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Evaluation of the Endowment of Geothermal Resources and Its Impact on Regional Industrial Structure: A Case Study of Qinghai Province (China)

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Abstract: Geothermal resources are considered a clean energy source, and their development plays a key role in achieving sustainable development. This energy contributes to environmental protection, energy security, and economic growth, while also helping to alleviate energy poverty. Qinghai Province, rich in geothermal resources, holds significant potential for development. First, this study evaluated the geothermal resources in the uplifted mountainous regions of Qinghai Province using the volumetric method and analyzed their spatial distribution. Next, the degree of geothermal resource endowment was measured, and the relationship between geothermal resources and industrial structure was analyzed. Finally, the Vector Autoregression (VAR) model and impulse response function were applied to assess the impact and duration of geothermal resources on changes in the industrial structure from 2000 to 2020. Geothermal resources in Qinghai Province exhibit significant regional variation, with the northern and western regions being particularly rich in geothermal resources, peaking at 3.58×10^{17} J in Banma County. Geothermal resources in Qinghai are predominantly utilized for power generation, averaging 42.20% of energy consumption. The interplay between geothermal resource use and industrial structure is intensifying, notably in secondary and tertiary sectors. Initially restrictive, the influence of industrial structure on geothermal resource use is projected to become facilitative as clean energy technologies advance. This study revealed the relationship between geothermal resources and the local industrial structure in Qinghai Province, providing a scientific basis for the sustainable and efficient development and utilization of these resources. It contributed to the long-term sustainability of geothermal resource exploitation.

Keywords: geothermal resource; industrial structure; VAR regression model; Qinghai province

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1. Introduction

Human utilization of geothermal resources dates back over 2000 years [1]. At that time, people directly used geothermal resources for activities such as bathing, medical treatment, and heating. Therefore, "direct use" became the oldest and most common form of geothermal resource utilization [2]. Human use of geothermal resources dates back over 2000 years. Initially, geothermal resources were primarily used directly for activities such as bathing, medical treatments, and heating. As a result, direct utilization became the oldest and most common form of geothermal energy use [3].

The development and transformation of geothermal resources are significant for achieving sustainable development. As a low-carbon, clean energy source, geothermal resources help reduce greenhouse gas emissions and mitigate global climate change. Furthermore, geothermal resources offer long-term sustainability, providing a stable energy supply without dependence on climate variations. This ensures energy security and reduces reliance on external energy sources. As environmental awareness grows and energy resources become increasingly scarce, the sustainable development and utilization of geothermal resources have garnered increasing attention from scholars.

The volume method is the most used approach for evaluating geothermal resources. Although it has limitations in terms of accuracy [4–6], its simplicity, low parameter requirements, and broad applicability make it suitable for regions with limited exploration data [7]. To address the limitations of the volume method, several improvements have been proposed by scholars, such as the Monte Carlo volume method based on probability and statistical theory [8]. This method effectively considers the uncertainty of thermal reservoir parameters by means of probability distribution, including thermal reservoir area, thermal reservoir thickness, porosity of thermal reservoir rock, specific heat capacity of thermal reservoir rock, etc. Li Yongyi et al. [4] applied Monte Carlo simulation, based on the volume method, to assess the geothermal resource potential in the uplifted mountainous regions of Guangdong. Chen Haiwen et al. [9] used both the volume method and the Monte Carlo volume method to evaluate the geothermal resources in the depression area of the Yinggehai Basin. They also provided recommendations for the development of these resources based on the evaluation results. Zhang Jiang et al. [10] introduced a Bayesian correction framework and Gaussian process regression to improve the Monte Carlo volume method and assessed the geothermal resources in the southern Songliao Basin, demonstrating the effectiveness of the improvements. Current research on geothermal resource evaluation primarily focuses on improving the accuracy of evaluation methods [11–13]. However, recommendations for the development and utilization of geothermal resources after evaluation are often oversimplified. This has led to the stagnation of many geothermal projects in the early stages, preventing them from realizing the expected social and economic benefits. The primary reason for this is that geothermal resources are often developed and utilized based solely on evaluation results, such as temperature, geothermal reserves, fluid availability, and water quality, while neglecting the local industrial structure. The industrial structure refers to the distribution of agriculture, industry, and services within a region's economy. This neglect prevents geothermal resource development from aligning with the local industrial structure, thereby hindering its sustainable development. Therefore, exploring the relationship between geothermal resources and industrial structure, along with the extent and impact of changes in industrial structure, is crucial for the sustainable development and utilization of geothermal resources.

The development of geothermal resources not only drives local economic growth and improves regional energy efficiency, but also promotes the optimization and diversification of the local industrial structure. By closely aligning geothermal resource development with local economic and social needs, the efficient utilization and continuous output of geothermal resources can be ensured, facilitating the region's transition to a green, low-carbon economic model. Currently, studies on industrial structure commonly employ methods such as regression analysis, VAR models, and surveys [14]. Survey methods often have significant limitations and subjectivity, which impose strong constraints on the results. In contrast, regression analysis is unable to account for the dynamic correlations between the parameters. The VAR model effectively avoids the aforementioned issues. It considers the interdependencies between multiple variables, offering a more comprehensive understanding of their interactions. This makes it particularly advantageous for analyzing dynamic relationships between multiple endogenous variables. In studies related to natural resources and regional industrial structures, traditional methods often fail to capture spatial interactions and spillover effects. The spatial VAR model, however, introduces spatial lag effects, allowing for the simultaneous analysis of both temporal and spatial data, thus revealing interactions and influences across regions. Compared to other multivariate models, the spatial VAR model has significant advantages in analyzing the dynamic relationships between multiple endogenous variables. It not only accurately captures the interactions between regional industrial structures but also provides a better explanation of the impact depth between geothermal resource development and changes in industrial structure.

Qinghai Province is one of the most geothermal resource-rich regions in China, featuring favorable conditions for both geothermal reservoirs and cap rocks. The development and utilization of geothermal resources not only help reduce fossil energy consumption and contribute to achieving China's carbon neutrality goal by 2060 [15], but also generate substantial socio-economic benefits. Currently, the development and utilization of geothermal resources here remain in the early stages. The focus is limited to activities such as bathing, medical applications, and swimming, reflecting an extensive and inefficient development model. Most geothermal exploration wells are in a "survey but not extract" state, with many either idle or abandoned [16]. To address the aforementioned issues, this study first applied the volume method to evaluate the geothermal resources and analyze their spatial distribution. Based on this, the endowment of geothermal resources is measured, and the relationship between these resources and the industrial structure is explored. Finally, a VAR model is employed to examine the scope and extent of the impact of geothermal resources on changes in the industrial structure. This analysis provides a scientific foundation for the future development and utilization of geothermal resources in Qinghai Province, contributing to the sustainable development of geothermal resources.

2. Study Area

2.1. Physical Geography

Qinghai Province is located in the western part of China, between latitudes 31°39′ N and 39°19′ N, and longitudes 89°35′ E and 103°04′ E. It spans about 1200 km from east to west and 800 km from north to south, covering a total area of approximately 72.23×10^4 km^2. The terrain is higher in the west and lower in the east, with a high northern and southern region and a lower central region. The elevation ranges from 1655 m to 6718 m, with more than four-fifths of the province's area being plateaus and mountains above 3000 m. The climate is classified as plateau continental, with long winters, cool summers, an average annual temperature of 4 °C, and average annual precipitation of around 300 mm. The study area shows considerable regional variation, with the eastern region receiving more rainfall, while the western region is characterized by dryness, cold temperatures, and oxygen deficiency. Uninhabited zones still exist. As a result, most of the geothermal resources in the study area have been identified in the northern and western parts (Figure 1). These resources can be categorized into two types based on geomorphological features: the convective type in the uplifted mountains and the conductive type in the sedimentary basins. The convective geothermal resources in the uplifted mountain areas are particularly widespread.

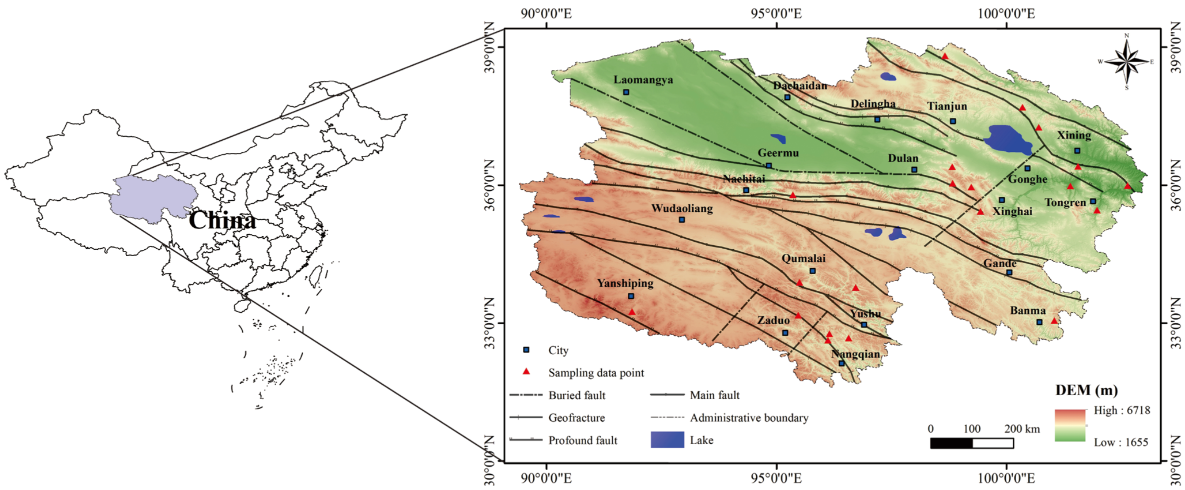


Figure 1. Topography, geological structure and distribution of geothermal resources in Qinghai Province.

2.2. Geological Structure

Qinghai Province is vast, with pre-Quaternary strata exposed across various areas. These strata are fully developed. The Proterozoic, Paleozoic, and Triassic of the Mesozoic, as well as the Paleogene and Neogene of the Cenozoic, were the most developed. The development of the Jurassic and Cretaceous of the Mesozoic was relatively poor. The lithology of the Proterozoic and Paleozoic strata primarily includes gneiss, granite, and granodiorite. The stratum was primarily distributed in the southwestern Yanshiping area of the study region. The early Mesozoic Triassic strata are mainly composed of conglomerate, sandstone, and shale. The Middle to Late Jurassic, Cretaceous, Paleogene, and Neogene strata primarily consist of sandstone, gravelly sandstone, carbonaceous mudstone, and coal-bearing formations [17].

Magma activity in the study area was frequent and intense across different geological periods, with volcanic eruptions occurring from the Ediacaran to the Quaternary. Volcanic activity during the Paleogene and Neogene was concentrated in the southwestern Yanshiping area of the study region. An angular unconformity was observed, with marine Triassic, Jurassic, and continental Paleogene and Neogene strata lying beneath it. These strata are further overlain by an angular unconformity from the Pliocene. Since the Quaternary period, the area has experienced a hiatus in volcanic activity. These eruptions were controlled by geological structures, primarily involving intermediate and acidic rocks. The subduction of the Indian Plate beneath the Eurasian Plate not only led to the formation of the towering Himalayan Mountain range but also influenced the fault structures in the study area. A total of 24 major active faults were identified [18]. Tectonic movements since the Middle Pleistocene have shaped the basic structural and geomorphological features of the study area. These fault structures act as pathways for geothermal and groundwater movement. Convective geothermal resources in the uplifted mountain areas are distributed along fault zones or confined between several major deep faults. Hot springs are exposed at the intersections of these fault zones.

2.3. Geothermal Background

Geothermal flux is the amount of heat transferred to the Earth's surface per unit area per unit of time through conduction from the Earth's interior. It is the most direct parameter for assessing the thermal characteristics of a region's temperature field [19]. Global geothermal heat flux data were referenced to obtain measurements from 110 geothermal heat flux points in Qinghai Province [20]. A distribution map of geothermal heat flux in the study area was then created (Figure 2). The average heat flow value across mainland China is 63 mW/m^2, which is very close to the global continental average of 65 mW/m^2 [17]. Geothermal heat flow values show that the central area, including the Golmud Basin, has relatively low values, while the northern and southern regions exhibit higher values. This creates a pattern of lower values in the center and higher values around the periphery. In most of central Qinghai, the heat flow values are below 60 mW/m^2, classifying it as a low heat flow region. In contrast, the heat flow values around the province are generally above 60 mW/m^2. In the Yanshiping area, the heat flow value exceeded 90 mW/m^2, which was associated with active volcanic activity during the Paleogene and Neogene periods. This area had the highest heat flow value in Qinghai Province.

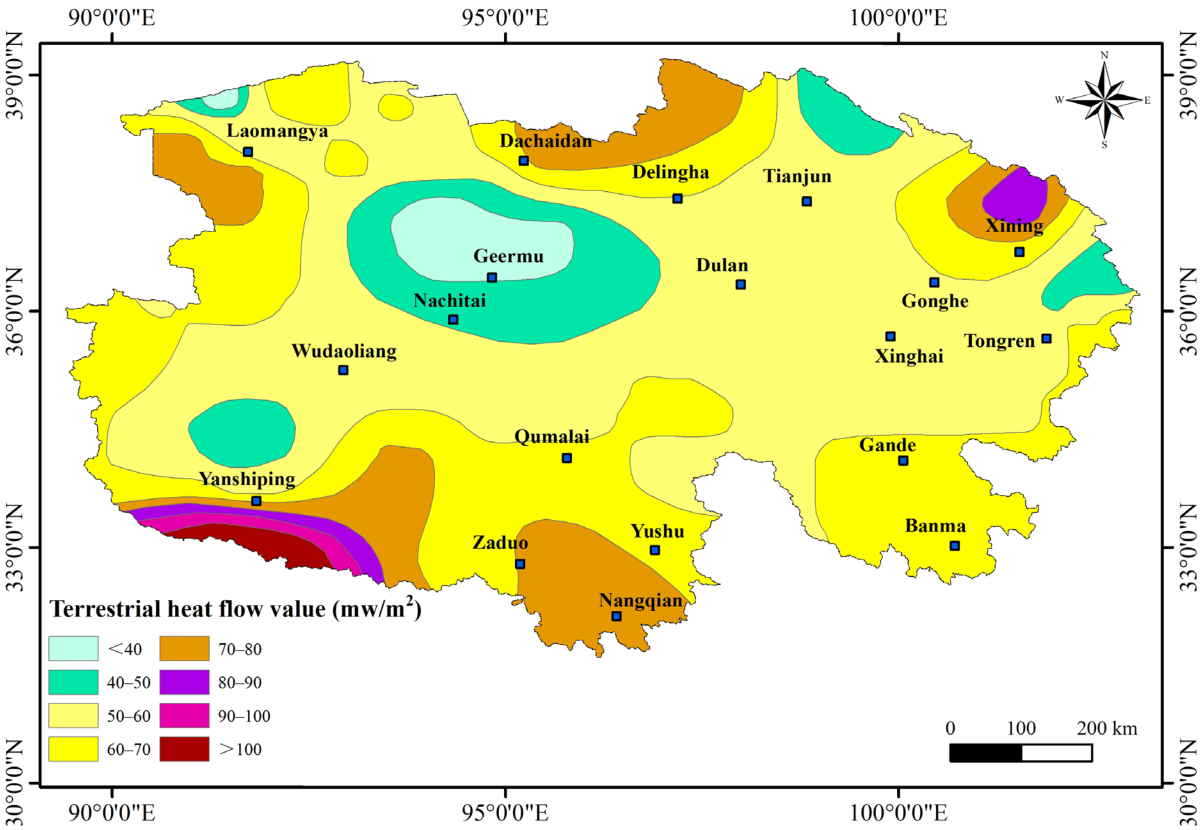


Figure 2. Hydrogeochemical simulation paths.

The geothermal resources in the uplifted mountain areas of the study area are of a hydrothermal type. The geothermal resources are controlled by faults of varying sizes within the tectonic plate, and they are distributed around major deep fault zones. These resources are formed when atmospheric precipitation, surface water, or mountain runoff infiltrates through fractures in the bedrock. After being heated by deep hot rocks, the geothermal fluids rise along deep faults and are either exposed at the surface or exploited for human use (Figure 3).

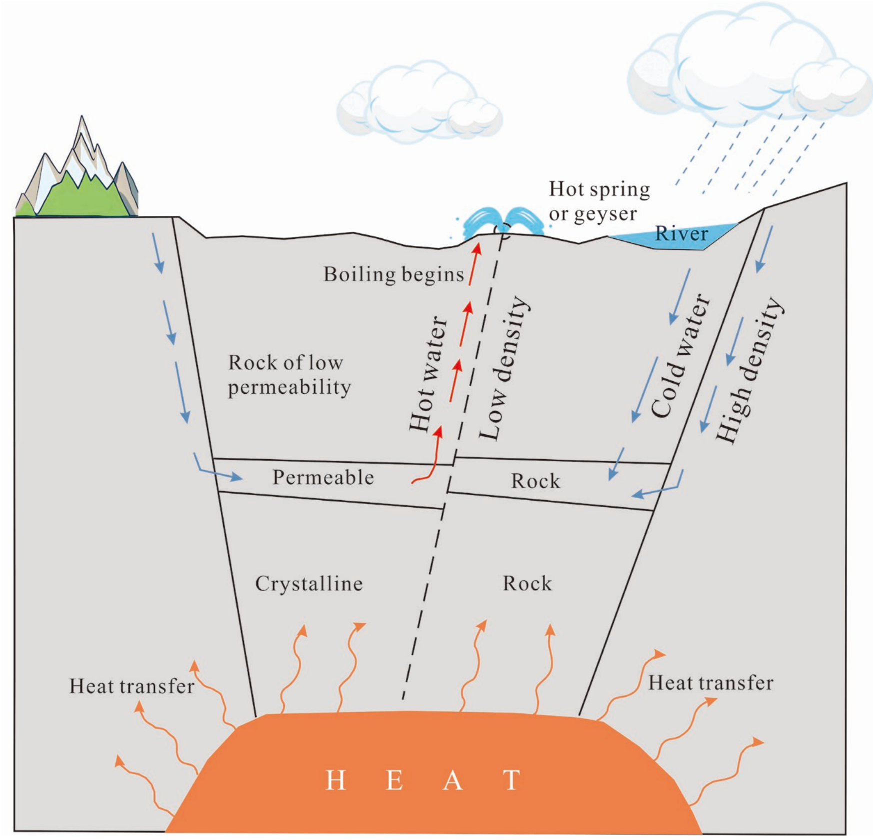


Figure 3. The formation schematic diagrams of uplifted mountain geothermal resources (modified after [4]).

3. Methods and Parameters

3.1. Evaluation Method

This study employs the widely used volumetric method for geothermal resource assessment. The method assumes the geothermal reservoir functions as a closed system. By measuring parameters such as the reservoir's volume, temperature, and specific heat, it is possible to estimate the total geothermal resource potential [21]. The general calculation formula for the thermal storage method, as outlined in the geothermal resource assessment methods and estimation guidelines (DZ/T 0331-2020 [22]) is presented below (Equation (1)).

$$Q = C_r \rho_r (1 - \varphi) V (T_1 - T_0) + C_w \rho_w q_w (T_1 - T_0) \tag{1}$$

In the equation, Q (J) denotes the geothermal reserves, C_r (J·kg^{-1}·K^{-1}) is the specific heat capacity of the thermal storage rock, C_w (J·kg^{-1}·K^{-1}) represents the specific heat capacity of water, ρ_r (kg·m^{-3}) is the density of the thermal storage rock, ρ_w (kg·m^{-3}) is the density of the geothermal water, and φ is the porosity of the thermal storage rock. V (m^3) is the thermal storage volume, T_1 (°C) refers to the thermal storage temperature, and T_0 (°C) is the local annual average temperature. Finally, q_w (m^3) represents the static storage volume of geothermal water in the pores of the thermal storage. The calculation formula for q_w is given below (Equation (2)).

$$q_w = \varphi \cdot V \tag{2}$$

Following the evaluation above, the potential for usable geothermal resources can be assessed based on the geothermal energy recovery rate of the thermal storage, as expressed in the equation below (Equation (3)). In this equation, Q_k (J) denotes the usable geothermal resource potential, and R_E represents the geothermal energy recovery rate of the thermal storage. In Qinghai Province, the local conversion factor from geothermal energy (J) to tons of standard coal equivalent was 1.761×10^{10}. This meant that 1.761×10^{10} J of geothermal energy was equivalent to 1 ton of standard coal equivalent.

$$Q_K = R_E \cdot Q \tag{3}$$

3.2. Vector Autoregression Model

To further investigate the relationship between geothermal resource consumption and industrial structure, this study utilizes a Vector Autoregression (VAR) model. This method is one of the models used for analyzing and forecasting multiple interrelated economic indicators. It regresses the current values of all variables on their respective lagged values. The model is designed to estimate the dynamic relationships between jointly endogenous variables, without imposing any a priori constraints [23].

Typically, the first step is to perform a unit root test to check whether the time series contains a unit root. A non-stationary series can be converted into a stationary one through differencing, as illustrated by the following formula:

$$\Phi(L)(1-L)^d x_t = \Theta(L) u_t \tag{4}$$

In the equation, $\Phi(L)$ denotes the autoregressive operator, L represents the first-order lag operator, $\Theta(L)$ signifies the moving average operator, and u_t corresponds to the white noise process.

The ADF test (Augmented Dickey–Fuller test) is further applied to examine the presence of unit roots in non-stationary sequences, using the following formula:

$$\Delta y_t = \hat{\rho} y_{t-1} \sum_{i=1}^{k} \hat{\gamma}_t \Delta Y_{t-1} + \hat{v}_t \tag{5}$$

Once the sequence becomes stationary, the VAR model can be established, as shown by the following formula:

$$y_t = \Phi_1 y_{t-1} + \cdots + \Phi y_{t-p} + H x_t + \varepsilon_t,\ t = 1, 2, \cdots, T \tag{6}$$

In the aforementioned equation, y_t represents a k-dimensional column vector of endogenous variables, x_t is a d-dimensional column vector of exogenous variables, p denotes the lag order, T signifies the number of samples, the $k \times k$ matrix $\Phi_1 \ldots \Phi_1$ and the $k \times d$ matrix H are coefficient matrices to be estimated, and ε_t is a k-dimensional column vector of disturbances.

3.3. Parameters

3.3.1. Geothermal Parameters

Data on the temperature, flow rate, and local annual average temperature of 20 geothermal resources in Qinghai Province were obtained from the Qinghai Provincial Bureau of Environmental Geology and Survey. Since most of the geothermal resources in the province are at the preliminary investigation stage, detailed monitoring data were unavailable. Consequently, the specific heat capacity and density of geothermal reservoir rocks, the specific heat capacity and density of geothermal water, the porosity of the reservoir rocks, the volume of the geothermal reservoir, and the geothermal energy recovery rate were estimated using the geothermal resource evaluation methods and guidelines (DZ/T 0331-2020). The energy conversion efficiency of different utilization methods of geothermal resources is shown in Table 1.

Table 1. Energy conversion efficiency of different utilization modes of geothermal resources.

Application	Energy Conversion Efficiency
Electricity Production	10–25%
Geothermal Heating	90–100%
Industrial Production	80–90%
Agricultural Production	80–90%
Tourism and Wellness	100%

3.3.2. Social Parameters

This study utilizes time series data from 2000 to 2022 on the added value of the primary, secondary, and tertiary industries and total energy consumption in Qinghai Province. To examine the relationship between industrial structure and geothermal resource consumption, the endogenous variables are defined as follows: the industrial structure of Qinghai (S), which represents the proportion of geothermal energy consumption in each industry, and the geothermal resource consumption in Qinghai (E), which refers to the total energy consumption per unit of industrial added value. To address the issue of heteroscedasticity, all variables are log-transformed in the analysis. The industrial structure is represented by lnS, and resource consumption by lnE. The sample data are sourced from the annual "Qinghai Provincial Statistical Yearbook" (http://tjj.qinghai.gov.cn/tjData/qhtjnj/) (accessed on 11 November 2024) and the "China Energy Statistical Yearbook" (https://www.stats.gov.cn/sj/ndsj/) (accessed on 11 November 2024).

3.4. Research Route

This study evaluated the geothermal resource potential in the study area using methods such as the volumetric method, VAR model, and impulse response function. It analyzed the relationship between geothermal resources and industrial structure, highlighting the impact of geothermal resources on industrial structure changes. The research approach was divided into two main parts: the collection and evaluation of geothermal resource data, and the collection of industrial structure data and model application (Figure 4).

First, data for geothermal resource assessment needed to be collected, including the specific heat capacity and density of reservoir rocks and geothermal water, porosity, reservoir volume, reservoir temperature, and annual average air temperature. Due to factors such as exploration extent and site conditions, data gaps were likely. When this occurred, missing values were supplemented using empirical values from the Geothermal Resource Assessment Methods and Estimation Procedures (DZ/T 0331-2020). The assessment was then performed using the volumetric method (Equation (1)).

Next, energy consumption and industrial structure data were collected to analyze the relationship between geothermal resources and industrial structure. The data were obtained from the China Energy Statistical Yearbook and the Qinghai Statistical Yearbook. First, data stationarity was tested using the ADF test. If the data were non-stationary, differencing was applied. Then, the lag order of the VAR model was determined based on the AIC, SC, and HQ criteria. After the model setup, the VAR model was estimated. Model stability was assessed through residual diagnostic tests, including autocorrelation, heteroscedasticity, and normality. If instability was detected, model parameters were adjusted, lag orders were increased, or differencing was applied until the model met diagnostic criteria. Finally, impulse response functions and variance decomposition were used to examine the dynamic relationship between geothermal resources and industrial structure. These analyses provided deeper insights into the role of geothermal resources in economic development and their influence on industrial structure.

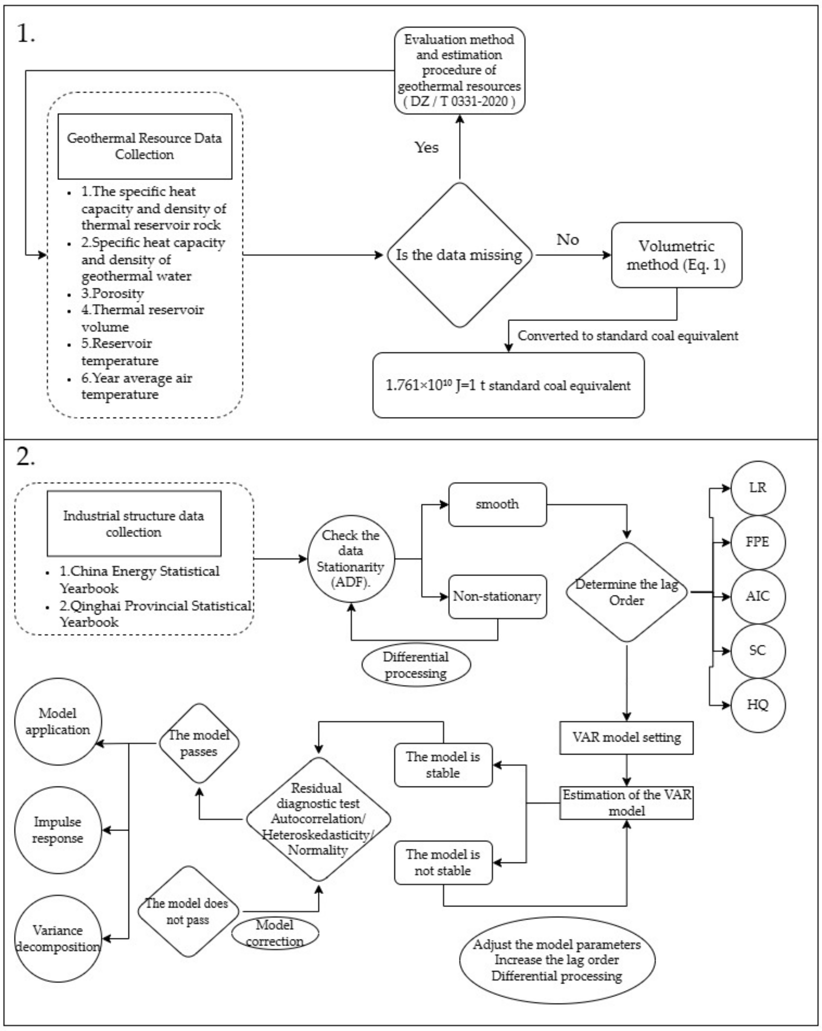


Figure 4. Research roadmap.

4. Result and Discussion

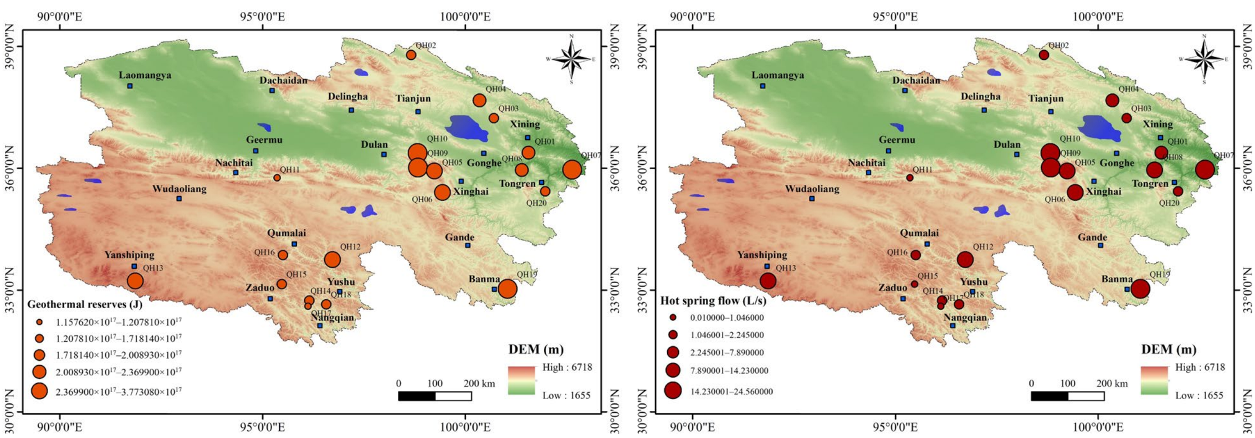
4.1. Geothermal Resources Evaluation

The geothermal resources at 20 sites in the study area were evaluated using the volumetric method (Table 2). The total geothermal resource in the upland mountainous region was 4.23×10^{18} J, or approximately 2.41×10^{8} tec. The total available geothermal resource was 3.18×10^{17} J, or approximately 1.81×10^{7} tec. The geothermal resource distribution in the upland mountainous region of the study area was characterized by higher values in the north and west, and lower values in the south and east. The highest geothermal resource was found at point QH19 in Banma County, with a total of 3.58×10^{17} J, or approximately 2.04×10^{7} tec. The lowest geothermal resource was found at point QH11 in Golmud City, with a total of 1.16×10^{17} J, or approximately 6.58×10^{6} tec. The distribution of hot spring flow followed the same pattern as the geothermal resource distribution. The highest hot spring flow, 24.56 L/s, was recorded at point QH06 in Xinghai County. The lowest hot spring flow was found at point QH13, located in Yanshiping County, with a flow rate of 0.01 L/s. The average temperature of the geothermal resources in the region was 86.94 °C. Eight geothermal sites (QH05, QH06, QH07, QH08, QH09, QH10, QH12, QH19) had temperatures above the average. The highest temperature, 156.1 °C, was recorded at QH19 in Banma County, while the lowest temperature, 47.2 °C, was recorded at QH17 in Nangqian County.

Table 2. Evaluation results of geothermal resources.

Field	Hot Spring Flow (L/s)	Geothermal Reserves (J)	Standard Coal Equivalent (t)	Geothermal Static Reserves (J)	Available Geothermal Resources (J)	Standard Coal Equivalent (t)	Temperature (°C)
QH01	14.23	1.99×10^{17}	1.13×10^{7}	1.50×10^{8}	1.50×10^{16}	8.51×10^{5}	76
QH02	6.23	1.51×10^{17}	8.57×10^{6}	1.20×10^{8}	1.13×10^{16}	6.43×10^{5}	61.2
QH03	6.42	1.57×10^{17}	8.92×10^{6}	1.20×10^{8}	1.18×10^{16}	6.70×10^{5}	62.7
QH04	10.23	1.89×10^{17}	1.07×10^{7}	1.20×10^{8}	1.42×10^{16}	8.06×10^{5}	75.6
QH05	2.25	2.20×10^{17}	1.25×10^{7}	1.00×10^{8}	1.65×10^{16}	9.37×10^{5}	98.2
QH06	24.56	2.21×10^{17}	1.26×10^{7}	1.20×10^{8}	1.66×10^{16}	9.45×10^{5}	92.8
QH07	2.18	3.42×10^{17}	1.95×10^{7}	1.00×10^{8}	2.57×10^{16}	1.46×10^{6}	151.9
QH08	0.84	2.01×10^{17}	1.14×10^{7}	1.00×10^{8}	1.51×10^{16}	8.58×10^{5}	91.1
QH09	7.89	3.18×10^{17}	1.81×10^{7}	1.00×10^{8}	2.39×10^{16}	1.36×10^{6}	140.3
QH10	0.91	3.77×10^{17}	2.15×10^{7}	1.50×10^{8}	2.83×10^{16}	1.61×10^{6}	143.2
QH11	1.05	1.16×10^{17}	6.58×10^{6}	1.20×10^{8}	8.68×10^{15}	4.94×10^{5}	48.2
QH12	2.03	2.37×10^{17}	1.35×10^{7}	1.20×10^{8}	1.78×10^{16}	1.01×10^{6}	95.1
QH13	0.01	2.14×10^{17}	1.21×10^{7}	1.20×10^{8}	1.60×10^{16}	9.12×10^{5}	85.6
QH14	22.16	1.72×10^{17}	9.77×10^{6}	1.50×10^{8}	1.29×10^{16}	7.33×10^{5}	65
QH15	1.00	1.53×10^{17}	8.68×10^{6}	1.50×10^{8}	1.14×10^{16}	6.51×10^{5}	55.9
QH16	7.28	1.63×10^{17}	9.30×10^{6}	1.50×10^{8}	1.23×10^{16}	6.98×10^{5}	59.9
QH17	13.00	1.21×10^{17}	6.87×10^{6}	1.50×10^{8}	9.06×10^{15}	5.16×10^{5}	47.2
QH18	1.50	1.70×10^{17}	9.66×10^{6}	1.50×10^{8}	1.27×10^{16}	7.25×10^{5}	65.3
QH19	10.09	3.58×10^{17}	2.04×10^{7}	1.00×10^{8}	2.69×10^{16}	1.53×10^{6}	156.1
QH20	0.55	1.56×10^{17}	8.85×10^{6}	1.00×10^{8}	1.17×10^{16}	6.64×10^{5}	67.5

Based on the geothermal resource volume, spring flow, and temperature, it was concluded that the geothermal resources in the northern part of the study area were superior to those in the southern part, and the resources in the western part were superior to those in the eastern part (Figure 5).



(a) (b)

Figure 5. (**a**) Distribution of geothermal reserves; (**b**) Flow distribution of hot springs.

4.2. Geothermal Resource Endowment Degree

Endowment refers to the natural distribution, superiority, and abundance of a particular resource or condition in a specific area [24]. To ensure the rationality of geothermal resource endowment in Qinghai Province and eliminate uncertainties introduced by geothermal exploration and utilization levels, the total energy consumption in the study area from 2000 to 2020 was analyzed. The total geothermal resource volume obtained from current evaluations was generalized as the total geothermal resources in the province. It was assumed that the geothermal resource endowment in Qinghai remained unchanged over time.

Based on the total energy consumption data for Qinghai Province from 2000 to 2020 as reported by the National Bureau of Statistics of China [25], and the geothermal resource total converted to coal equivalent, the total geothermal resource consumption and the proportions of coal, oil, natural gas, and electricity were ascertained (Table 3). Over the 21-year period from 2000 to 2020, the total geothermal resource consumption in the study area saw an overall increase of 3253.13×10^4 tec. However, in recent years, there has been a decline in the total consumption of geothermal resources, dropping from 4364.22×10^4 tec in 2018 to 4150.36×10^4 tec in 2020. In the development and utilization of geothermal resources, auxiliary energy sources, including coal, oil, natural gas, and electricity, are often required. Between 2000 and 2020, electricity accounted for the largest share of geothermal resource consumption in Qinghai Province, with an average proportion of 42.20%. In recent years, this share has continued to rise. This suggested that the utilization of geothermal resources in Qinghai has primarily focused on power generation rather than other applications, such as direct heating. Geothermal power, together with photovoltaic and wind energy, formed a key component of Qinghai's "West-to-East Power Transmission" strategy [26].

Coal, the second-largest energy source in geothermal resource consumption, accounted for an average share of 34.33%. This suggests that coal played a key auxiliary role in the early stages of geothermal development, providing reliability and stability. It helped address the current limitations of geothermal utilization. Furthermore, the cold climate, vast land area, sparse population, and significant regional variations in the study area have prevented geothermal resources from covering all production and domestic needs [27]. These factors have made coal an essential auxiliary and transitional energy source for geothermal resources. However, with the continued development of geothermal resource utilization technologies and increased government support, the share of coal in geothermal consumption has decreased [28]. After 2016, this share declined, falling to below 30% by 2020. Oil and natural gas constituted minor shares in the consumption of geothermal resources, averaging 10.88% and 12.60%, respectively. This indicated that these two energy sources played a secondary role in the utilization of geothermal resources (Figure 6a).

Data on total energy consumption in Qinghai Province from 2000 to 2020, as reported by the National Bureau of Statistics of China, along with the shares of coal, oil, natural gas, and electricity in geothermal resource consumption, were utilized to determine the proportion of geothermal resources in the three major industries and domestic consumption (Table 4). The term "three major industries" denotes the principal economic sectors categorized by their production characteristics and functions. The primary sector encompasses agriculture, forestry, livestock, and fishing. The secondary sector comprises mining, manufacturing, and the generation and supply of electricity and heat. The tertiary sector includes all other industries not classified as primary or secondary [29]. Domestic consumption, an economic activity, involves the utilization of material resources and the enjoyment of services by individuals in their daily lives and production processes [30].

Table 3. Total geothermal resources consumption and coal, petroleum, natural gas and electricity as a proportion of total geothermal resources consumption.

Years	Total Consumption of Geothermal Resources (10^4 tec)	The Proportion of Total Geothermal Resources Consumption (%)			
		Coal	Petroleum	Natural Gas	Electricity
2000	897.23	30.18	18.96	4.83	46.03
2001	989.38	28.02	18.05	7.52	46.41
2002	1018.83	26.42	15.77	13.25	44.56
2003	1122.70	28.72	13.47	15.07	42.74
2004	1364.38	27.56	14.07	15.79	42.58
2005	1830.48	44.20	8.63	8.00	39.17
2006	2085.84	45.18	7.75	8.46	38.61
2007	2295.91	47.56	8.09	8.29	36.06
2008	2497.74	43.72	8.95	12.20	35.13
2009	2573.44	42.99	7.79	12.69	36.53
2010	2814.57	34.14	7.61	11.21	47.04
2011	3145.28	28.58	10.68	12.97	47.77
2012	3475.88	31.43	9.40	14.60	44.57
2013	3768.16	31.67	8.24	13.95	46.14
2014	3991.70	29.77	8.21	12.86	49.16
2015	4124.97	31.60	9.11	14.75	44.54
2016	4101.36	43.37	10.13	15.00	31.50
2017	4193.10	37.87	11.46	15.97	34.70
2018	4364.22	31.68	10.29	15.93	42.10
2019	4235.23	29.15	10.87	16.38	43.60
2020	4150.36	27.06	10.95	14.79	47.20

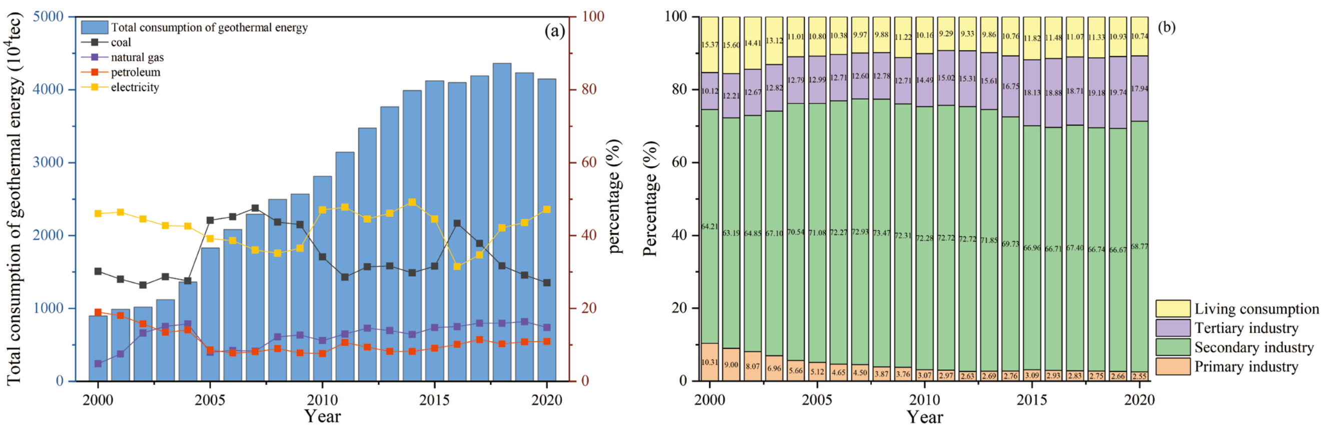


Figure 6. (**a**) Total geothermal resources consumption and coal, petroleum, natural gas and electricity as a proportion of total geothermal resources consumption; (**b**) The proportion of geothermal resources in the three major industries and living consumption.

Table 4. The proportion of geothermal resources in various industries.

Years	Primary Industry (10^4 tec)	Secondary Industry (10^4 tec)	Tertiary Industry (10^4 tec)	Domestic Consumption (10^4 tec)	Proportion (%)			
					Primary Industry	Secondary Industry	Tertiary Industry	Domestic Consumption
2000	399.16	2487.01	391.88	595.36	10.31	64.21	10.12	15.37
2001	373.10	2620.11	506.26	646.64	9.00	63.19	12.21	15.60
2002	366.17	2941.77	574.75	653.70	8.07	64.85	12.67	14.41
2003	340.44	3281.97	626.80	641.84	6.96	67.10	12.82	13.12
2004	317.60	3961.00	718.23	618.06	5.66	70.54	12.79	11.01
2005	329.39	4569.86	835.39	694.41	5.12	71.08	12.99	10.80
2006	326.41	5077.11	893.04	729.08	4.65	72.27	12.71	10.38
2007	339.17	5497.25	949.54	751.74	4.50	72.93	12.60	9.97
2008	306.53	5815.52	1011.55	782.30	3.87	73.47	12.78	9.88
2009	317.20	6100.98	1072.48	946.48	3.76	72.31	12.71	11.22
2010	278.76	6562.44	1315.79	922.26	3.07	72.28	14.49	10.16
2011	295.82	7231.83	1493.58	924.13	2.97	72.72	15.02	9.29
2012	285.48	7882.22	1659.87	1011.18	2.63	72.72	15.31	9.33
2013	281.52	7527.33	1635.01	1033.31	2.69	71.85	15.61	9.86
2014	299.35	7572.73	1819.29	1168.54	2.76	69.73	16.75	10.76
2015	334.95	7251.68	1963.43	1279.71	3.09	66.96	18.13	11.82
2016	326.45	7425.30	2101.19	1278.09	2.93	66.71	18.88	11.48
2017	326.83	7796.70	2164.42	1280.70	2.83	67.40	18.71	11.07
2018	330.04	8005.13	2300.46	1359.47	2.75	66.74	19.18	11.33
2019	334.16	8375.69	2480.12	1372.77	2.66	66.67	19.74	10.93
2020	341.05	9205.91	2401.68	1438.38	2.55	68.77	17.94	10.74

Geothermal resources in Qinghai Province were predominantly consumed in the secondary industry, which on average constituted 69.26% of the total from 2000 to 2020. In contrast, the primary industry's consumption was minimal, averaging only 4.42% during the same period. From 2000 to 2020, the share of geothermal resources in Qinghai Province's primary industry and domestic consumption saw a gradual decline, amounting to 7.76% and 4.63%, respectively. Conversely, the secondary and tertiary industries experienced an increase in their geothermal resource consumption, with gains of 4.56% and 7.82%, respectively, over the same period (Figure 6b). Amidst the swift economic growth in China, there has been an expansion of industrial scale and a surge in electricity demand. Concurrently, China's robust support for renewable energy development has increasingly highlighted the significance of geothermal resources in Qinghai's power generation. This has been the primary factor contributing to geothermal resources holding the largest share in Qinghai's secondary industry, a trend that continues to rise. The swift growth of geothermal resources in the secondary industry has also catalyzed their expansion in the tertiary industry. With advancements in socio-economic conditions and scientific progress, the share of the tertiary industry in the overall industrial structure is expected to keep increasing. These combined factors have resulted in a substantial rise in the proportion of geothermal resources within both the secondary and tertiary industries.

Since 2000, as the economic structure has shifted, the primary industry's share of Qinghai's GDP has seen a steady annual decline. The primary industry's overall demand is low and its applications are limited, resulting in a corresponding annual decrease in the amount and proportion of geothermal resources, when converted to standard coal, within this industry. Despite a reduction in its proportion, the actual quantity of geothermal resources used in domestic consumption has risen. This increase is attributed to advancements in energy-saving technologies, which have enhanced energy efficiency and consequently lowered the demand for geothermal resources in domestic consumption. Additionally, the growth rate of domestic consumption is slower compared to the secondary and tertiary industries. As a result, while the quantity of geothermal resources, when converted to standard coal, used in domestic consumption has increased, its proportion has declined.

4.3. The Influence of Geothermal Resources on Industrial Structure

To verify the model's accuracy, an ADF unit root test was conducted on the industrial structure (lnS) and geothermal resource consumption (lnE) in Qinghai Province from 2000 to 2020 to assess their stationarity. The test results showed that the ADF statistics for both industrial structure (lnS) and geothermal resource consumption (lnE) were below the critical value at the 5% significance level, with p-values exceeding 0.05 for both. This indicates that both variables are non-stationary. To address the non-stationarity issue, second-order differencing was applied to both industrial structure (lnS) and geothermal resource consumption (lnE). After second-order differencing, the ADF statistics for the resulting series were below the 5% critical value, with p-values less than 0.05. This confirmed that the two variables became stationary, meeting the prerequisite for conducting a cointegration test (Table 5).

Table 5. The results of the ADF (Augmented Dickey–Fuller) statistic test for lnS and lnE.

Variable	Test Type	ADF Value	1% Significance Level	5% Significance Level	10% Significance Level	AIC	SC	HQ	p	Result
lnS	C,T,0	−0.7776	−3.7672	−2.9657	−2.5909	−3.0206	−2.8217	−2.9869	0.6719	unsteady
dlnS	C,T,0	−12.8313	−2.6281	−1.8959	−1.5428	−3.0796	−3.0299	−3.0712	0.0001	steady
lnE	C,T,0	0.1189	−3.7237	−2.9481	−2.5818	−2.2988	−2.1994	−2.2773	0.7273	unsteady
dlnE	C,T,0	−6.4866	−2.6281	−1.8959	−1.5428	−1.8544	−1.8047	−1.8460	0.0001	steady

To avoid errors in the autocorrelation of the error terms and inconsistent parameter estimation caused by incorrect lag selection, this study used a method that combined multiple criteria (including LR, FPE, AIC, SC, and HQ) to assess and determine the optimal lag length. After careful evaluation, a lag length of 4 was selected as the optimal choice (Table 6).

Table 6. Comprehensive evaluation results of the lag order for the VAR model.

Order	LogL	LR	FPE	AIC	SC	HQ
0	15.6778	NA	0.00008816	−1.5373	−1.4393	−1.5275
1	55.0067	64.8414	0.00000806	−5.6936	−5.3996	−5.6644
2	55.5411	0.8186	0.00001406	−5.2859	−4.7958	−5.2372
3	69.7355	16.7637	0.0003026	−6.4853	−5.7991	−6.4171
4	86.4282	15.7751 *	0.0000056 *	−7.9785 *	−7.0963 *	−7.8908 *
5	89.7453	2.4057	0.00029911	8.0268	6.9485	7.9196

Note: "*" denotes the optimal choice.

When all four eigenvalues were less than 1, a stable relationship between the variables dlnS and dlnE was confirmed. This indicated that the VAR model was stable and met the prerequisite for impulse response analysis (Table 7). The stability test confirmed that the VAR model used in this study demonstrated strong stability, scientific rigor, and reliability in analyzing the relationship between Qinghai's industrial structure and geothermal resource consumption.

Table 7. Stability of VAR Model.

Root	Modulus
0.928833	0.92883284
0.59126864	0.59136084
−0.295627	0.295627
0.04690284	0.046903

The impulse response function analysis method was used to explore the interaction between the industrial structure (lnS) and geothermal resource consumption (lnE) in Qinghai Province. After a one-unit shock to geothermal resource consumption (lnE), the industrial structure (lnS) showed an immediate response of 0.7%, which gradually stabilized (Figure 7a). In the first phase, the impact of industrial structure (lnS) on geothermal resource consumption (lnE) was most significant and positive. From the fifth phase onward, this effect gradually stabilized (Figure 7c). In summary, driven by new productive forces, the adjustment of industrial structure exerted a constraining effect on energy consumption, and this constraining effect gradually intensified over time. This trend was primarily attributed to the continuous optimization and upgrading of the industrial structure in Qinghai Province since 2003, with the proportion of the tertiary sector continuously increasing. Additionally, the study found that energy consumption had an impact on the evolution of the industrial structure. In the short term, energy consumption exerted a certain constraining effect on the adjustment of the industrial structure, partly due to the low energy conversion efficiency in the province's industry, as evidenced by the low output benefits per unit of electricity in high-energy-consuming industries (Table 8).

In the variance decomposition analysis of geothermal resource consumption (lnE), the role of industrial structure (lnS) was relatively small, but it showed a steady increasing trend. By the 10th issue, the contribution of industrial structure (lnS) to the utilization of geothermal resources (lnE) had escalated to 49%. In contrast, the influence of geothermal resource use (lnE) on the variance decomposition of industrial structure (lnS) had its contribution rate steadily climb, ultimately reaching 90% by the 10th issue. The analysis suggests that the reciprocal influence between geothermal resource utilization (lnE) and industrial structure (lnS) has grown stronger. Consequently, future research should emphasize the interplay between geothermal resource consumption patterns and industrial structures, investigating how adjustments to geothermal resource consumption can drive the optimization and upgrading of industrial structures. Simultaneously, the transformation of geothermal resource consumption patterns should be facilitated through industrial structure optimization. Such research holds significant value for a profound comprehension of the dynamic shifts in the relationship between industrial structures and geothermal resource consumption patterns in the Qinghai region, propelled by new forms of productive forces.

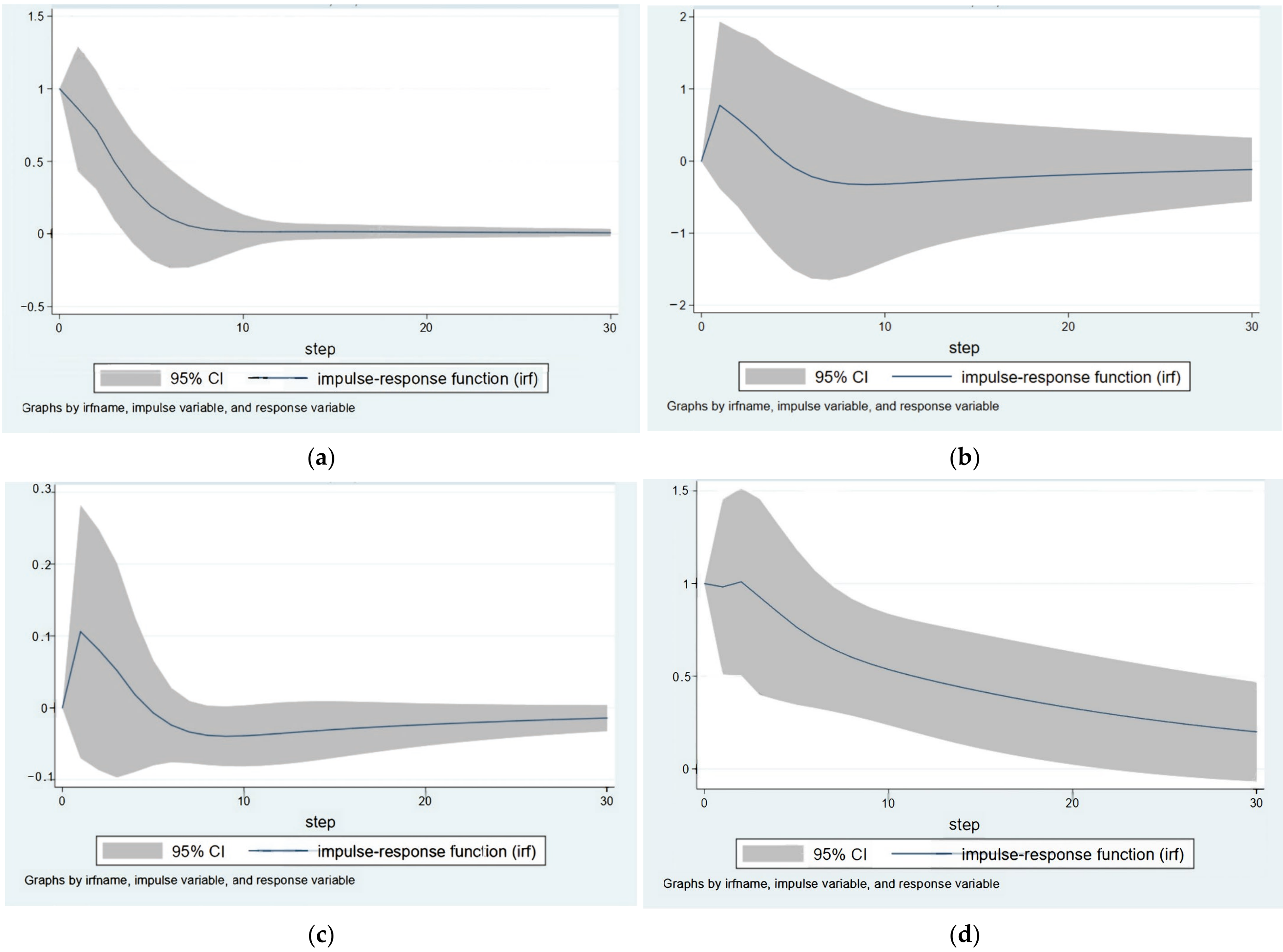


Figure 7. The results of variable impulse response. (**a**) Impulse response from ln E to ln E. (**b**) Impulse response from ln E to ln S. (**c**) Impulse response from ln S to ln E. (**d**) Impulse response from ln S to ln S.

Table 8. The result of variance decomposition.

Number of Periods	Variance Decomposition of lnS	Variance Decomposition of lnE
0	0.00000	0.000000
1	0.757493	0.000000
2	0.875665	0.496583
3	0.899694	0.496669
4	0.90582	0.493746
5	0.904547	0.490642
6	0.902361	0.488821
7	0.901354	0.488264
8	0.901729	0.488537
9	0.902985	0.489214
10	0.904602	0.490012

5. Conclusions

Qinghai Province, endowed with abundant geothermal resources, holds considerable potential for development. First, this study employed the volumetric method to assess the geothermal resources characteristic of mountainous uplift areas, revealing their spatial distribution in the province. Following this, the study quantified the endowment of geothermal resources and examined their interplay with the industrial structure. Ultimately, a Vector Autoregression (VAR) model was applied to analyze the extent and impact of geothermal resources on the evolution of local industrial structures. The conclusions are as follows:

Geothermal resources in Qinghai Province's mountainous uplift areas are distributed with a higher concentration in the north and west compared to the south and east. Banma County was identified as the region with the most abundant geothermal resources, totaling 3.58×10^{17} J, while Golmud City had the least, at 1.16×10^{17} J. Furthermore, the temperature and flow rate distributions of Qinghai's geothermal resources were found to be significantly correlated with the quantity of these resources.

Geothermal resource consumption in Qinghai Province was mainly concentrated in power generation, representing about 42.20% of the total. Since 2000, the overall consumption of geothermal resources has risen annually; however, a downward trend has been observed in recent years. With ongoing technological innovation, the development and utilization of geothermal resources gradually reduced the reliance on traditional energy sources, such as coal, thereby promoting the optimization of the regional energy structure. This provided strong support for the study area's transition to green and sustainable energy. As a clean and renewable energy source, geothermal resources became one of the core drivers of Qinghai's green development.

The development and utilization of geothermal resources in Qinghai Province were profoundly influenced by the industrial structure, with changes in the industrial structure playing a crucial role in adjusting the demand for geothermal resources. From 2000 to 2020, the share of geothermal resources used by the secondary and tertiary industries increased annually, while the share used by the primary industry gradually decreased. The secondary industry, particularly sectors related to energy development and manufacturing, became the primary field for geothermal resource utilization.

In the short term, geothermal resource consumption in Qinghai Province had a certain constraining effect on the adjustment of the industrial structure. However, as time progressed, the contribution of the industrial structure to geothermal resource consumption gradually increased, reaching a contribution rate of 49% to geothermal resource usage by 2020. With the continuous advancement of clean energy technology, the development and utilization of geothermal resources would, in turn, promote the optimization of the industrial structure in terms of green energy and sustainable development.

Overall, the development and utilization of geothermal resources in Qinghai Province has significant potential, particularly in the field of geothermal power generation. In the future, it should continue to promote the upgrading and optimization of its industrial structure, focusing on enhancing the development of the tertiary sector, while also strengthening the development and utilization of geothermal resources to ultimately achieve a green transition in the energy structure. By optimizing the energy structure, reducing dependence on conventional energy sources, and improving the efficiency of sustainable energy use, the development of geothermal resources will contribute to the long-term sustainable development of the socio-economy.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17041751/s1, Table S1: Evaluation results of geothermal resources.

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Conflicts of Interest: Authors Zhen Zhao and Guangxiong Qinare employed by Qinghai 906 Engineering Survey and Design Institute Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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