation of the energy consumption and ERCE in the past and future. However, there are some limitations. Firstly, this study simplifies relationships among the internal driving factors of the energy system in the analysis of long-term energy scenarios. Secondly, the study focuses on the energy consumption and ERCE in Xinjiang, but ignores energy transitioning through Xinjiang obtained by imports and then exported to other regions, which has been a substantial volume in the past. In the next step, it is suggested to further improve the considerations of the internal driving factors of the energy system in the SD modeling and scenario analysis, and to pay more attention to the energy transitioning through Xinjiang.

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Abbreviations

Xinjiang	Xinjiang Uygur Autonomous Region
ERCE	energy-related carbon emissions
SD	system dynamics
LMDI	Logarithmic Mean Divisia Index
tce	ton of standard coal equivalent; 1 tce is equal to 0.7 toe (ton of oil equivalent)
CNY	Chinese Yuan

Appendix A

Table A1. Corresponding relationships of the industry classifications in this study with those in the Statistical Yearbook.

This Study	The Statistical Yearbook
Mining and washing of coal	Mining and Washing of Coal
Crude oil and natural gas	Extraction of Petroleum and Natural Gas
Non-energy resource mining	Mining and Processing of Ferrous Metal Ores Mining and Processing of Non-ferrous Metal Ores Mining and Processing of Non-metal Ores
Food	Processing of Food from Agricultural Products Manufacture of Food; Manufacture of Beverages Manufacture of Tobacco;
Textiles	Manufacture of Textiles Manufacture of Textile Wearing Apparel, Footwear, and Caps Manufacture of Leather, Fur, Feather, and Related Products
Papers	Timber Production, Wood, Bamboo, Cane, and Grass Manufacture of Furniture Manufacture of Paper and Paper Products Printing and Copying of Medium for Record
Oil products, coke products, and nuclear materials	Processing of Oil Processing, Coking, and Nuclear Fuel
Chemical products	Manufacture of Raw Chemical Material and Chemical Products Manufacture of Medicine Manufacture of Chemical Fiber
Non-metallic products	Manufacture of Rubber Products Manufacture of Plastic Products Manufacture of Non-metallic Mineral Products
Ferrous metallic products	Smelting and Pressing of Ferrous Metals
Non-metallic products	Smelting and Pressing of Non-ferrous Metals
Mechanical equipment and vehicle manufacturing	Manufacture of General Purpose Machinery Manufacture of Special Purpose Machinery Manufacture of Transport Equipment Manufacture of Electric Equipment and Machinery

Table A1. *Cont.*

This Study	The Statistical Yearbook
Other manufacturing	Metal Products Manufacturing Communication Equipment, Computer and Other Electronic Equipment Manufacture of Equipment, Meter, Culture, and Office Machinery Manufacture of Artwork and Other Manufacturing Sector
Electricity and heat	Electric Power, Gas, and Water Production and Supply Production and Distribution of Power, Steam, and Hot Water Production and Supply of Water
Gas	Production and Supply of Gas
Construction	Construction

Table A2. Main factors of the SD model.

Type	Factor	Meaning	Unit	Value/Equation
Constant	InitialP	Total population in 2005	10^4 person	2010.35
	InitialGDP	GDP in 2005	10^8 CNY	2520.49
	CCoalFactor	CO_2 emission coefficient of coal	tCO_2/tce	2.459
	COilFactor	CO_2 emission coefficient of oil	tCO_2/tce	2.148
	CGasFactor	CO_2 emission coefficient of gas	tCO_2/tce	1.643
Flows	PGrowth	Population growth per year	10^4 person	PGrowth = Population × PGrowthRate
	GDPGrowth	GDP growth per year	10^8 CNY	GDPGrowth = GDP × GDPGrowthRate
Stocks	Population	Total population	10^4 person	d(Population)/dt = PGrowth
	GDP	Gross domestic product	10^8 CNY	d(GDP)/dt = GDPGrowth
Variables	PGrowthRate	Natural population growth rate	%	Table Function(Time, [(2006, 2.20)–(2060, −1.73)], (2006, 2.20), (2010, 1.99), (2015, 1.80), (2020, 1.47), (2030, 0.67), (2040, −0.13), (2050, −0.93), (2060, −1.73))
	GDPGrowthRate	GDP growth rate	%	Table Function(Time, [(2006, 11.00)–(2060, 2.20)], (2006, 11.00), (2010, 10.60), (2015, 8.80), (2020, 3.40), (2030, 5.20), (2040, 4.20), (2050, 3.20), (2060, 2.20))
	UrbanP	Urban population	10^4 person	UrbanP = UrbanRate × Population
	RuralP	Rural population	10^4 person	RuralP = Population-UrbanP
	UrbanRate	Urbanization rate	%	Table Function(Time, [(2006, 37.94)–(2060, 76.53)], (2006, 37.94), (2010, 43.01), (2015, 48.78), (2020, 56.53), (2030, 61.53), (2040, 66.53), (2050, 71.53), (2060, 76.53))
	EUrban	Urban living energy consumption	10^4 tce	EUrban = UrbanP × EperUrban
	ERural	Rural living energy consumption	10^4 tce	ERural = RuralP × EperRural
	GDPperP	GDP per capita	10^4 CNY/person	GDPperP = GDP/Population
	EperUrban	Energy consumption per urban resident	tce/person	EperUrban = 0.1623 × GDPperP + 0.4028
	EperRural	Energy consumption per rural resident	tce/person	EperRural = 0.1123 × GDPperP − 0.0641
	PriGDP	GDP of primary industry	10^8 CNY	PriGDP = GDP × PriStructure
	SecGDP	GDP of secondary industry	10^8 CNY	SecGDP = GDP × SecStructure
	TerGDP	GDP of tertiary industry	10^8 CNY	TerGDP = GDP × TerStructure
	PriStructure	Primary industry structure	%	PriStructure = 1 − SecStructure − TerStructure
	SecStructure	Secondary industry structure	%	Table Function(Time, [(2006, 47.67)–(2060, 18.39)], (2006, 47.67), (2010, 46.26), (2015, 37.03), (2020, 34.39), (2030, 30.39), (2040, 26.39), (2050, 22.39), (2060, 18.39))

Table A2. *Cont.*

Type	Factor	Meaning	Unit	Value/Equation
	TerStructure	Tertiary industry structure	%	Table Function(Time, [(2006, 35.34)–(2060, 71.25)], (2006, 35.34), (2010, 35.08), (2015, 47.83), (2020, 51.25), (2030, 56.25), (2040, 61.25), (2050, 66.25), (2060, 71.25))
	EPri	Primary industrial energy consumption	10^4 tce	EPri = PriGDP × EperPri
	ESec	Secondary industrial energy consumption	10^4 tce	ESec = EperSec × SecGDP
	ETer	Tertiary industrial energy consumption	10^4 tce	ETer = TerGDP × EperTer
	EperPri	Energy intensity of primary industry	10^{-4} tce/CNY	EperPriTable(floor(Time()))
	EperSec	Energy intensity of secondary industry	10^{-4} tce/CNY	EperSecTable(floor(Time()))
	EperTer	Energy intensity of tertiary industry	10^{-4} tce/CNY	EperTerTable(floor(Time()))
	EL	Total residential energy consumption	10^4 tce	EL = EUrban + ERural
	EI	Total industrial energy consumption	10^4 tce	EI = EPri + ESec + ETer
	ET	Total energy consumption	10^4 tce	ET = EL + EI
	Coal	Energy consumption of coal	10^4 tce	Coal = ET × CoalStructure
	Oil	Energy consumption of oil	10^4 tce	Oil = ET × OilStructure
	Gas	Energy consumption of gas	10^4 tce	Gas = ET × GasStructure
	NFossil	Energy consumption of non-fossil energy	10^4 tce	NFossil = ET × NFossilStructure
	CoalStructure	Energy structure of coal	%	Table Function(Time, [(2006, 56.70)–(2060, 42.90)], (2006, 56.70), (2010, 65.70), (2015, 67.10), (2020, 68.90), (2030, 62.40), (2040, 55.90), (2050, 49.40), (2060, 42.90))
	OilStructure	Energy structure of oil	%	OilStructure = 1 − CoalStructure − GasStructure − NFossilStructure
	GasStructure	Energy structure of gas	%	Table Function(Time, [(2006, 14.30)–(2060, 17.50)], (2006, 14.30), (2010, 13.00), (2015, 11.60), (2020, 6.70), (2030, 11.50), (2040, 14.50), (2050, 16.50), (2060, 17.50))
	NFossilStructure	Energy structure of non-fossil energy	%	Table Function(Time, [(2006, 4.30)–(2060, 33.70)], (2006, 4.30), (2010, 6.00), (2015, 8.60), (2020, 13.70), (2030, 18.70), (2040, 23.70), (2050, 28.70), (2060, 33.70))
	CCoal	CO_2 emissions from coal	10^4 tCO_2	CCoal = Coal × CCoalFactor
	COil	CO_2 emissions from oil	10^4 tCO_2	COil = Oil × COilFactor
	CGas	CO_2 emissions from gas	10^4 tCO_2	CGas = Gas × CGasFactor
	CTotal	Total CO_2 emissions	10^4 tCO_2	CTotal = CCoal + COil + CGas
	CperGDP	CO_2 emission intensity	10^4 tCO_2	CperGDP = CTotal/GDP

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