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# Comparative Study on Relative Fossil Energy Carrying Capacity in China and the United States

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**Abstract:** Based on resource carrying capacity, this study used the revised theory of relative resource carrying capacity (RRCC) and introduced an innovative concept of relative fossil energy carrying capacity (RFECC), which evaluates the degree of fossil energy sustainability based on the relationship between economy, population, and environment. This study took China and the United States as the study objects, took the whole country as the reference area, and calculated the RFECC of population, economic, and environmental resources from 2000 to 2018. Therefore, based on the comparative analysis, the following conclusions were drawn: (i) there is a big difference in the RFECC between China and the United States, which is manifested in the inverted U-shaped trend in China and the U-shaped trend in the United States; (ii) the relative fossil energy carrying states in China and the United States are different, mainly reflected in the economy and environment; (iii) the gap in RFECC between China and the United States has gradually widened; in general, China's economic RFECC is better than that of the United States, while environmental RFECC and population RFECC in the United States is better than that of China; and (iv) coal and oil should be used as a breakthrough point for the sustainable fossil energy and sustainable development for China and the United States, respectively.

**Keywords:** relative fossil energy carrying capacity (RFECC); China; the United States; comparative analysis



**Citation:** Zuo, Z.; Cheng, J.; Guo, H.; Li, Y. Comparative Study on Relative Fossil Energy Carrying Capacity in China and the United States. *Energies* **2021**, *14*, 2972. https://doi.org/10.3390/en14102972

Academic Editor: Dalia Štreimikienė

Received: 6 April 2021
Accepted: 18 May 2021
Published: 20 May 2021



## 1. Introduction

Energy is an important material basis for the operation of the national economic system and an essential driving force for economic and social development. The carrying capacity of resources is limited, especially fossil energy [1]. China, as the largest developing country in the world, has made a dramatic change after rapid economic growth. China's fossil energy structure has distinctive characteristics, mainly manifesting as "coal-rich, oil-poor and gas-poor" [2]. Over the past 40 years of reform and opening-up, China's fossil energy production and consumption have risen to the top of the world. Production with coal, oil, and natural gas has increased by 5.9 times, 1.9 times, and 11.7 times respectively, and consumption has increased by 6.5 times, 6.8 times, and 20.3 times compared with 1978 ("China Energy Development Report", 2018). Moreover, the United States, as the largest developed country in the world, became the dominant country in oil production in the first half of the 20th century, accounting for more than 50% of the world's annual production [3]. The energy system load is getting higher and higher and environmental pressure is more and more intensified. Global energy structure is facing transformation and upgrading, and the world is undergoing a transition from the era of fossil energy to the era of new energy. However, the importance of fossil energy for economic development determined that the energy structure cannot be completely reversed in the short-term. Therefore, it is urgent to clarify the carrying capacity and sustainable development potential of fossil energy. Furthermore, how to determine the load status of fossil energy for the population, economy, and environment, and to maintain the balance between energy and population, the economy, and the environment is of great significance. Furthermore, it plays a vital role in optimizing and adjusting the energy structure dynamically and achieving balanced development and the sustainable development of fossil energy and each subsystem.

Therefore, based on energy carrying capacity, dynamically examining the maximum load supported by fossil energy can provide a measure of sustainable fossil energy development. An innovative concept of relative fossil energy carry capacity (RFECC) is introduced in this paper, which evaluates the degree of fossil energy sustainability based on the relationship between economy, population, and environment. Thus, we define RFECC as the ability of fossil energy to meet the demand of the population, economy, and environment load with satisfying service. This paper focuses on the expansion of the relative resources carry capacity (RRCC) model and selects data from 2008 to 2018 to conduct a comparative study on the RFECC of China and the United States. We calculated the RFECC after comprehensively considering population, economic, and environmental factors. The main contributions of this research are as follows: (i) we proposed the concept of RFECC to reflect the sustainable status of fossil energy dynamically; (ii) we selected the two most representative countries in developed countries and developing countries for comparison, which can reflect the differences in the sustainability status of fossil energy under the different developed modes; and (iii) based on the RFECC, we compared the carrying status of fossil energy by type of China with the United States, and made recommendations for the breakthrough point of their energy structure adjustment to achieve sustainable development.

The remainder of this paper is organized as follows. Section 2 reviews the related literature on carrying capacity. Section 3 introduces the research framework and methodology. Section 4 then discusses the results. Section 5 summarizes the study and provides related policy recommendations for China to achieve the sustainable development of fossil energy.

## 2. Literature Review

In 1921, Park and Burgess first proposed the concept of carrying capacity, that is, the highest limit of the number of specific individuals under a particular environmental condition [4]. Carrying capacity is a quantitative limit, and the selection of indicators for quantitative expression is abundant. Verhulst [5] adopted the Logistic equation to describe the restriction of environmental factors on the population under Malthus theory, and Odum [6] highlighted the restriction of land factors on the population. In the 1980s, UNESCO defined carrying capacity as the number of people that can be sustained in the foreseeable period, using energy and other natural resources, intelligence, technology, and other conditions of the area, while ensuring a material standard of living in line with its socio-cultural norms. This means that carrying capacity focuses on the harmony and sustainable development of nature, environment, economy, society, and people. The threshold is the limit of the carrying capacity.

Carrying capacity is an effective tool to measure the level of regional sustainable development under the corresponding system [7–9]. The concept of carrying capacity is widely discounted, in part because it is fluid and virtually unquantifiable [10]. Subsequently, various concepts and theories of carrying capacity were introduced in different development stages and resources conditions. These theories, mainly focusing on the carrying capacities of natural resources, among which the carrying capacities of land, minerals, forest, ocean, etc., have been studied for a long time and achieved fruitful research [11–15]. Carrying capacity is a kind of portrayal of the survival ratio and consumption coefficient among human, nature, and society, and it is a sustainable development capacity under the threshold of harmonious development without being broken [16]. Carrying capacity models are mainly used to estimate the self-sufficiency of a population and generally include necessary needs for human survival such as food, water, shelter, and energy [17,18]. Mao and Yu [19] defined comprehensive carrying capacity as the capacity of the total population and economic development carried by the resources and environment in the region under the premise of rational economic development and utilization of resources. Carrying capacities are not static and fixed. They depend not only on economic development, technological innovation, preferences, production structure, and consumption structure, but also on changes in the environment [20].

Most of that is focused on absolute carrying capacity, that is, the quantity and quality of resources in a country or a region to support the basic survival and development of the population in the space. With technological progress and internal development, production and lifestyle change, its value is subjective and dynamic; therefore, to measure whether the carrying capacity is beyond the threshold, there is a reference standard and the carrying capacity should be relative rather than absolute [20]. Due to the large population of China and the limited amount of resources, when the traditional absolute resource carrying capacity method is used to measure the carrying capacity of resources, we almost arrive at the conclusion that carrying states are overloaded or even severely overloaded. This conclusion has limited guiding significance for practice [21]. Given this, Zhu proposed [22] a "Population-Economy-Resources (P-E-R)" modeling framework for regional matching, and concluded that the population carrying capacity should be decomposed from both resource and economic dimensions, but should also be analyzed comprehensively. Then, the concept of relative resource carrying capacity (RRCC) was further constructed; that is, using one or several areas larger than the study area as the reference area, the relative resources carrying capacity in the study area is calculated based on the per capita resource possession, consumption, or the resource stock in the study area [23]. This expands the research scope of resource carrying. Compared with the traditional resource carrying capacity, the RRCC emphasizes the openness of the research area and the complementarity between natural resources and economic resources. The model was adopted to analyze the RRCC of the Yangtze River Basin, Northeast China, Jiangsu, Jilin, and Ningxia [24–28]. Moreover, the RRCC model has been applied to water, land, forest, and other natural resources [29,30]. Some scholars have extended and improved the calculation of relative comprehensive carrying capacity [31,32]. Even today, the research on RRCC is still endless, and the research on the calculation model, research object, and evaluation index of RRCC is still being enriched and explored [33].

## 3. Research Framework and Methodology

### 3.1. Relative Fossil Energy Carry Capacity Model

Some scholars conclude that the economy and the environment are the main factors that constrain the regional carrying capacity and apply system theory to incorporate the subsystems of population, resources, and environment into the RRCC model [32]. According to the relevant research on RRCC, the RFECC is defined as follows: under the premise of rational resource utilization and economic development, fossil energy can ensure the sustainable development of the study area in a certain period relative to the reference area. This reflects the sustainable development potential of fossil energy. Therefore, the traditional RFECC model was selected:

$$C_s = \omega_1 C_{pop} + \omega_2 C_{gdp} + \omega_3 C_{ef} \tag{1}$$

$$C_{pop} = \frac{Q_{pop\_0}}{Q_{com\_0}} Q_{pro} \tag{2}$$

$$C_{gdp} = \frac{Q_{gdp\_0}}{Q_{com\_0}} Q_{pro} \tag{3}$$

$$C_{ef} = \frac{Q_{ef\_0}}{Q_{com\_0}} Q_{pro} \tag{4}$$

where $C_s^*$, $C_{pop}$, $C_{gdp}$, and $C_{ef}$ denote the comprehensive RFECC, population RFECC, economic RFECC, and environmental RFECC, respectively. $\omega_1$, $\omega_2$, and $\omega_3$ are the weights of population, economic, and environmental resources. $Q_{pop\_0}$, $Q_{gdp\_0}$, and $Q_{ef\_0}$ are the population, GDP, and ecological footprint of the reference area. $Q_{com\_0}$ is the fossil energy (coal, oil, natural gas) of the reference area, $Q_{com\_0}$ is the fossil energy output in the study area. We selected the world as the reference area, China and the United States as the research areas. The results can indicate the position and status of China and the United States in the world. Moreover, selecting the same reference area is more conducive to comparing the RFECC of two countries.

The traction effect of advantage resource was selected:

$$\max C_s^1 = w_1 C_{pop} + w_2 C_{gdp} + w_3 C_{ef} \tag{5}$$

$$\begin{cases} \beta \le |w_i - w_j| \le \alpha \\ \delta < w_i, w_j < 1, (i,j = 1,2,3, i \ne j) \\ \sum_{i=1}^{3} w_i = 1, \quad \delta \text{ is the lower limit of the weight of each factor.} \\ \alpha, \beta \text{ are the upper and lower limits of the weight difference between the factors.} \end{cases}$$

The constraint effect of disadvantage resource was selected:

$$\min C_s^2 = w_1 C_{pop} + w_2 C_{gdp} + w_3 C_{ef} \tag{6}$$

$$\begin{cases} \beta \le |w_i - w_j| \le \alpha \\ \delta < w_i, w_j < 1, (i,j = 1,2,3, i \ne j) \\ \sum_{i=1}^{3} w_i = 1, \quad \delta \text{ is the lower limit of the weight of each factor.} \\ \alpha, \beta \text{ are the upper and lower limits of the weight difference between the factors.} \end{cases}$$

$$C_{s\_2} = \sqrt{C_s^1 * C_s^2} \tag{7}$$

We used the exploratory factor analysis to determine $\omega_1 = 0.5324$, $\omega_2 = 0.2437$, and $\omega_3 = 0.2239$, and calculated $C_{s\_1}$, according to Equation (3). In order to further make up for the lack of experience weight, we calculated $C_{s\_2}$ based on the traction effect of the advantage resource and the constraint effect of disadvantage resource [34]. Therefore, RFECC was selected:

$$C_s^* = 1/2(C_{s\_1} + C_{s\_2}) \tag{8}$$

We divided the carrying states into three types: overload, surplus, and balance, that is, P-$C_s^*$ > 0, P-$C_s^*$ < 0, and P-$C_s^*$ = 0. Among them, P is the actual population. In addition, P can be replaced with actual GDP and ecological footprint according to the situation to measure the economic and environmental carrying state.

### 3.2. The Prediction Model of GM-BP-SVM

For a long time, forecasting theories and methods have continued to emerge; they can be divided into two categories: (1) the traditional method represented by the time series method, and (2) the new artificial intelligence method represented by the artificial neural network method. The main traditional methods are the time series method, the multiple linear regression method, and the Fourier expansion method [35]. The traditional method has features such as simplicity and fast operation. However, the traditional methods are powerless when it comes to the nonlinear problems. The main artificial intelligence methods include the expert system method, the fuzzy logic method, the fuzzy neural model, and the artificial neural network method [36,37]. The neural network method can capture various trends due to their ability to distribute information in parallel, self-learning, especially to achieve complex nonlinear mappings. In general, the mathematical statistics methods are more suitable for linear systems, and usually require large amounts of raw data for modeling. Artificial intelligence methods also need to rely on abundant data to ensure the accuracy of prediction. Fuzzy logic does not require complex mathematical models, but fuzzy processing of simple information can lead to a loss of prediction accuracy.

Deng proposed the gray system theory [38], which is suitable for researching uncertainty problems with a small amount of data and poor information. In control theory, "black" represents "lack-of-information", "white" indicates "sufficient-information", while "gray" denotes a model in which some information is known and some information is unknown [39]. It takes uncertainty systems with partly known information and partly unknown information as the research object, and realizes the description and prediction of system operation behavior and evolution law by extracting the valuable law with known information. The gray model (1,1) quantifies the concept of system information abstraction through some known data and finally optimizes the model to predict some unknown data [40]. Analyzing the data characteristics of RFECC is beneficial for selecting the appropriate method from the existing forecasting methods. The gray prediction model has been widely used in energy prediction, such as natural gas [41], oil [42], coal [43], etc. Considering the complexity of RFECC calculation, the amount of data, and the difference in fossil energy statistics and measurement methods between China and the US, it is difficult to obtain reasonable prediction results with existing big data techniques or fuzzy logic, and the gray prediction method is a good attempt.

The back propagation neural network (BPNN) prediction model is a neural network for interpolation in a high-dimensional space. It consists of three layers: an input layer, a hidden layer, and an output layer. The input layer, the hidden layer, and the output layer are composed of a large number of single neurons that are not connected. As a mature and classic forecasting model, the BP neural network is widely used in traffic flow forecasting, price trend forecasting, oil reservoir prediction [44], and air pollution forecasting [45–47].

The support vector machine (SVM) was proposed by Vapnik [48]. It differs from traditional neural network learning methods by implementing the structural risk minimization principle (SRM), which minimizes both the empirical risk and the VC dimensional bound. It has superior performance in solving small sample, nonlinear, and high-dimensional pattern recognition problems, and it overcomes the problems of "dimensional disaster" and "over-learning." Furthermore, it has a solid theoretical foundation and a precise and straightforward mathematical model. Therefore, it has been dramatically developed in the fields of text recognition [49], handwriting recognition [50], face image recognition [51], gene classification [52], and time series prediction [53].

To prove the accuracy of the prediction results, we chose the mean absolute percentage error (MAPE) as an indicator to reflect the prediction performance. The smaller the MAPE, the better the prediction accuracy [54,55].

$$MAPE = \frac{i}{n} \sum_{i=1}^{n} \left| \frac{x_i - y_i}{x_i} \right| *100\% \tag{9}$$

where $x_i$ is the actual value and $y_i$ is the estimated value.

### *3.3. Data Sources*

The data in this paper include global GDP, total global population, global ecological footprint, global fossil energy consumption, China's fossil energy production, and fossil energy production in the United States from 2000 to 2018. Of those, GDP and total population were derived from World Bank (https://data.worldbank.org.cn/ accessed on 16 October 2020); ecological footprint was derived from the Global Footprint Network (https://www.footprintnetwork.org/ accessed on 1 September 2020); and the fossil energy production and consumption data were derived from the "BP Energy Statistical Yearbook" and the United States Geological Survey (https://www.usgs.gov/ accessed on 15 August 2020).

*3.4. Research Framework*

We selected China and the United States as the research objects to further explore the RFECC. In order to improve comparability, we introduced a relative concept. Based on the concept of RRCC proposed by Huang and Kuang [23], and comprehensive considerations of population, economic, and environmental resources, here we proposed the RFECC to reflect the carrying state and sustainable level of fossil energy. Then, the traditional RRCC model was improved in the calculation. We determined the RFECC by combining the weight of exploratory factor analysis and the traction effect of the advantage resource and constraint effect of disadvantage resource. Additionally, we conducted predictions and analyses of each indicator and RFECC. Finally, in order to realize the dynamic adjustment of the energy structure while maintaining the sustainable carrying states of fossil energy in population, economy, and environment, we calculated RFECC by type. We determined an adjusted ratio range for coal, oil, and natural gas. The research framework is shown in Figure 1.

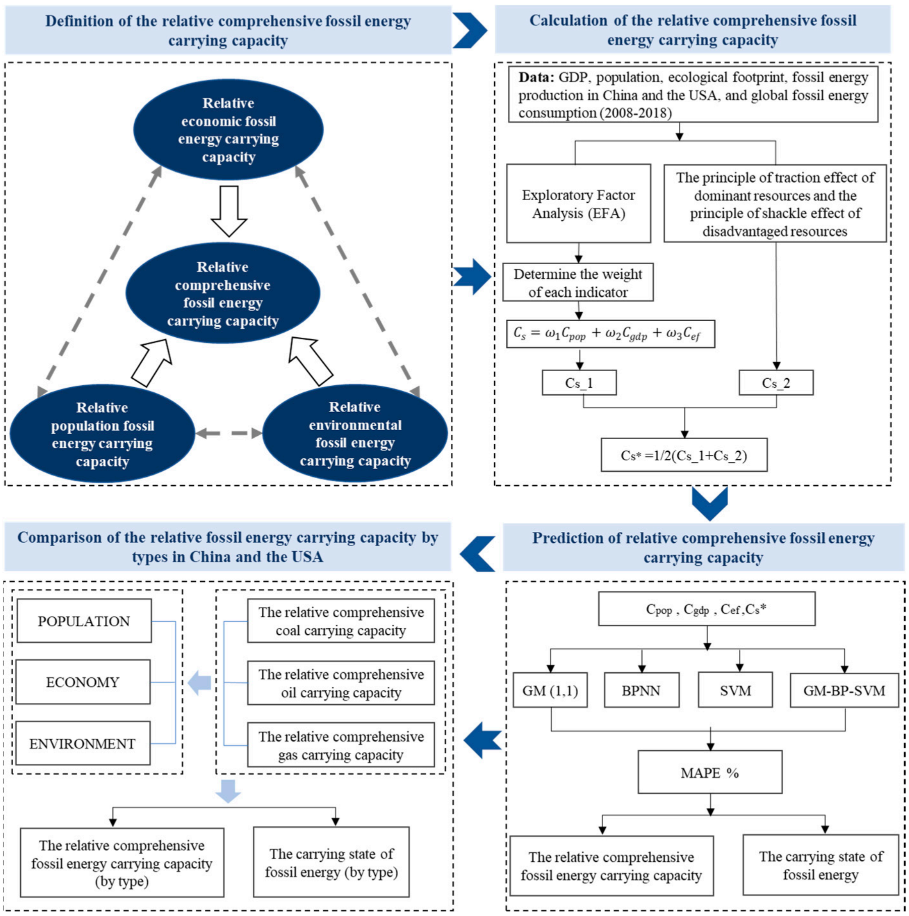



**Figure 1.** Research framework.

## 4. Results and Discussion

*4.1. Comparative Analysis of RFECC in China and the United States*

As shown in Figure 2, the population RFECC and relative economic fossil energy carrying capacity in China have gradually increased, but the relative environmental fossil energy carrying capacity has shown a downward trend. In 2007, the population RFECC and relative economic fossil energy carrying capacity in China exceeded the relative environmental fossil energy carrying capacity for the first time. The development between population, economy, and environment showed a "scissor gap" state, which suggests that China's population, economy, and environment are uneven to some extent. Fossil energy has played an essential role in promoting China's national economy during the "Eleventh Five-Year Plan" period, which significantly improved its population RFECC and relative economic fossil energy carrying capacity. However, the large-scale use of fossil energy has brought enormous pressure to the environment, which has led to a substantial decline in the relative environmental fossil energy carrying capacity. In 2013, the number of smog and siege events increased, which made people pay more attention to the environment. Most of these events are attributed to the use of fossil energy. China's relative environmental fossil energy carrying capacity has fallen sharply since 2012 and has been at a low level. The reasons leading to the change of China's relative environmental fossil energy carrying capacity are: (i) the air pollution caused by the use of fossil energy has an irreversible impact on the environment, and breaks the balanced development between fossil energy with the environment, (ii) it has been subject to the reform policy of the energy supply side in recent years, which caused the decline of demand for fossil energy, and in addition, (iii) with the development of clean energy, the relative environmental fossil energy carrying capacity has rebounded slightly.

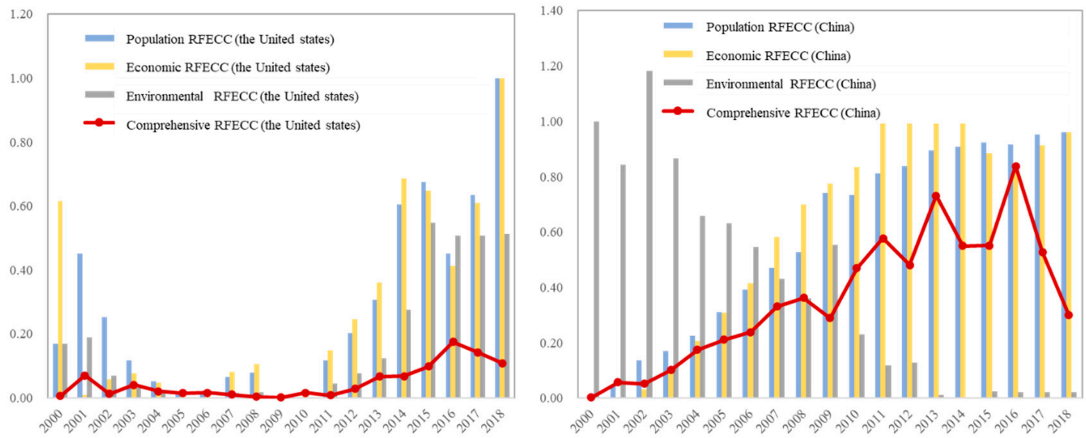



**Figure 2.** RFECC of the United states and China.

In addition, the comprehensive RFECC in China has been showing an inverted U trend, which was in a continuous climbing stage from 2000 to 2008, a volatile rising stage from 2008 to 2016, and a sharp decline stage from 2016 to 2018. This development trend shows that the comprehensive RFECC is closely related to the national energy demand strategy to a certain extent. China's energy policy has gone from optimizing the energy structure during the Tenth Five-Year Plan to developing a diversified energy structure during the Eleventh Five-Year Plan period, to implementing dual control of energy consumption intensity and total consumption during the Twelfth Five-Year Plan period, to promoting energy supply-side structural reforms during the Thirteenth Five-Year Plan period. The promulgation of this series of energy planning and the adjustment of energy policies reflects China's determination to achieve sustainable development and its emphasis on environmental protection.

As shown in Figure 2, the comprehensive RFECC in the United States has been at a continuously low level compared with China and has increased slightly in recent years. On one hand, the energy consumption structure of the United States is that oil accounted for 40.87%, natural gas accounted for 28.45%, and coal accounted for 14.86% in 2017, but the overall demand of fossil energy is smaller than China. On the other hand, it is closely related to the Trump energy policy of "oil and coal first", the goal of Donald Trump's energy policy was to pursue energy independence and promote economic development and employment. Its core measure was to develop fossil energy, which injects vitality into the traditional fossil energy market. Donald Trump stopped more than 30 rules on environmental protection, approved the construction of two oil pipelines, and opened up more land for oil development. The United States also withdrew from the "Paris

Agreement" and ceased support for the United Nations climate funds. This series of measures has made the United States fossil energy market warm up quickly, but with it comes its imbalance between fossil energy, population, economy, and environment.

The RFECC is closely related to energy policy. As shown in Figure 3, the two countries have different styles of fossil energy policies. China's energy policy has undergone a transition from fossil energy to clean energy, and the energy policy has shown consistency; the United States energy policy has undergone a transition from clean energy to fossil energy. The development of US energy policy is characterized by continuity, by gradualness, and by being crisis-driven. It is undeniable that the impact of the oil and gas policy in the United States on the world is enormous. Since the Arab oil embargo in the 1970s, the United States energy policy has focused on three goals: (1) ensuring a reliable supply of energy, (2) maintaining reasonable energy costs to meet the needs of economic growth, and (3) protecting the environment while producing and consuming energy. Successive US presidents pursued "energy independence" or "energy security". Trump, however, proposed "energy dominance". The main manifestation of "energy dominance" is the unbundling of fossil energy, which significantly eases federal regulations and environmental regulations to encourage the development of fossil energy in the United States. The unconventional oil and gas revolution in the United States is now changing the global energy landscape while exerting a profound impact on global political and economic developments [2]. China's energy policy has undergone a process from "organizational policy" to "regulatory policy" to "guidance policy". This trend reflects the role of the government in economic and social development from direct organization and strong control to moderate guidance. Moreover, China is gradually paying more attention to the development of clean energy and the reform of fossil energy is gradually deepening. The reforms are primarily focused on (1) curbing irrational energy consumption, (2) establishing a diverse supply system, (3) driving the industry to upgrade, and (4) opening up a fast lane for energy development [56].

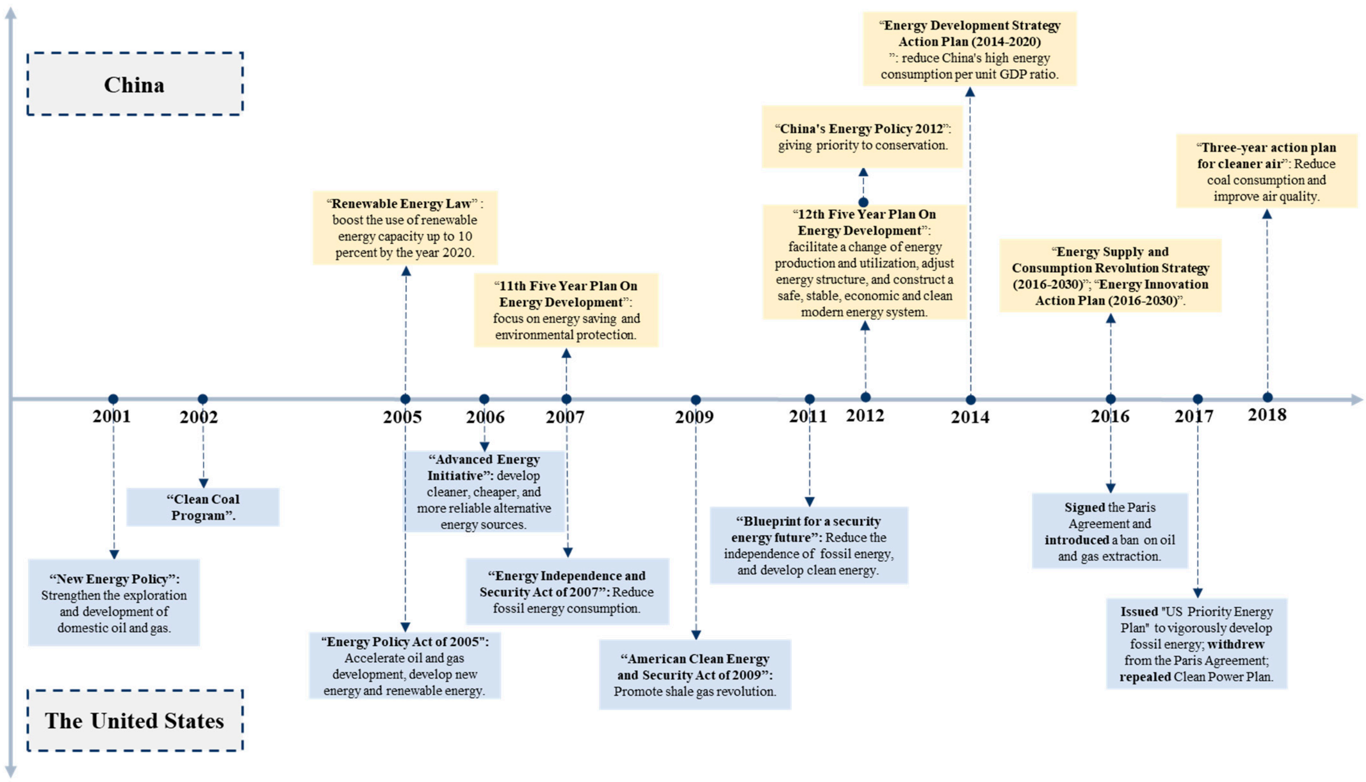



**Figure 3.** Comparison of significant fossil energy policies between China and the United States.

*4.2. Prediction of RFECC in China and the United States*

According to Table 1, GM-BP-SVM has a high prediction accuracy, so we used GM-BP-SVM to compare the relative population, economy, environment, and comprehensive fossil energy carrying capacity in China and the United States and analyzed their carrying status.

**Table 1.** MAPE value of each prediction model.

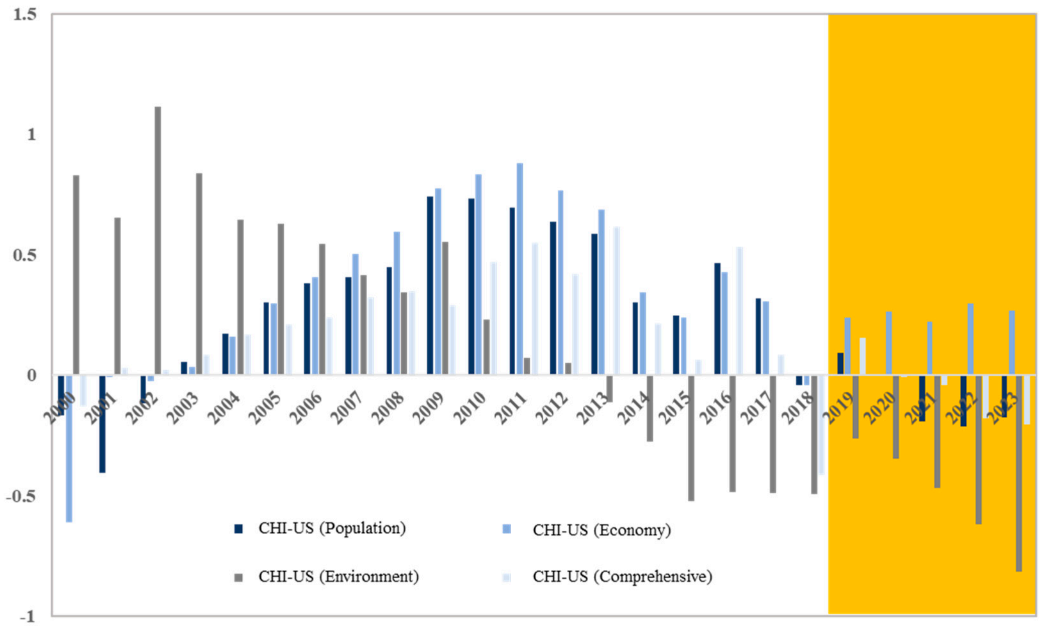
| | **GM(1,1)** | **BPNN** | **SVM** | **GM-BP-SVM** |
|---|---|---|---|---|
| China | 25.32% | 18.76% | 22.37% | 10% |
| The United States | 22.34% | 19.23% | 20.12% | 7.23% |

In Figure 4a, the yellow part (2019–2023) is the predicted year. The gray part of the table is the surplus state, that is, the current fossil energy is sufficient to support the development of its population, economy, or environment, and it shows a sustainable development state; the blue is the overload state, that is, the current fossil energy is insufficient to support the development of its population, economy, or environment, it shows a state of uneven development. China's relative population fossil energy carrying states continue to be under load because of the large population base. According to the prediction results, with the full opening of the "two-child policy," China's population will maintain a specific growth rate, which will cause the relative population fossil energy carrying states to remain overloaded in the next few years. The relative environmental fossil energy carrying states in China continued to be in surplus from 2000 to 2013, but with 2013 as the turning point, it began to enter the overload state. The smog and siege events in 2013 led to a significant increase in the environmental awareness of the government and the public. The implementation of a series of energy policies and environmental protection policies that adjusted the structure to reduce energy consumption and energy intensity and increase energy efficiency have reduced the environmental load. According to the prediction results, China's relative environmental fossil energy carrying states will be reversed from the state of overload to the state of surplus in the future, and the sustainable development of fossil energy is improving.

In order to further compare the RFECC in China and the United States, we calculated the difference between the RFECC of China and the United States. The positive values mean that China is better than the United States and vice versa. The larger the difference, the greater the gap, and the higher the RFECC. As shown in Figure 4b, the relative economic fossil energy carrying capacity of China is generally better than that of the United States, and a small peak formed in 2009–2012. It is worth mentioning that the relative environmental fossil energy carrying capacity of China reversed from positive to negative in 2013, and the gap gradually widened. Although the relative environmental fossil energy carrying state of China is better than that of the United States, the relative environmental fossil energy carrying capacity needs to be improved. In order to improve the relative environmental fossil energy carrying capacity, China should unswervingly promote the clean and efficient use of fossil energy, drive the development of the energy system transition to clean and low-carbon energy, and build a clean, low-carbon, high-efficiency, and safe energy system. According to the forecast results, we can conclude that the relative environmental fossil energy carrying capacity in the United States is gradually overloading. With the implementation of the "energy dominance" strategy, the impact of fossil energy on the environment will gradually deepen. The core content of the policy includes giving priority to the development of the fossil energy industry, accelerating the local development of coal, oil, and gas, expanding the export of fossil energy, and passively treating the development of the clean energy industry. The "energy dominance" has continued the boom of the oil and gas industry since the "shale revolution". This policy has led to a sustained easing of supply and demand in the global oil and gas market, resulting in a high degree of decoupling of international oil prices from geopolitical risks. In addition, it has had an adverse impact on the global response to climate change and a profound impact on the relative environmental fossil energy carrying capacity. Moreover, relative economic fossil energy carrying capacity is increasingly significant, which shows that fossil energy has further deepened the traction of the economic growth in the United States.

| | China | | | The United States | | |
|---|---|---|---|---|---|---|
| | POPULATION | ECONOMY | ENVIRONMENT | POPULATION | ECONOMY | ENVIRONMENT |
| 2000 | 0.00 | 0.01 | 0.00 | -0.17 | -0.61 | -0.17 |
| 2001 | 0.01 | -0.05 | -0.04 | -0.39 | 0.02 | -0.17 |
| 2002 | 0.08 | -0.03 | -0.02 | -0.13 | 0.01 | -0.04 |
| 2003 | 0.09 | -0.06 | -0.06 | 0.06 | 0.04 | 0.01 |
| 2004 | 0.07 | -0.11 | -0.13 | 0.19 | 0.14 | 0.03 |
| 2005 | 0.10 | -0.12 | -0.16 | 0.29 | 0.26 | 0.05 |
| 2006 | 0.12 | -0.11 | -0.16 | 0.35 | 0.34 | 0.07 |
| 2007 | 0.08 | -0.14 | -0.25 | 0.36 | 0.33 | 0.06 |
| 2008 | 0.10 | -0.09 | -0.27 | 0.41 | 0.33 | 0.07 |
| 2009 | 0.22 | 0.02 | -0.19 | 0.55 | 0.41 | 0.10 |
| 2010 | 0.09 | -0.08 | -0.03 | 0.60 | 0.46 | 0.15 |
| 2011 | 0.03 | -0.07 | -0.06 | 0.54 | 0.37 | 0.12 |
| 2012 | 0.18 | 0.11 | -0.06 | 0.50 | 0.33 | 0.10 |
| 2013 | -0.02 | -0.06 | -0.11 | 0.45 | 0.28 | 0.08 |
| 2014 | 0.21 | 0.19 | 0.06 | 0.20 | 0.02 | -0.03 |
| 2015 | 0.26 | 0.24 | 0.20 | 0.18 | 0.13 | 0.07 |
| 2016 | 0.03 | -0.04 | 0.16 | 0.46 | 0.41 | 0.49 |
| 2017 | 0.47 | 0.35 | 0.18 | 0.32 | 0.29 | 0.22 |
| 2018 | 0.68 | 0.70 | 0.11 | 0.00 | 0.00 | -0.05 |
| 2019 | 0.38 | 0.43 | 0.09 | 0.06 | 0.12 | 0.83 |
| 2020 | 0.45 | 0.42 | 0.00 | -0.02 | -0.03 | 0.99 |
| 2021 | 0.42 | 0.46 | -0.09 | -0.20 | -0.23 | 1.15 |
| 2022 | 0.41 | 0.53 | -0.12 | -0.21 | -0.51 | 1.33 |
| 2023 | 0.40 | 0.55 | -0.07 | -0.15 | -0.88 | 1.58 |

(**a**)




(**b**)

**Figure 4.** (**a**). The relative fossil energy carrying states of China and the United States. (**b**). The difference value of the RFECC between China and the United States.

### *4.3. Comparative Analysis of RFECC by Type in China and the United States*

In order to understand the RFECC of different fossil energies, we conducted calculations by types, as shown in Figure 5. The RFECC of coal, oil, and natural gas in the United States showed a sharp decline before 2005. In comparison, the RFECC of coal in China has remained at a low level after 2013 and is close to 0, which shows that China has achieved excellent results in energy saving and emission reduction, restricting the development of coal, and optimizing the energy structure to a certain extent. Furthermore, the RFECC of oil in the United States rebounded slightly after 2008. The RFECC of oil in the United States reversed the trend and once again exceeded China in 2017, which is because of Trump's oil and coal priority plan.

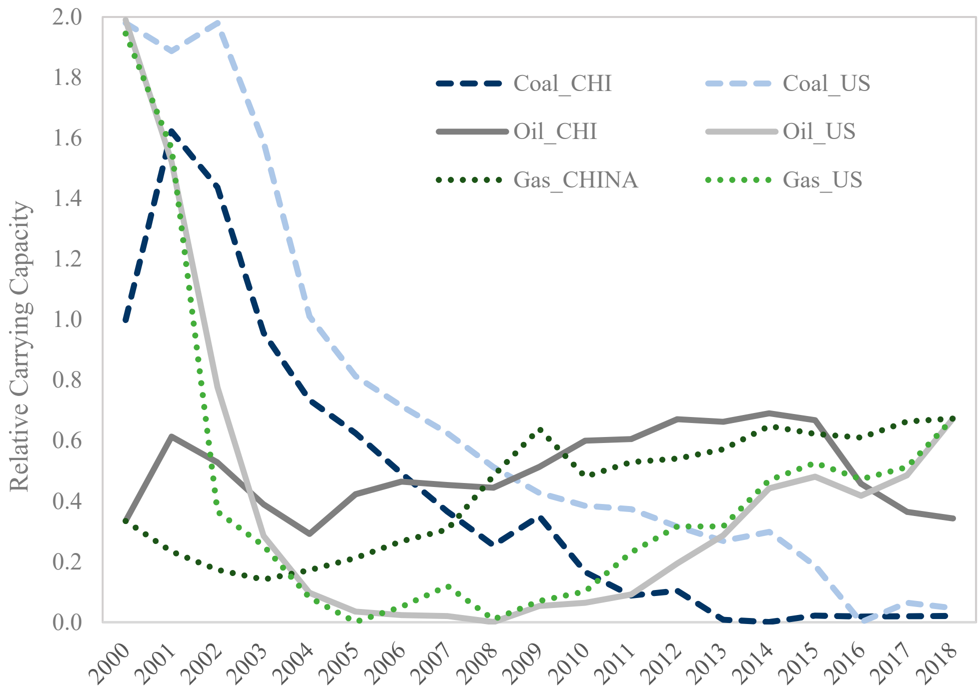



**Figure 5.** Relative carrying capacity of fossil energy by type.

As far as the fossil energy carrying state is concerned, as shown in Figure 6, where red represents surplus and blue represents overload, the darker the color, the higher the degree of surplus or overload. According to the environmental carrying status of fossil energy, we can see that natural gas is better than oil than coal. We can conclude that there is a big difference between China and the United States, which is mainly reflected in coal and oil. According to the environmental carrying status of fossil energy, we can indicate that natural gas is superior to oil and coal in terms of environmental sustainability. Moreover, the overload status of China's coal RFECC on the population and economy is significantly higher than that of the United States. This is related to China's long-term energy consumption structure. China's dependence on coal has a profound impact on the population and economy. Therefore, China should focus on limiting coal use and looking for renewable fuels or clean energy to upgrade the traditional energy consumption structure in order to achieve the sustainable development of fossil energy with the population, economy, and environment [57]. The overload state of oil RFECC in the United States is much higher than China, which shows that the United States should focus on oil in adjusting its energy structure to promote the sustainability of fossil energy. In short, according to the carrying status, we can conclude that coal should be used as a breakthrough point for China to achieve sustainable fossil energy, and oil should be used as a breakthrough point for sustainable development for the United States. This conclusion is similar to Wang et al. [57].

| | COAL | | | | | | OIL | | | | | | GAS | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | POPULATION | | ECONOMY | | ENVIRONMENT | | POPULATION | | ECONOMY | | ENVIRONMENT | | POPULATION | | ECONOMY | | ENVIRONMENT | |
| | CHI | US | CHI | US | CHI | US | CHI | US | CHI | US | CHI | US | CHI | US | CHI | US | CHI | US |
| 2000 | -0.03 | -2.39 | -0.03 | -2.39 | 0.97 | -1.39 | -0.28 | -2.93 | -0.28 | -2.93 | 0.72 | -1.94 | -0.28 | -2.45 | -0.28 | -2.45 | 0.72 | -1.38 |
| 2001 | -0.10 | -1.10 | -0.15 | -1.15 | 0.82 | -0.19 | -0.47 | -1.54 | -0.53 | -1.60 | 0.44 | -0.63 | -0.15 | -1.29 | -0.20 | -1.35 | 0.77 | -0.60 |
| 2002 | -0.12 | 0.10 | -0.20 | 0.02 | 0.71 | 0.93 | -0.36 | -0.58 | -0.45 | -0.67 | 0.46 | 0.24 | -0.05 | -0.22 | -0.13 | -0.30 | 0.78 | 0.57 |
| 2003 | -0.16 | -0.41 | -0.21 | -0.46 | 0.50 | 0.25 | -0.20 | -0.11 | -0.26 | -0.16 | 0.45 | 0.55 | 0.03 | -0.08 | -0.03 | -0.13 | 0.68 | 0.56 |
| 2004 | -0.19 | -0.37 | -0.21 | -0.39 | 0.22 | 0.04 | -0.07 | 0.12 | -0.09 | 0.10 | 0.35 | 0.54 | 0.05 | 0.13 | 0.03 | 0.12 | 0.46 | 0.55 |
| 2005 | -0.14 | -0.17 | -0.14 | -0.17 | 0.14 | 0.11 | -0.15 | 0.23 | -0.15 | 0.23 | 0.13 | 0.51 | 0.06 | 0.27 | 0.06 | 0.27 | 0.34 | 0.55 |
| 2006 | -0.07 | -0.09 | -0.05 | -0.07 | 0.06 | 0.04 | -0.14 | 0.30 | -0.12 | 0.32 | -0.01 | 0.43 | 0.06 | 0.27 | 0.08 | 0.29 | 0.18 | 0.40 |
| 2007 | 0.01 | -0.09 | 0.10 | 0.00 | -0.03 | -0.12 | -0.07 | 0.36 | 0.01 | 0.45 | -0.11 | 0.33 | 0.07 | 0.26 | 0.16 | 0.35 | 0.04 | 0.23 |
| 2008 | 0.04 | 0.02 | 0.18 | 0.17 | -0.10 | -0.11 | -0.01 | 0.43 | 0.13 | 0.57 | -0.15 | 0.30 | -0.05 | 0.43 | 0.09 | 0.57 | -0.18 | 0.29 |
| 2009 | 0.08 | 0.06 | 0.10 | 0.09 | -0.04 | -0.06 | -0.02 | 0.44 | 0.00 | 0.46 | -0.15 | 0.31 | -0.15 | 0.42 | -0.13 | 0.44 | -0.27 | 0.30 |
| 2010 | 0.23 | 0.07 | 0.31 | 0.15 | -0.14 | -0.30 | -0.04 | 0.48 | 0.03 | 0.56 | -0.42 | 0.11 | 0.07 | 0.45 | 0.15 | 0.52 | -0.30 | 0.07 |
| 2011 | 0.37 | 0.12 | 0.53 | 0.28 | -0.14 | -0.40 | 0.01 | 0.51 | 0.17 | 0.67 | -0.50 | 0.00 | 0.09 | 0.38 | 0.25 | 0.54 | -0.43 | -0.15 |
| 2012 | 0.40 | 0.13 | 0.53 | 0.27 | -0.16 | -0.43 | 0.00 | 0.47 | 0.14 | 0.60 | -0.55 | -0.09 | 0.13 | 0.35 | 0.27 | 0.49 | -0.43 | -0.22 |
| 2013 | 0.64 | 0.24 | 0.76 | 0.37 | -0.07 | -0.46 | 0.08 | 0.44 | 0.20 | 0.56 | -0.63 | -0.27 | 0.16 | 0.41 | 0.29 | 0.53 | -0.54 | -0.31 |
| 2014 | 0.74 | 0.29 | 0.85 | 0.40 | -0.03 | -0.48 | 0.11 | 0.35 | 0.21 | 0.45 | -0.66 | -0.42 | 0.15 | 0.32 | 0.25 | 0.42 | -0.62 | -0.47 |
| 2015 | 0.69 | 0.36 | 0.66 | 0.32 | -0.11 | -0.45 | 0.19 | 0.37 | 0.15 | 0.33 | -0.62 | -0.44 | 0.23 | 0.32 | 0.19 | 0.29 | -0.58 | -0.50 |
| 2016 | 0.75 | 0.33 | 0.68 | 0.26 | -0.12 | -0.54 | 0.45 | 0.48 | 0.37 | 0.41 | -0.42 | -0.38 | 0.30 | 0.43 | 0.23 | 0.36 | -0.57 | -0.45 |
| 2017 | 0.80 | 0.29 | 0.76 | 0.25 | -0.12 | -0.63 | 0.59 | 0.48 | 0.55 | 0.44 | -0.33 | -0.45 | 0.30 | 0.45 | 0.27 | 0.41 | -0.62 | -0.49 |
| 2018 | 0.85 | 0.38 | 0.85 | 0.38 | -0.12 | -0.60 | 0.67 | 0.35 | 0.67 | 0.35 | -0.31 | -0.63 | 0.35 | 0.35 | 0.35 | 0.35 | -0.63 | -0.65 |

**Figure 6.** Carrying state of fossil energy by type.

## 5. Conclusions

We improved and extended the relative resources carrying capacity model, introducing RFECC. We compared the population RFECC, economic RFECC, environmental RFECC, and comprehensive RFECC between China and the United States. Through a series of analytical studies, the conclusions are as follows:

1. The population RFECC and relative economic fossil energy carrying capacity in China have gradually improved. On the contrary, the relative environmental fossil energy carrying capacity is declining, and the comprehensive RFECC of China is showing a trend of inverted U. In addition, the population RFECC, economic RFECC, and environmental RFECC present a "scissors" state. On the other hand, the population RFECC, economic RFECC, and environmental RFECC of the United States show a U-shaped trend. The comprehensive RFECC of the United States is at a continuously low level compared with China and has increased slightly in recent years.
2. The relative fossil energy carrying states in China and the United States are different, mainly reflected in the economy and environment. The relative economic fossil energy carrying states in China continued to be in the surplus state until 2008 and then showed a gradual overload state. The relative economic fossil energy carrying states continued to be in an overload state and then showed a surplus state. In addition, the relative environment fossil energy carrying states in China showed a transition of "surplus→overload→surplus," and the relative environment fossil energy carrying states in the United States showed "short-term surplus→sustained overload."
3. The economic RFECC in China is generally better than that of the United States. The population RFECC in China was better than that of the United States from 2001 to 2007. The environmental RFECC in China reversed from advantage to disadvantage in 2013, and the gap has gradually widened. The population RFECC and economic RFECC in the United States in recent years have been slightly higher than in China. However, its environmental RFECC in recent years has been significantly higher than that of China.
4. According to the calculation of the comprehensive RFECC of different types, coal should be used as a breakthrough point for China to achieve sustainable fossil energy, and oil should be used as a breakthrough point for sustainable development for the United States.

The central problem of sustainable development is that the development should be coordinated with the fossil energy carrying capacity. In view of this, the following suggestions were put forward. (1) The government should pay more attention to the resource utilization and guarantee system, strengthening the establishment of the energy reserve system and enhance energy security, by improving the legal system of energy reserves;

focusing on the issue of functional positioning of the national energy reserve system; adopting a government-led and enterprises-joint energy reserves mode; and implementing diversified international cooperation to reduce the risk of resource disruptions. (2) A new concept of energy consumption and reducing social operation costs should be established, easing the pressure on energy supply by saving energy and reducing consumption; forcibly eliminating the backward production capacity with high consumption and low efficiency; widely carrying out energy-saving activities for all people; improving industrial structure and product structure; establishing a conservation-oriented economic system; transforming the economic development mode from high-carbon to low-carbon; and gradually reducing the proportion of energy-intensive industries in the national economy. (3) The key to the sustainable development of fossil energy is scientific and technological innovation, strengthening the exploration of cutting-edge energy technologies and promoting the application of advanced technologies. Through scientific research and innovation, it is possible to accelerate the development of renewable energy and clean energy such as solar energy, wind energy, and biomass. Under the current circumstances, it is difficult for China to replicate the shale gas revolution in the United States and the full development of nuclear power is an important way to ensure China's energy security. Actively developing clean renewable energy, promoting the diversification of the energy production structure, taking the path of energy and the environment, and the economic development of the virtuous cycle, is the fundamental way to solve the problem of energy security. Hence, governments should actively support large multinational companies, such as CNPC, Sinopec, CNOOC, so that they can participate in international competition in the fields of exploration, development, processing, sales, and trade, and occupy a place in the international market for China.

We have studied and analyzed the RFECC status of China and the United States based on the RFECC model, revealing the interrelationship and evolution of population, resources, and environment in both countries. This not only provides a reference for the two countries to achieve the sustainable development of fossil energy, but also has theoretical and practical significance to enrich and expand the research background of relative resource carrying capacity. However, there are still certain limitations in the selection of indicators. For example, we selected GDP to reflect the economic resources, which is somewhat one-sided. In the future, we will use comprehensive indicators to reflect the interaction between fossil energy and economic resources, population resources, and environmental resources.

**Author Contributions:** Conceptualization, writing—review and editing, and writing—original draft preparation, Z.Z.; supervision, J.C. and H.G.; methodology, Y.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research is supported by the National Natural Science Foundation of China under Grant No. 71991482, 71991480, 72074198, and 71874165; National Social Science Fund of China (Grant No. 21AZD074).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

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