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Is China's Energy Supply Sustainable? New Research Model Based on the Exponential Smoothing and GM(1,1) Methods

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Abstract: Energy supply sustainability is an important issue in the field of energy security. To successfully achieve the goals of sustainable economic and social development and to implement the "Paris Agreement", we need to accurately evaluate and predict the energy supply sustainability of countries or regions. However, it is very difficult to evaluate and predict energy supply sustainability, because it belongs to a complex multi-attribute decision-making problem. This paper proffered a new definition of the energy supply sustainability in China and put forward sixteen indicators for it from the four dimensions of energy availability, economic sustainability, environmental sustainability and technical sustainability. First, the energy supply sustainability index (ESSI) was quantified by a comprehensive evaluation method. Secondly, based on the exponential smoothing and GM(1,1) prediction models, two ideas were put forward to predict the sustainable level of China's energy supply, enriching the theoretical study of energy security prediction. The study found that: (1) China's energy supply sustainability index changes dynamically; it has an asymmetric "W" trend from 2000 to 2016. The energy supply sustainability level of China is low; it cannot satisfy the Chinese people's need for high-quality eco-energy products or the needs of social sustainable development. The three indicators of reserve and production ratio, production diversity and clean power generation are very important to China's energy supply sustainability. (2) Referring to the accuracy criteria, the Mean absolute percentage error (MAPE) of the Exponential smoothing-GM(1,1) hybrid model for forecasting China's energy supply sustainability is only 2%, and the Root mean square error (RMSE) is 0.0278; therefore, it is suitable for use in the forecasting of the energy supply sustainability level in China. (3) In the short term, from 2017 to 2020, many unsustainable factors remain within China's energy supply, and the sustainable level is level II. In the long term, the sustainable level of China's energy supply will be greatly improved and will increase to 0.8765 by 2030, attaining a sustainable level. However, China remains far behind other countries, with high levels of energy sustainability and energy security in the world.

Keywords: energy supply; energy security; sustainability assessment; exponential smoothing; GM(1,1); hybrid forecasting

1. Introduction

Climate change is becoming one of the key scientific issues that must be addressed globally, and many scientists attribute climate change to increased carbon dioxide emissions from fossil fuel combustion [1]. According to the International Energy Agency (IEA) [2], the annual global CO_2

emissions from fossil fuels have increased, from almost 23.6 billion tons of carbon dioxide ($GtCO_2$) in the 1990s to around 32.4 $GtCO_2$ in 2014. Carbon emissions are expected to increase by 50% between 2014 and 2050, which will result in the global average temperature being 3.2 °C to 4 °C higher than the pre-industrial level. These phenomena are the consequences of global warming, which is caused by the massive use of fossil fuels by humans. Fossil fuels and climate change are inextricably linked [3], and a high proportion of carbon-intensive energy causes great damage to the sustainable development of the environment, the economy and society. Since the beginning of the industrial revolution, access to clean, affordable and reliable energy has been the cornerstone of the world's growing prosperity and economic growth. However, energy use in the 21st century must also be sustainable [4]. Energy sustainability has become a key issue of global concern.

The concept of sustainable development has been widely integrated into energy and industrial systems. In 2015, the international community [5] formulated the "The 2030 Agenda for Sustainable Development", which is intended to address global environmental degradation and resource depletion. Among the agenda items, sustainable energy provision and access, one of the central themes of the 2030 Agenda, whose preamble calls for 'universal access to affordable, reliable and sustainable energy,' recognizes that 'social and economic development depends on the sustainable management of our planet's natural resources' [6]. Energy security, environmental sustainability and energy equity are the three core challenges to be met with in achieving the transition to a Low-Carbon Economy [7]. The United States has stricter requirements for energy security; renewable energy, solar energy, and wind energy are all safe and very cheap in the United States. However, not every country has similar policies. China is the world's second largest economy and the world's largest energy producer and carbon dioxide emitter. China's energy is first and foremost affordable, because all rural areas in China have access to electricity. Except for rural areas, which rely on government subsidies, China's electricity is basically affordable, and there are no reports that its citizens cannot afford to pay their electricity bills. Second, China's energy is also available. Compared with the power grids of countries all over the world, China's power grid reliability is very high, and the possibility of interruption is very small; there have been almost no interruptions to the power grid in China. However, China's energy is far from sustainable.

China's energy is not sustainable, first, because the energy supply is not sustainable. According to the BP World Energy Statistical Yearbook 2018 [8], China's energy consumption increased by 3.1% in 2017, and China has been the country with the largest increase in global energy consumption for 17 consecutive years. However, more than 60% of the energy supply is coal. In contrast, coal use in the United States is only approximately 15%. This finding means that, as time passes, environmental pollution caused by the energy supply will continue to threaten China's energy security [9]. Energy security is a key driver of current and future energy policies in the world [10]. The Chinese government attaches great importance to this feature. Li Keqiang, Premier of the State Council, at the first meeting of the National Energy Committee in 2014, said that energy supply and security are related to the overall situation of China's modernization. China should actively develop clean energy, improve environmental quality and embark on a clean, efficient, safe and sustainable energy development path. Since 2014, China's coal consumption has declined for three years, and it decreased by 4.7% year-on-year in 2016. Thus, can the transformation of the energy supply structure be successful? Can China's energy sustainable development goals be achieved? When will they be achieved? To solve these problems, we need to have a deep understanding of China's history and future sustainable energy supply level. Given this history, this paper accurately evaluates and predicts China's energy supply sustainability to provide a reference for decision-making departments.

2. Literature Review

Energy supply sustainability stems from energy security and has become more specific with the growing energy security research. Energy supply security is vital for the whole world [11]. For many years, organizations and scholars have carried out profound and extensive research on this

issue. Because of the different research backgrounds and objects, the definitions of energy security are also different. Among them, the two most popular concepts are gaining an adequate energy supply at reasonable prices, which was put forward by the International Energy Agency (IEA) [12,13], and the "4A" concept of energy security, which comprises availability, accessibility, affordability and acceptability, and was put forward by the Asia Pacific Energy Research Centre (APERC) [14]. Over the years, scholars, such as Le [15], Sovacool [16], Ren [17] et al., have conducted empirical research based on these two definitions. The definition of energy security is dynamic, and environmental sustainability and energy efficiency are increasingly emphasized by scholars, such as Sovacool [18], Radovanović [19], Ang [20], Zhang [21] et al. Especially considering the proposal of the World Energy Council's energy sustainable development, more and more scholars have taken energy sustainability as the focus of their research. Brown [22] constructed an energy sustainability index (ESI) and conducted practical research, taking the United States as an example. Afgan [23] evaluated the quality of hybrid energy systems, using sustainability assessment methods from the economic, environmental and social perspectives. Tsai [24] established Taiwan's sustainable development indicators (TSDI) system in 2003 and conducted an analysis of energy sustainability from Taiwan's renewable energy production. Kumar [25] evaluated the sustainability of the run of the river (RoR) hydropower projects in hydro-rich regions of India from social, environmental, and economic perspectives. Mainali [26] used the principal component analysis (PCA) method to evaluate the sustainability performance of energy technologies applied in rural electrification. Iddrisu [27] proposed a comprehensive Sustainable Energy Development Index (SEDI) to measure the sustainability of a country's energy system. This article provides a further overview of energy sustainability, as shown in Table 1.

The researches on energy sustainability clearly show that, first, from the research topic, many scholars conduct research on energy sustainability or research energy supply security but consider energy sustainability an important aspect of their research. The authors' research areas include oil, natural gas, coal, water and hybrid energy systems. Second, the research dimension is relatively extensive, involving economic, social, environment, sustainability, technology, hybrid energy systems and many other aspects. In summary, the dimensions are mainly availability, the economy, sustainability, the environment, energy technology and efficiency. Among these topics, energy security and related sustainability issues have, in recent years, begun to garner the focus of scholars. Third, from the research methodology, in the early years, scholars focused on the comprehensive evaluation of regional energy security using a comprehensive evaluation method. In recent years, research methods have become increasingly diversified, from statistical methods to artificial intelligence, and machine learning methods, such as agent, have become more popular among scholars because of the speed and accuracy of their calculations. In summary, the following problems continue to need further study. First, among the research objects, the issue of environmental sustainability has garnered the attention of some scholars. However, their focus is on the sustainability of hybrid energy systems, energy technologies or renewable energy. Energy supply is the core of energy security. Most of the unsustainable problems of energy security stem from the unsustainable supply. Thus, the sustainability of an energy supply is a problem that requires in-depth research. Second, regarding the research methodology, scholars mainly focus on the comprehensive evaluation of energy sustainability or the prediction of individual indicators of energy demand/supply. There are few predictions for multi-criteria decision-making, such as energy supply sustainability.

Energy supply sustainability requires intelligent forecasting algorithms and models. There are five main types of commonly used forecasting techniques: The multiple linear regression analysis, random time series model, exponential smoothing method, adaptive load forecasting model [28], and machine learning method [29]. These techniques can be grouped into two types of models, those based on statistics and those based on artificial intelligence, which are mainly studies on energy forecasting methodology, as shown in Table 2. The first type of model, that based on statistics, which is usually expressed by mathematical equations, automatic regression (AR), moving average (MA), automatic regression moving average (ARMA), automatic regression synthetic moving average

(ARIMA) and exponential smoothing, belong to the category of statistical modeling [30,31]. The second type of model is based on artificial intelligence as an expert system, the Grey Model (GM), the artificial neural network (ANN), fuzzy logic, support vector regression and the Agent-Oriented Intelligent model [32–34]. These models have significant advantages in relation to prediction and high-precision fitting, and they are widely used in the forecasting of energy price, wind speed and renewable energy [35–37]. However, artificial intelligence models are complex, and they have high requirements in relation to the amount of data. Therefore, this type of model is not necessarily suitable for all prediction studies, such as the multi-indicator decision-making problem. I have creatively carried out the relevant research, proposing a method for predicting the level of energy supply security and mentioning the environmental problems of energy supply, and fortunately published it in this journal of energies [38]. However, it focuses on the level of energy supply security from the perspective of the overall national security concept. In 2001, the European Commission green book, "Towards a European energy supply security strategy," claimed that the European Union's long-term strategy for energy supply security must focus on environmental protection for the well-being of its citizens and the normal functioning of its economy [39]. China is a populous country. It should take into account the equality and sustainability of an energy supply to ensure the sustainable and healthy development of the economic society. Therefore, based on the previous paper, this paper focuses on energy availability, economic sustainability, environmental sustainability and technical sustainability, further studying the sustainability of China's energy supply and further optimizing the evaluation method, taking into account the dynamic change of the indicator weight over time.

However, the forecasting object of this paper is the sustainability of China's energy supply, and there are still great difficulties in forecasting work: (1) Energy sustainability is greatly affected by various uncertain factors, and it is dynamic. Therefore, it is difficult to forecast it. (2) The data selected in this article contain many time series. The time series data are easily affected by external noise and present complex characteristics, such as being nonstationary and random, which makes forecasting more difficult. Sustainable energy development has both short-term goals and long-term goals. Therefore, the forecast of energy supply sustainability must be both short-term and long-term. The exponential smoothing model, based on statistics, considers both the extensibility of sequence development and randomness, which usually performs well in medium- and long-term predictions. This model is widely used for energy demand, energy supply, and solar radiation prediction [40,41]. Compared with ARIMA, LES and the random walk (RW) model, the exponential smoothing model has better performance in short-term prediction [42,43]. The GM(1,1) model, based on artificial intelligence, is effective at predicting multifactor variables and provides an error test of model estimation parameters for easy calculation [44,45]. Even with a very small sample size, this model continues to have a better predictive power. The GM(1,1) model can achieve a higher prediction accuracy through parameter improvement or combination with other models [46–48]. Through the above analysis, this paper adopts the statistical model exponential smoothing model and the artificial intelligence model GM(1,1) model and attempts to use the combination of these two models to predict China's sustainable energy supply level. In Section 3, we propose the definition and impact indicators of energy supply sustainability and proffer a measurement method for energy supply sustainability. In Section 4, based on the exponential smoothing and GM(1,1) prediction models, two ideas are put forward to predict the sustainable energy supply level. In Section 5, based on Sections 3 and 4, and using China as an example, the effectiveness of the above methods is further verified. Section 6 concludes the research.

Table 1. Primary studies on energy sustainability dimensions: indicators and methods.

No.	Author	Themes	Dimension	No. of Countries	No. of Indicators	Model
1	Brown [22]	Energy sustainability	Oil security, Electricity reliability, Energy efficiency, Environmental quality	1	12	-
2	Su [49]	Energy security, energy supply network	The production, Refining, consumption, Reserve, and transit sectors, Various external supply sources	1	-	Ecological network analysis (ENA)
3	Chester [50]	Energy security, Security of supply	Availability, Adequacy of capacity, Affordability, Sustainability	-	-	Reviews
4	Sovacool [18]	Energy security, Energy supply	Availability, Affordability, Technology development, Sustainability and regulation	10	320	Subjective scoring
5	Carrera [51]	Sustainability energy technologies	Security and reliability of energy provision, Political stability and legitimacy, Social and individual risks, Quality of life	4	9	Expert interviews
6	Begi [52]	Multi-criteria sustainability assessment	Resource indicator (RI), Environment indicator (EI), Economic indicator (EI), Social indicator (SI)	2	14	Multi-criteria decision-making methods
7	Matsumoto [11]	Energy security	Energy availability, Infrastructure, Energy prices, Societal effect, Environment, Governance, Energy efficiency	29	7	Time-series clustering, Shannon Wiener diversity index
8	Santoyo [53]	Sustainability assessment of energy systems	Environmental indicators, Economic indicators, Social indicators	1	17	Multi-criteria decision analysis (MCDA)
9	Tsai [24]	Energy sustainability	Economic, Environmental	1	5	Pressure–State Response (PSR)
10	Krey [54]	Energy sustainability	Security of supply, Climate change mitigation, Air-pollution reduction,	1	3	MESSAGE
11	Stefano [55]	Sustainability assessment	technical, Economic and energetic	1	-	Analysis of variance (ANOVA test)
12	Mondal [56]	Renewable energy, Sustainability	Solar energy, Wind energy, Biomass potential, Hydro resource potential	1	-	GIS-based Geospatial Toolkit (GsT), Hybrid System
13	Zhang [21]	Provincial energy security	Availability and diversity, Affordability and equality, Technology and efficiency, Environmental sustainability, Governance and innovation	1	-	Multicriteria Decision-Making methods
14	Duan [57]	Energy investment assessment	Political risk, Economic foundation, Investment environment, Resource potential, Environmental constraint	50	36	A fuzzy integrated evaluation model
15	Narula [58]	Sustainable energy security	Availability, Affordability (economic dimension), Efficiency, Acceptability	15	-	PCA (principal component analysis), Weighting and Aggregation
16	Sovacool [59]	Sustainable development, Energy security	Security, Poverty, Development, Fiscal responsibility, Governance	-	-	Regression and comparative country analyses

Table 2. Review of energy forecasting methodology.

No.	Source	Study Field	Country	Forecasting Model	Single/Combination	Forecasting Scope	Data Used	Forecasted Years
1	Bacher [60]	Solar power	Denmark	ARX	Single	Monthly	2006	Up to 2 h ahead
2	Mellit [61]	Solar irradiance	Italy	ANN, MLP	Single	Days	2009	24 h ahead of solar irradiance
3	Pinson [62]	Wind power	Jutland	Non-parametric Probabilistic Forecasts	Single	Hours	2001–2003	24 h ahead
4	Pedro [63]	Solar energy	California	ARIMA, KNNs, ANS, GAS, ANN	Single	Hours	2009–2011	1 h and 2 h
5	Lorenz [64]	Photovoltaic (PV) systems	Germany	European Centre for Medium-Range Weather Forecasts (ECMWF)	Combination	-	2006	Predictions up to 72 h
6	Bludszuweit [65]	Wind power	-	Beta pdf	Single	Mins	-	Up to 24 h ahead
7	Ekonomou [66]	Energy consumption	Greek	Multilayer perceptron model MLP ANN	Single	Yearly	1992–2004	2005–2015
8	Tan [67]	Electricity price	Spanish and PJM electricity markets	ARIMA and GARCH	Combination	Hours	2002, 2006	2002, 2006
9	Wang [68]	Real oil prices	-	Time-varying parameter (TVP)	Combination	-	1986–2015	1 h to 12 h ahead
10	Du [69]	Electrical power system	Penglai, China, Australia and Singapore	complementary ensemble Empirical mode decomposition (CEEMD), LSSVM, Whale optimization algorithm (WOA)	Combination	Mins	2011–2015	30 min ahead
11	Ziel [70]	Electricity price	European	periodic VAR-TARCH	Combination	Monthly	2012	1 h ahead
12	Matsumoto [71]	ACEGES model	Saudi Arabia, Iran, Canada, Venezuela	Unconventional oil	Single	Yearly	2020–2100	-
13	Prema [72]	Solar power	India	Moving average model, Exponential smoothing models	Combination	Monthly	2012–2013	1 week ahead
14	Dong [42]	Solar irradiance	Singapore, Colorado, USA	Exponential smoothing	Single	Mins	2010–2011	5 min ahead
15	Trapero [73]	Solar irradiance	Spanish	Persistence model, Seasonal persistence model, Exponential smoothing, ARIMA model	Combination	Hours	2009–2011	24 h ahead
16	Meng [74]	CO_2 emissions	China	The traditional linear model, GM(1,1), and the hybrid mode	Combination	Yearly	1982–1991	1992–2011
17	Xiong [75]	Energy production, Energy consumption	Iran, Argentin	Novel GM(1,1)	Single	Yearly	2003–2009	2010–2012
18	Wang [47]	Electricity consumption	China	Seasonal GM(1,1)	Single	Yearly	2010–2016	2017–2020
19	Steinert [70]	Electricity Price	Germany and Austria	AR24-X model	Combination	Daily	2011–2014	1 day ahead

3. Conceptualizing and Measuring Energy Supply Sustainability

Energy supply sustainability is affected greatly by various uncertain factors, and it is dynamic in nature. So far, there is no uniform standard to measure it. Research shows that public opinion of energy security reflects geographic variation, and the national energy security index can explain this difference [76]. Referring to the "International Index of Energy Security Risk" [77,78], EU Standards for Energy Security of Supply [79] and the "Energy Sustainability Index" proposed by the World Energy Council [19], and according to the United Nations' requirements of sustainable energy development, we have proposed a new definition for the energy supply sustainability of China. This definition conceptualizes energy supply sustainability in the four dimensions of energy availability, economic sustainability, environmental sustainability and technical sustainability. In addition, the measurement method of energy supply sustainability index (ESSI) is put forward.

3.1. Definition and Intent of Energy Supply Sustainability

Since 1990 "sustainable development" and "resources" have been the two most commonly used keywords in the scientific literature related to the Green Economy (GE) concept [80]. They involve reducing negative health and environmental impacts, while increasing energy availability, affordability, safety and efficiency [81]. Energy policy directives from various industrialized countries indicate that the process of entering this new era includes common interests, such as improving energy productivity, ensuring reliable supply, energy security and diversity, economic efficiency, support for research and development and regional partnerships for the development of more advanced technologies [82]. In 2004, the United Nations Development Program (UNDP) introduced sustainable energy security concepts in the Global Energy Assessment report, with an emphasis on environmental sustainability. In 2010, the World Energy Council [19] launched the Energy Architecture Performance Index (EAPI), which focused on energy and climate policies. In the second year, the index was revised in the Energy Sustainability Index 2011, while the methodology and the approach did not change. The World Energy Council (2013) [83] noted that energy security, energy equity, and environmental sustainability constitute the 'energy trilemma' of the world. Thus, the world energy sustainable development index was proffered. Sovacool [76] noted that the concept of energy security is multifaceted and can cover a number of apparently distinct energy and climate-related risks. Sustainability can be defined as ensuring that the development of an energy system is most effectively synchronized with a country's natural endowments, technological capabilities, social expectations and economic development profiles [84]. David [85] noted that energy supply is dynamic; with the emergence of climate change, local air pollution, acid rain and other issues, its definition should reflect these emerging risk factors to guide countries' energy policies. Regarding energy sustainability, Kleber [86] believed that energy sustainability refers to the extent to which an energy supply can be extended to reduce the use-related environment. Bringezu [87] conceptually intersected the Sustainable Development Goals (SDGs) with resource use "challenges and risks". Laldjebaev [88] conceptualizes energy security as a low vulnerability of vital energy systems and the sustained provision of modern energy services. Based on the research of the above organizations and scholars, this article maintains that the energy supply is the starting point of energy security and the core of energy security. First, the sustainability of energy systems must be addressed from the supply side to ensure that the supplied energy does not affect the environment during production and that its use can promote sustainable economic and social development. This article defines energy supply sustainability as: energy supply sustainability exceeding an energy supply. Sustainability is an important function of an energy security system. Based on a sustainable and sufficient energy supply, energy supply sustainability focuses more on the fairness of the energy supply and environmental sustainability. It is necessary, not only to ensure that sufficient energy is provided to all people and enterprises at reasonable prices in the short and long term, but also to ensure that the supply of energy in the process of usage will not cause damage to society and the environment or to minimize the degree of damage. Ultimately, the sustainable development of the energy supply and the economy, society and the environment will be realized.

According to this definition and referencing the research results of scholars (Table 1), the connotation of energy supply sustainability can be understood as follows:

(1) *Energy availability*: Availability refers to the possibility of obtaining energy supplies geographically. Specifically, availability refers to obtaining a sufficient energy supply from local resources to promote energy production and a diversified supply. Fossil fuels are constrained by declining production and are being used in order of availability, and the cheapest energy use is ranked first [89]. This means that, before fossil fuels are eventually exhausted, either alternative or renewable sources of energy are available to ensure an adequate supply of energy or there is another fossil fuel to replace those that are less acceptable or more expensive [90]. In other words, energy reserves and diverse energy resources are key factors affecting energy supply sustainability [91]. Strategic petroleum reserve (SPR) and alternative fuels are both important for energy security [92].

(2) *Economic sustainability*: This dimension evaluates whether the energy supply is cost effective and affordable. On the one hand, economic sustainability refers to reasonable and stable energy prices [93], because energy prices determine the affordability of energy supply. Fluctuations in fossil fuel prices may lead to energy supply problems and influence decision-makers' capacity to plan [94]. If the supply of energy is too expensive, society cannot consume it. On the other hand, economic sustainability also requires that the supplied energy is not just physically available but actually accessible to society, because they can afford to consume it. Personal payment ability also directly affects the affordability of the energy supply. The two complement each other to ensure the sustainability of the supply system [27].

(3) *Environmental sustainability*: Energy and the environment are closely related. The sustainability of an energy supply requires the coordinated development of energy supply and the environment. Environmental sustainability is the basic premise of sustainable energy supply. Fossil fuels have adverse environmental impacts during mining and use, especially environmental pollution caused by burning, even if clean energy causes damage to the environment [95]. The European Commission [96] stresses the importance of the environment and sustainability to energy security. Environmental protection is the focus of the international community. It is necessary to focus on the environmental sustainability of an energy supply, that is, to form a spatial pattern that conserves resources, protects the environment and provides a safer and cleaner energy supply to society.

(4) *Technical Sustainability*: Access to sustainable and modern energy for the people requires improvement indicators of energy efficiency and carbon saving from energy technologies [97]. This is the supply side of the cycle, which captures the ability of the energy supply system to reliably and effectively meet the present and future needs of society. The efficiency of a sustainable energy supply includes both the efficiency, in an economic sense, and the profit and loss of natural resources and the environment, that is, the minimum energy consumption and energy loss under the same energy supply service, involving the construction of energy infrastructure, the development of energy technologies and the improvement of energy efficiency. The level of energy efficiency can reflect the level of national energy technology, and energy consumption can be reduced effectively by improving energy efficiency. Energy technology is an important support for achieving a sustainable energy supply [98–100]. Improving energy technologies and efficiency can help to reduce energy demand and improve energy supply sustainability in order to meet current and future energy demands.

3.2. Energy Supply Sustainability Indicators

Indicators are generally considered to be parameters that provide information regarding the state of the system. Since sustainability refers to the long-term evolution of a complex system, there are many uncertainties in the evolution process, and the purpose of indicators is to make decision-making less risky. Sustainability indicators and composite indexes are gradually used as powerful tools for communicating sustainability performance to policy makers and the general public [101]. The energy supply system is a complex system that is rapidly affected by many uncertainties and changes. Therefore, it is very important to select scientific evaluation objects and indicators for this system.

According to the definition and connotation of energy supply sustainability, shown in Section 3.1, which are based on the research results of relevant scholars (Table 1), according to the design principle that the number of indicators should not be excessive (no more than 20) [20], and considering the data availability, the energy supply sustainability indexes for China were determined from the following four first-grade indexes: energy availability, economic sustainability, environmental sustainability and technical sustainability. These dimensions are shown in Table 3. The proposed framework constitutes 16 indicators, which are as follows.

Table 3. Indicators for the energy supply sustainability index.

Dimensions	Indicators	Equation	Variable Description	Indicator Source
Energy availability	Reserve and production ratio (X_1)	$\sum r_i p_i$	r_i—Reserve and production ratio of energy i p_i—Proportion of energy i produced in energy sources' production	[16,18,102,103]
	Production diversity index (X_2)	$\sqrt{\sum_{i=1}^{n} p_i^2}$	p_i—Proportion of energy i produced in energy sources' production	[20,102,104–106]
	Energy dependence (X_3)	$\frac{Q_{eit}}{Q_{est}}$	Q_{est}—TPES Q_{eit}—Energy dependence	[16,77,102,107]
	TPEC per capita (X_4)	$\frac{Q_{eit}}{T_p}$	Q_{est}—TPES, T_p—total number of populations	[9,83,107]
	Market liquidity (X_5)	$\frac{I_{mc}}{I_{mw}}$	*Imc*—Domestic oil imports, *Imw*—Total world oil imports	[18,102,107–109]
Economic sustainability	The economic vulnerability index (X_6)	$EVI = \frac{C_o}{GDP} = P_o \times \frac{Q_{oip}}{Q_{oit}} \times \frac{Q_{oit}}{Q_{ect}} \times \frac{Q_{ect}}{GDP}$	EVI—oil import economic vulnerability index; *Co*—crude oil import cost; *Qoip*—total crude oil import, *Qoit*—crude oil consumption amount, *Qect*—amount of energy consumption, *Po*—Brent spot price.	[103,110]
	Energy price index (X_7)	-	Purchase price index of fuel and power by industrial producers	[18,20,77,102,108,111]
	GDP per capita (X_8)	$\frac{GDP}{T_p}$	T_p—Total number of populations	[19,109,112]
Environment sustainability	Water pollution (X_9)	$\frac{E_{wat}}{T_p}$	E_{wat}—Total waste water emissions	[16,18,20,108,113,114]
	Sulfur dioxide emissions per capita (X_{10})	$\frac{E_{so_2}}{T_p}$	E_{so_2}—Total sulfur dioxide emissions	[20,77,104,107,111,113]
	NOx emissions per capita (X_{11})	$\frac{E_{NO_x}}{T_p}$	E_{NO_x}—Total NOx emissions	[18,77,105,113]
	Land use (X_{12})	-	Forest coverage	[16,18,20,108,113,114]
	Clean power generation (X_{13})	-	Generation in power-generation capacity	[9,19,80,103,115]
Technical sustainability	Domestic infrastructure	-	Investment in fixed assets of energy industry	[110,116]
	Electricity distribution efficiency (X_{15})	$\frac{E_{dis}}{E_{tot}}$	E_{dis}—Electricity distribution losses, E_{tot}—Total electricity generation	[16,20,77,107,117]
	Energy efficiency (X_{16})	GDP/Ec	Ec—Total energy consumption	[18,20,104,107,117]

3.3. Evaluation Methodology

3.3.1. Indicator Normalization

To ensure comparability, the original data of the indicators should be normalized. There are many different types of methods for data normalization. Ang provides us with a comprehensive summary of the data normalization methods [20]. Referring in this paper to Narula et al. [118], indicators of the energy supply system are normalized by the Min-max normalization method, in which each indicator is transformed using the following equation. Indicators can be categorized into two types: the first type constitutes indicators that have a positive impact on ESSI, which can be normalized from Equation (1), and the second type constitutes those indicators that have a negative impact on ESSI, which can be normalized from Equation (2):

$$x'_{ik} = \frac{x_{ik} - \min(x_{ik})}{\max(x_{ik}) - \min(x_{ik})} \quad (1)$$

$$x'_{ik} = \frac{\max(x_{ik}) - x_{ik}}{\max(x_{ik}) - \min(x_{ik})} \quad (2)$$

where x'_{ik} is the indicator i in the year k, after normalization. x_{ik} is the value of indicator i in the year k, before normalization, $k = 1, 2, \ldots, t$, $i = 1, 2, \ldots, m$.

3.3.2. Weighting and Aggregation

Energy supply sustainability evaluation is a typical issue involving multiple indicators. Before evaluation, the weights of these indicators need to be determined. First, the objectivity and rationality of each index weight will greatly affect the final evaluation results. Currently, there are many methods for determining the weight of indicators, which can, according to different data sources, be approximately divided into three categories when calculating the weight: subjective weighting, objective weighting and synthetic weighting [119]. The commonly used subjective weighting methods include: The Delphi method and the analytic hierarchy process (AHP) method. Because the judgment matrix of this kind of method is determined by expert experience, it is difficult to exclude the influence of individual factors on the index weight. The objective weighting methods include the entropy method and principal component analysis. The entropy method (EM) is a commonly used objective weighting method. This method directly uses the inherent information of the evaluation indicators to empower the indicators and, to an extent, avoids the bias caused by subjective factors [120]. After normalizing the indicators, the steps for calculating the weight of the index by the entropy method are shown below:

First: The decision matrix, $X = \{x'_{ik}, i = 1, 2, \ldots, m; k = 1, 2, \ldots, t\}$, is normalized for each criterion C_i ($i = 1, 2, \ldots, m$). The normalized values s_{ik} are calculated by Equation (3):

$$s_{ik} = x'_{ik} / \sum_{t=1}^{n} x'_{ik} \tag{3}$$

Secondly: The entropy Hi for each criterion C_i is calculated by Equation (4):

$$H_i = -v \sum_{t=1}^{n} s_{ik} \ln(s_{ik}),\ v \text{ is a constant, let } v = 1/\ln(n), \alpha_i \geq 0 \tag{4}$$

Thirdly: The degree of divergence DIV_i for the intrinsic information in each criterion C_i is calculated by Equation (5):

$$DIV_i = 1 - H_i \tag{5}$$

Fourthly: The entropy weight w_i for each criterion C_i is calculated by Equation (6):

$$w_i = DIV_i / \sum_{i=1}^{m} DIV_i \tag{6}$$

Aggregation is the most commonly used method in measuring energy security; it involves combining the weighted indicators into a composite index. Approximately 83% of the energy security indexes use this method to aggregate their indicators. Among them, the additive aggregation method, by which the indicators are first multiplied by the weights assigned, then added together to get the index, is most commonly used [77,121]. After the weight is calculated, the ESSI is constructed using the aggregation methods as follows:

$$ESSI_k = \sum_{i=1}^{m} (x_{ik} \times w_i) \tag{7}$$

where $ESSI_k$ is the energy supply sustainability index of year k, x_{ik} is the normalized value of indicator i in the year k, and w_i is the weight of indicator i.

3.3.3. Evaluation Criterion

The ESSI reflects a country or region's energy supply sustainability level, the value range of ESSI is [0, 1]. The corresponding energy supply sustainability level was divided into five grades by reference to Liu [122], and its step length was 0.2, which is clearly shown in Table 4.

Table 4. Sustainable energy supply level table.

Sustainable Level	Score	Sustainable Characteristics
I	0.8–1	There were a few unsustainable factors, but overall it was in a sustainable state.
II	0.6–0.8	There were some unsustainable factors; however, overall, it was in a basically sustainable state.
III	0.4–0.6	There were many unsustainable factors, and overall, it was in a weakly sustainable state.
IV	0.2–0.4	The sustainable factor had either been close to or exceeded half, and overall, it was not in a sustainable state.
V	0–0.2	There were mainly unsustainable factors, and overall, it was in a seriously unsustainable state.

4. Forecasting Methodology

4.1. Forecasting Principles and Processes

Based on the exponential smoothing model, the GM(1,1) model and the exponential smoothing-GM(1,1) hybrid model, this paper put forward two experimental schemes to forecast the sustainable level of China's energy supply, as shown in Figure 1, which could advance the energy security theory.

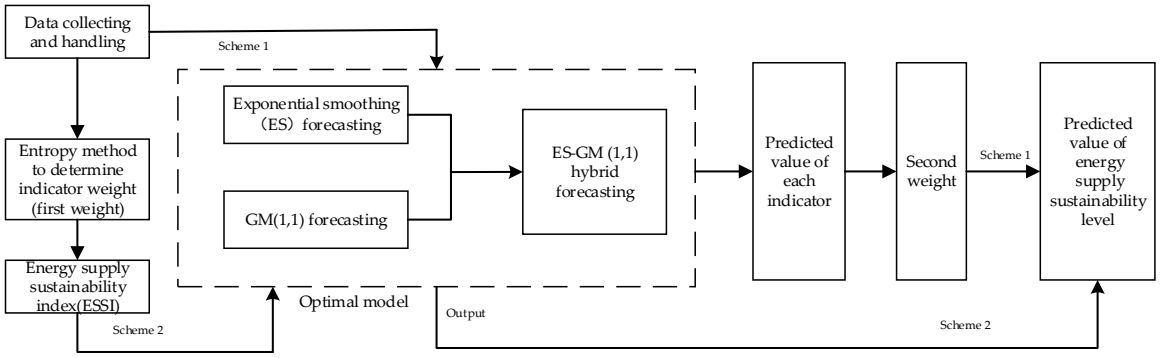

Figure 1. Forecasting principles and processes for energy supply sustainability.

(1) The first scheme: Calculate the predicted value of the energy supply sustainability index $ESSI_1^*$ by weighing the predicted value of each indicator. The specific process is as follows:

Step 1: Forecasting by the exponential smoothing method.

First, calculate the ESSI of the sample interval, according to the comprehensive evaluation method in Section 3.3, based on the sample observations. We build the time series x_{ik} according to the annual distribution of ESSI and its influencing factors. We then test the stationary and white noise of the time series using the difference method.

Then, we perform the order selection for the matrix. In determining ESSI and its influencing factors' optimal smoothing times based on the BIC matrix, we obtain the optimal exponential smoothing model for ESSI and its influencing factors and forecast their observations. We let $\hat{x}_{ik}^{es}$ refer to the forecast value of each time series in the year k.

Step 2: Forecasting by the GM(1,1) method.

We write a GM(1,1) function and call to the function. Then, ESSI and its influencing factors are regarded as independent variables. We categorize these variables as the training set and the test set, then we obtain a forecasted value of ESSI and its influencing factors. In this model, we let $\hat{x}_{ik}^{gm}$ refer to the forecast value of each time series in the year k.

Step 3: Forecasting by the exponential smoothing-GM(1,1) hybrid model.

Based on the predicted values of observations in step 1 and step 2, we adopt the grid searching method, utilizing minimum errors as the objective. Then, we obtain the optimal weight of the

exponential smoothing model and GM(1,1) model. Therefore, we obtain the optimal exponential smoothing-GM(1,1) hybrid model as:

$$\hat{x}_{ik} = p\hat{x}_{ik}^{es} + (1-p)\hat{x}_{ik}^{gm} \tag{8}$$

We predict the observations of ESSI again using the exponential smoothing-GM(1,1) hybrid model. The results of ESSI forecasted by the three models are analyzed to select the optimal forecasting model. The choice of the model has a minimum error to improve the prediction accuracy of the prediction model.

Step 4: Using the ESSI and its influencing factors' observations as the test set, and using the chosen model whose deformation error is the lowest, we obtain the forecasted value of ESSI and its influencing factors $\hat{x}_{ik}$. Then, based on the entropy method, shown in Section 3.3.2, we obtain the second weight of each indicator. Finally, based on the comprehensive evaluation method in Section 3.3, we obtain the forecasted value of energy supply sustainability index ($ESSI_1^*$) as follows:

$$ESSI_1^* = \sum_{i=m}^{n} \hat{x}_{ik} \times v_i \tag{9}$$

(2) The second scheme: Forecast $ESSI_2^*$ directly from ESSI.

First, we calculate the ESSI based on the sample observations. Then, we utilize the ESSI as a time series, according to the optimal model screened by approach 1. Running its program directly, we obtain the forecasted value of the energy supply sustainability index ($ESSI_1^*$) directly.

4.2. Forecasting Methodology

4.2.1. Exponential Smoothing Model

Exponential smoothing is a kind of moving average (MA) method, which is a class of methods that imply exponentially decreasing weights as observations age. This method is characterized by the assigning of a different weight to different past observations, that is, the weights of the recent observations are larger than those of the older observations. In exponential smoothing, one or more smoothing parameters need to be explicitly determined, and these choices determine the weight assigned to the observed value [123].

The fundamental formulas of exponential smoothing method are:

$$s_k = \alpha x_k + (1-\alpha)s_{k-1} \tag{10}$$

s_k—smooth value of the variable that is the next forecast value of the variable
x_{k-1}—present actual value of the variable
s_{k-1}—present forecast value of the variable
α—a constant between 0 and 1

Depending on the different smoothing times, the exponential smoothing method can be classified into three types: single exponential smoothing (SES), double exponential smoothing (DES) and triple exponential smoothing (TES). Referencing the principle of the exponential smoothing method and the basic steps of the three categories of the exponential smoothing method, this paper set the energy supply sustainability model as follows:

(1) The SES model for energy supply sustainability.

If the energy supply sustainability index and its influencing factors are simple data with no trend or seasonal component, the SES model is the best choice. The SES model provides an option for placing exponentially decreasing values of weights on past values of the variable to perform the forecast,

the immediately recent values having more weight. The equation for the SES forecasting model is given by Equation (11):

$$\widehat{x_{i(k+1)}} = \alpha x_{ik} + (1-\alpha)\hat{x_{ik}} \tag{11}$$

$\widehat{x_{i(k+1)}}$—forecast value of variable i in the next year, that is, the smooth value of the variable this year.
x_{ik}—current actual value of the variable.
$\hat{x_{ik}}$—current forecast value of the variable, that is, the smooth value of the variable last year.

From Equation (11), it can be observed that the prediction of the future value depends on the present value and the present value obtained from the past value. Obviously, it is an auto recursive process that can be represented as it is shown in Equation (12):

$$\widehat{x_{i(k+1)}} = \alpha x_{ik} + \alpha(1-\alpha)x_{i(k-1)} + \alpha(1-\alpha)^2 x_{i(k-2)} + \ldots + \alpha(1-\alpha)^{k-1}x_{i1} + (1-\alpha)^k \widehat{x_{ik}} \tag{12}$$

From Equation (12), it can clearly be observed that the weight of the past values of variables decreases exponentially. Therefore, this method is called the exponential smoothing method. Here, compared with other predictions, the recent past value has more bearing on the forecast.

(2) The DES model for energy supply sustainability.

When a linear trend appears in the variation of a time series an obvious lag deviation remains in the forecasting by the SES method. It is necessary to correct this deviation. The revised method conducts DES on the basis of the single exponential smoothing. DES is a feasible alternative to the derivative free motion model predictor based on the Kalman filter. DES uses a simple linear regression equation to establish a time series, in which the y-intercept and slope slowly change over time [124]. For these parameters, which decay exponentially over time, unequal weighting is applied. Therefore, newer observations obtain a higher weight than older ones. The degree of exponential decay is determined by the parameter, $\alpha \in [0, 1)$.

The formulas of the double exponential smoothing method are:

$$s_{ik}^{(2)} = \alpha s_{ik}^{1} + (1-\alpha)s_{i(k-1)}^{2} \tag{13}$$

where:
s_{ik}^{2}—double exponential smoothing value of the variable i in the year k
s_{ik}^{1}—smooth value of the variable i in the year k
$s_{i(k-1)}^{2}$—double exponential smoothing value of the variable i in the year $k-1$

The equation for the double exponential smoothing forecasting model for energy supply sustainability forecasting is given by Equation (14):

$$\widehat{x_{i(k+T)}} = \alpha_{ik} + b_{ik}T \tag{14}$$

$$\alpha_{ik} = 2s_{ik}^{(1)} - s_{ik}^{(2)} \tag{15}$$

$$b_{ik} = \frac{\alpha}{1-\alpha}(s_{ik}^{(1)} - s_{ik}^{(2)}) \tag{16}$$

(3) The TES model for energy supply sustainability.

The TES method is used when the data show trend and seasonality. TES is conducted on the basis of DES. The formulas of the TES method are:

$$s_{ik}^{(3)} = \alpha s_{ik}^{(2)} + (1-\alpha)s_{i(k-1)}^{3} \tag{17}$$

The equation for the TES forecasting model for energy supply sustainability forecasting is given by Equation (18):

$$\widehat{x_{i(k+T)}} = \alpha_{ik} + b_{ik}T + c_{ik}T^2 \tag{18}$$

$$\text{Where, } \alpha_{ik} = 3s_{ik}^{(1)} - 3s_{ik}^{(2)} + s_{ik}^{(3)} \tag{19}$$

$$b_{ik} = \frac{\alpha}{2(1-\alpha)^2}[(6-5\alpha)s_{ik}^{(1)} - 2(5-4\alpha)s_{ik}^{(2)} + (4-3\alpha)s_{ik}^{(3)}] \tag{20}$$

$$c_{ik} = \frac{\alpha^2}{2(1-\alpha)^2}[s_{ik}^{(1)} - 2s_{ik}^{(2)} + s_{ik}^{(3)}] \tag{21}$$

4.2.2. GM(1,1) Model

Grey system theory is an important method for studying discrete data sequences with small samples and incomplete information [47]. By fully exploiting and utilizing explicit and implicit information in existing data, the randomness that exists in the sequence is gradually diminished. In this way, the laws governing system changes are generated and can be used to study future time distributions at specific time intervals. We set the time series of ESSI and its influencing factors as $X_i^{(0)} = \left\{X_i^{(0)},\ i = 1,\ 2, \ldots,\ m\right\}$, which are non-negative origin data serials of a prediction object. To build GM(1,1) modeling, we must first conduct a first-order accumulation generation on the original data series as:

$$X_i^{(1)} = \left\{X_i^{(1)}(k),\ k = 1,\ 2, \ldots,\ t\right\} \tag{22}$$

where:

$$X_i^{(1)}(k) = X_i^{(0)}(k-1) + X_i^{(0)}(k) \tag{23}$$

Then, the mean series is calculated:

$$z_i^{(1)}(k) = 0.5X_i^{(1)}(k) + 0.5X_i^{(1)}(k-1),\ k = 2,\ 3, \ldots,\ t \tag{24}$$

Using this series, the first-order differential equation based on a single variable is established and used as the prediction model (that is, the GM(1,1) model). The standard form of the gray difference equation is:

$$X_i^{(1)}(k) + az_i^{(1)}(k) = b \tag{25}$$

where a and b are the development coefficient of the system and the grayscale of the endogenous control, respectively.

The estimation formula of the parameter vector $\hat{a}$ can be written in the following form:

$$\hat{a} = (a, b)^T = \left(B^T B\right)^{-1} B^T y \tag{26}$$

$$\text{where, } B = \begin{bmatrix} -z_i^{(1)}(2) & 1 \\ -z_i^{(1)}(3) & 1 \\ \cdots & \cdots \\ -z_i^{(1)}(n) & 1 \end{bmatrix}, \text{ and } Y = \begin{bmatrix} X_i^{(0)}(2) \\ X_i^{(0)}(3) \\ \cdots \\ X_i^{(0)}(n) \end{bmatrix}$$

The time-response function of the GM(1,1) model is:

$$\hat{x}_i^{(1)}(k) = (X_i^{(1)}(1) - \frac{b}{a})^{e^{-a(k-1)}} + \frac{b}{a} \tag{27}$$

Finally, the predicted values of the original series $\hat{x}_i^{(0)}$(k) can be obtained by an inverse accumulated generating operation (IAGO):

$$\hat{x}_i^{(0)}(\mathrm{k}) = \hat{x}_i^{(1)}(k) - \hat{x}_i^{(1)}(k-1) = (\hat{x}_i^{(1)}(1) - \frac{b}{a})(1-e^a)e^{-a(k-1)} \tag{28}$$

4.3. Prediction Accuracy Criterion

Evaluating the accuracy of the model helps to determine the predictive effect of the selected model and provides a reference for forecasting results. Scientists have developed a variety of criterion for judging the accuracy of models [125,126]. Referring to these studies, in this paper, we selected two typical standards for this research. The first method of judgment is the trend map. By drawing the forecast curve and the actual curve, the trend graph can reflect the model's predictive effect. However, the trend map does not quantify the accuracy of predictions with specific numbers. The second judgement method uses the error measurement. MAPE and RMSE are commonly used tools for measuring prediction errors. Their specific formulas are as follows:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} e^2(i)} \tag{29}$$

$$\mathrm{MAPE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{e(i)}{x^{(0)}(i)}\right| \times 100\% \tag{30}$$

where $\mathrm{e}(i) = x^{(0)}(i) - \hat{x}^{(0)}(i)$ is the error, $x^{(0)}(i)$ is the actual value, and $\hat{x}^{(0)}(i)$ is the predicted value at the ith time point. According to the MAPE evaluation criteria in Table 5, the prediction accuracy can be divided into four levels.

Table 5. MAPE evaluation criterion.

MAPE (%)	Forecasting Ability	MAPE (%)	Forecasting Ability
(−∞,10)	High	[20,50)	Reasonable
[10,20)	Good	(50,+∞)	Weak

4.4. Experiment Environment and Data

(1) Experiment environment

This thesis focuses on the forecasting of energy supply sustainability processing in the exponential smoothing and GM(1,1). The hardware resources environment of this experiment is Intel Core i5 2.70 GHz, and the starting modeled memory gain of the 8 GiB operating system environment is Ubuntu 18.04.1 LTS 64 bit. The programming language is Python3.6.5, and the third-party expansion package is NumPy pandas matplotlib stats models.

(2) Data sources

This research uses China as the sample and analyzes its energy supply sustainability. Primary data sources include: The National Bureau of Statistics of the People's Republic of China, China Statistics Yearbook (2000–2017), and the Wind Database of China [127]. The reserve and production ratios, the production diversity index, energy dependence, the total primary energy supply(TPES), total population number, energy price index, and clean power generation were taken from the National Bureau of Statistics of The People's Republic of China [128]. Imports of crude oil, gasoline, diesel oil, kerosene, natural gas and raw coal; distribution loss; power generation; market liquidity; and oil price, electricity distribution efficiency, and energy efficiency were taken from the Wind Database [127]. The waste water emissions, SO_2 emissions, NOx emissions, forest coverage and domestic infrastructure were taken from the National Bureau of Statistics of the People's Republic of China [128].

5. Empirical Findings

Based on the research methods for energy supply sustainability in Section 3, we utilize the influencing factors of China's energy supply sustainability from 2000 to 2016 as the sample. First, China's energy supply sustainability index from 2000 to 2016 is calculated. Then, utilizing China's energy supply sustainability index from 2000 to 2010 as a training sample, and based on the forecasting methodology in Section 4, the optimum method for forecasting China's energy supply sustainability is screened. The findings show the validity of the method. The results are as follows.

5.1. Comprehensive Evaluation Results

Based on the evaluation indicators for the energy supply sustainability of China in Table 3, we adopt the entropy method in Section 3.3.2, calculate the weight of each indicator in Table 6, then, according to Equation (6), the ESSI from 2000 to 2016 is calculated, as shown in Figure 2. As shown in Table 6, the weight of each indicator is arranged in order: reserve and production ratio > production diversity index > clean power generation > GDP per capita > market liquidity > sulfur dioxide emissions per capita > land use > NOx emissions per capita > electricity distribution efficiency > domestic infrastructure > water pollution > energy dependence > TPEC per capita > energy efficiency > economic vulnerability index > energy price index. Among these indicators, the reserve and production ratio, the production diversity index and the clean power generation indicators ranked in the top three. Analysis of the dimension level shows that energy availability had a maximum weight of 0.4321, and energy technology and efficiency ranked second, with a weight of 0.2319; environment sustainability ranked third, with a weight of 0.2077, and economic sustainability ranked fourth, with a weight of 0.1283. These results fully demonstrated the importance of energy availability and technical sustainability to China's energy supply sustainability. These findings also show that environmental sustainability is an important guarantee for energy supply sustainability.

Table 6. Weights for each indicator of ESSI.

Indicator	Reserve and Production Ratio	Production Diversity Index	Energy Dependence	TPEC Per Capita	Market Liquidity	Economic Vulnerability Index	Energy Price Index	GDP Per Capita
Weight	0.1648	0.1206	0.0412	0.04	0.0655	0.0326	0.0282	0.0675
Indicator	**Water Pollution**	**Sulfur Dioxide Emissions Per Capita**	**NOx Emissions Per Capita**	**Land Use**	**Clean Power Generation**	**Domestic Infrastructure**	**Electricity Distribution Efficiency**	**Energy Efficiency**
Weight	0.0422	0.0594	0.0505	0.0556	0.1003	0.0478	0.0496	0.0342

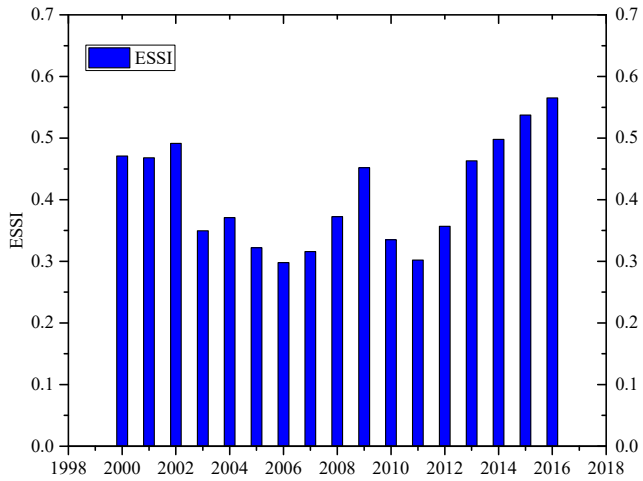

Figure 2. China's energy supply sustainability level from 2000 to 2016.

Figure 2 shows that China's energy supply sustainability has an asymmetric "W" trend from 2000 to 2016 and demonstrates an obvious phased characteristic. The energy supply sustainability level is low. The ESSI for China tends to increase from 2000 to 2002, and the sustainable level is

between 0.45 to 0.5, at level III. During this period, China's economic development was not high, and the GDP per capita was only approximately 0.8 million yuan. However, China had adequate energy reserves, low external dependence, strong availability and a low environmental pollution index. From 2003 to 2006, the ESSI significantly decreased to level IV, because China's economy developed rapidly during this period. The average annual GDP increased by 60% between 2000 and 2002. The energy dependence began to increase, and the pollutant emissions increased. Among these findings, the annual discharge of wastewater increased by 24%, compared with the previous period. At the same time, China's energy efficiency did not improve significantly. From 2007 to 2009, the ESSI increased to level III, because China's annual investment in the fixed assets of the energy industry developed rapidly during this period. Annual investment in the fixed assets of the energy industry increased by 27%, compared with 2003 to 2006. In 2009, energy consumption per GDP unit was 26% lower than in 2006. At the same time, people's livelihoods improved, and social security improved. By the end of 2009, per capita GDP was 55% higher than in 2006. However, in 2009, the ESSI showed a significant improvement. The main reason may be the 2008 financial crisis, which caused the growth rate of China's major energy consumption products to decrease sharply, the energy demand to decline rapidly, and the energy supply to change from a tighter to a relatively short-term relative surplus. Energy prices decreased sharply in 2009, down 26% from 2008. In 2010, the ESSI basically returned to the pre-2009 level, and it continued to improve after that year. The ESSI for China tended to increase from 2011 to 2016, with an average of 0.0589, and attained level II.

In recent years, China's energy supply sustainability level has increased significantly. This is due to the promotion of a series of national policies. China promulgated a new version of the "Emission Standards for Air Pollutants in Thermal Power Plants" (GB13223-2011) in 2011. The standard has significantly increased the emission concentration requirements for sulfur dioxide, nitrogen oxides and soot, and certain projects have been stricter than EU standards. The goal of the standard is to further promote thermal power plants to implement energy conservation and emissions reduction, reduce emissions, and increase waste treatment and disposal facilities to increase the treatment rate. In 2016, China put into operation 880 million kilowatts of flue gas desulfurization units in thermal power plants and 910 million kilowatts of flue gas denitrification units in thermal power plants, representing 83.8% and 86.7% of the capacity of thermal power units in China, respectively. Currently, the installation rate of denitrification and desulfurization units in China is at a relatively high level. Chinese Premier Li Keqiang made it clear that, to establish an energy and environmental security concept, it is necessary to move the environmental safety of energy to a strategic level and vigorously increase the proportion of green products and clean energy supply. China's clean energy development has made remarkable progress. In the first three quarters of 2017, wind power, photovoltaic power, and nuclear power generation represented 4.5%, 1.8%, and 3.9% of the total power generation, respectively, showing an increasing trend year over year. Among these energy items, Guangdong's no fossil energy consumption represents approximately 43.5% of the total electricity consumption. These items will help to create a cleaner and low-carbon energy supply system and promote the sustainable development of the energy supply. However, China's macroeconomic reform has also restricted the formation of China's energy policy to a certain extent, explaining why the sustainability of China's energy supply has not been greatly improved [129].

5.2. Optimality Analysis

5.2.1. Data Stationarity Test

First, the ADF method is used to test the stationarity of energy supply sustainability and its indicators. The test results are shown in Table 7. ADF test statistics are calculated by dividing an estimate of d by its standard error. According to the ADF statistical standard (SS) by Fuller ([130], p. 373), although nearly all the data are unstable, most of the data become smooth after the first-order difference. In addition, all the data become smooth after the second-order difference.

This finding shows that the sample data have the basic conditions of exponential smoothing prediction and GM(1,1) prediction.

Table 7. Stationary tests.

Variable	Level		First Difference		Second Difference	
	t-Statistic	Prob.	t-Statistic	Prob.	t-Statistic	Prob.
x1	(−2.0484) ***	0.2645	(−0.0789) ***	0.2544	(−0.4085) **	0.0291
x2	(−0.8801) ***	0.7672	(−4.1963) *	0.0064	(−7.5629) *	0
x3	(−0.5226) ***	0.859	(−0.0207) ***	0.0017	(−8.0130) *	0
x4	(−0.9265) ***	0.7521	(−0.6660) ***	0.1026	(−4.5970) *	0.0035
x5	(−0.3198) ***	0	(−0.6418) ***	0.1068	(−5.1573) *	0.0024
x6	(−1.4780) ***	0.5184	(−4.3508) *	0.0048	(−6.4814) *	0.0002
x7	(−3.0087) **	0.0454	(−7.7424) *	0	(−4.4103) *	0.0063
x8	(−3.1078) **	1	(−0.1200) ***	0.2401	(−4.9877) *	0.0021
x9	(−3.0290) ***	0.0548	(−6.4014) *	0.0001	(−5.6718) *	0.0012
x10	(0.4878) ***	0.9803	(−0.0435) ***	0.0534	(−4.7978) *	0.0025
x11	(0.2706) ***	0.9683	(−4.0184) **	0.0118	(−4.9198) *	0.0034
x12	(−1.0350) ***	0.7137	(−3.1679) **	0.0428	(−5.1758) *	0.0019
x13	(0.8848) ***	0.9919	(−5.1850) **	0.0011	(−8.1279) *	0
x14	(−0.8970) ***	0.7549	(−3.2774) **	0.0403	(−1.7765) *	0.0327
x15	(−6.3077) ***	0.0002	(−0.2786) ***	0.0002	(−6.3711) *	0.0003
x16	(0.2627) ***	0.9672	(−3.9333) **	0.0105	(−4.8876) *	0.0021
ESSI	(−1.0813) ***	0.6959	(−3.4268) **	0.0268	(−3.5197) *	0.027

*—In the 1% significance level, **—In the 5% significance level, ***—In the 10% significance level.

5.2.2. Bayesian Information Criteria for Time Series

The Bayesian information criteria is a method for determining the optimal model. Each variable obtains a different BIC value for each order of the MA, then obtains the optimal exponential smoothing model by calculating the BIC. For the same variable, smaller BIC values are better. Ledwina [131] proposed a data-driven smoothing test method based on BIC information selection criteria and used the BIC standard to select the dimension k of the smoothed density function. Kallenberg and Ledwina [132] used a Monte Carlo simulation to confirm that this method has suitable finite sample properties in practical applications. Inglot and Ledwina [133] theoretically proved that this method is progressively optimal regarding intermediate efficiency. Based on the historical data of the energy supply sustainability and its indicators from 2000 to 2016, the BIC values of energy supply sustainability and its indicators are shown in Table 8. Thus, the optimal smoothing times for each variable are obtained.

Table 8. BIC values of energy supply sustainability and its indicators.

Variable	Smoothing Times			Optimal Smoothing Times
	1	2	3	
x1	97.9123	96.8113	99.3577	2
x2	−46.8885	NaN	NaN	1
x3	−59.3967	NaN	NaN	1
x4	−9.2724	−7.7188	−5.9012	1
x5	58.2847	57.3680	55.6523	3
x6	−92.0690	NaN	NaN	1
x7	109.8997	NaN	NaN	1
x8	−15.9288	NaN	NaN	1
x9	88.0625	88.3366	90.8277	1
x10	−147.43	−145.267	NaN	1
x11	−171.003	−168.389	−166.609	1
x12	38.0677	39.0169	36.4788	3
x13	−69.4097	−67.2204	−64.7617	1
x14	232.4133	NaN	NaN	1
x15	−6.5838	NaN	NaN	1
x16	−30.8927	−31.2931	−29.8607	2
ESSI	−23.6834	−22.1323	NaN	1

NaN—The Bayesian information metric of the order is incalculable.

5.2.3. Experimental Results for the Accuracy of Different Models

The ADF method shows that energy supply sustainability and its indicators have the basic conditions of exponential smoothing prediction and GM(1,1) prediction, and the optimal smoothing times of energy supply sustainability and its indicators are finally obtained from the Bayesian information criterion, using the ESSI as an example, to determine the best prediction model for China's energy supply sustainability. The specific process is as follows: using ESSI from 2000 to 2010 as the test data, the exponential smoothing and GM(1,1) models are used to predict ESSI from 2011 to 2016. Then, a grid search is used to traverse the weight combination, and the MAPE minimum is used as the standard to determine the optimal combination weight value. The final results of the grid search are as follows: the weight of the exponential smoothing model is 0.59, and the weight of GM(1,1) is 0.41. The optimal combination model is:

$$\hat{x}_{ik} = 0.59\hat{x}_{ik}^{es} + 0.41\hat{x}_{ik}^{gm} \tag{31}$$

According to the combination model in Equation (31), we obtain the forecasting results of ESSI from 2011 to 2016, then compare these results with the forecasting results by the exponential smoothing single model, GM(1,1) single model, and the actual value of ESSI from 2011 to 2016. The forecasting trend map is shown in Figure 3. Figure 3 clearly shows that the prediction result of the exponential smoothing single model is higher than the original value, and the prediction result of the GM(1,1) single model is lower than the original value. The predicted results of ESSI by the exponential smoothing single model are more accurate than those of the GM(1,1) single model. However, overall, the exponential smoothing-GM(1,1) hybrid model is the most accurate for the prediction of ESSI. From the MAPE in Table 9, the MAPE of the exponential smoothing single model and the GM(1,1) single model are both less than 20%, which achieves a better prediction accuracy. The hybrid model is more accurate, and the MAPE is only 2%. The results of RMSE also show that the combined model has a high reliability, again proving the validity and reliability of the model selected in this paper.

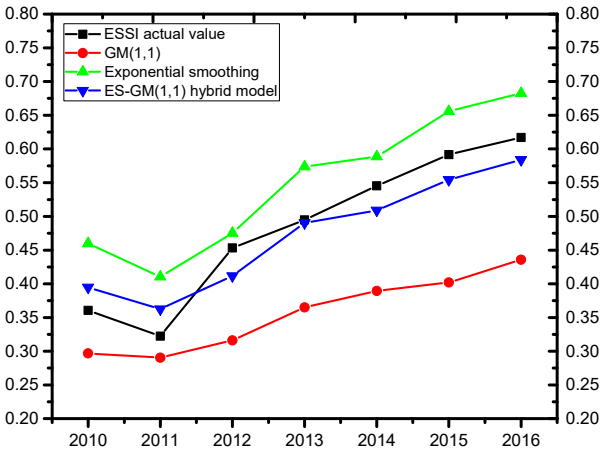

Figure 3. Comparison of the test results of single and combined models.

Table 9. The RMSE and MAPE values for the three models.

Error	GM(1,1)	Exponential Smoothing	ES-GM(1,1) Hybrid Model
RMSE	0.1123	0.0760	0.0278
MAPE	0.1920	0.1860	0.0201

5.3. Forecasting Results

5.3.1. Forecasting Results and Analysis of Each Dimension of ESSI

Using the historical data of each indicator of China's energy supply sustainability from 2000 to 2016 as a sample, adopting the optimal exponential smoothing-GM(1,1) hybrid model, we obtain the forecasting results of each indicator of China's energy supply sustainability, then analyze these results in depth, as shown in Figures 4–7.

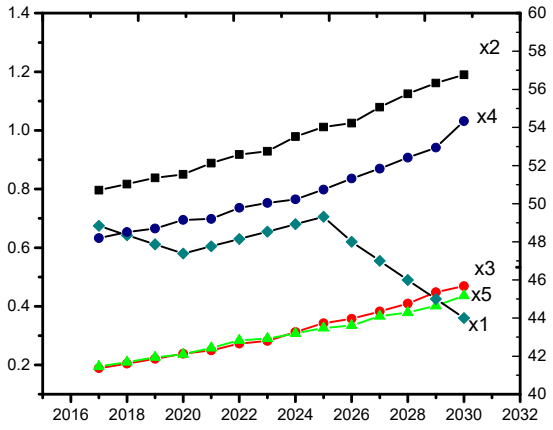

Figure 4. Predictions for the energy availability of ESSI.

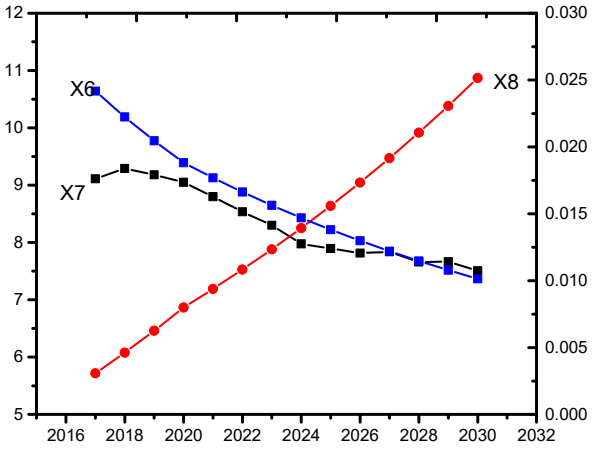

Figure 5. Predictions for the economic sustainability of ESSI.

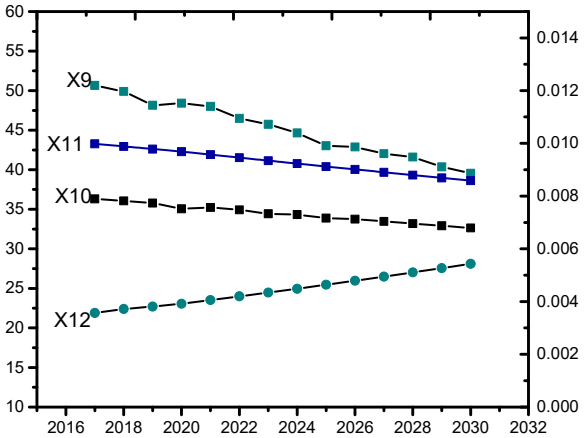

Figure 6. Predictions for the environmental sustainability of ESSI.

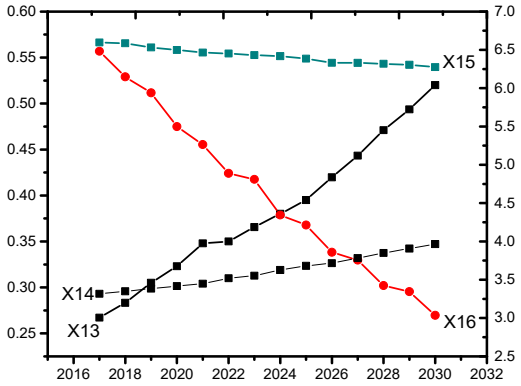

Figure 7. Predictions for the technical sustainability of ESSI.

The energy supply availability forecasting results in Figure 4 indicate that, except for a minor reduction in the reserve and production ratio, the remaining four indicators in this dimension are on the rise. In the short term, the reduction in energy reserve and production will be small, and in the long run, China's energy supply will remain relatively stable. By 2030, the reserve and production ratio will be 44. In recent years, the Chinese government has implemented a variety of measures to stabilize the energy supply and maintain the oil reserve and production ratio at approximately 13.8. Moreover, China has achieved breakthroughs in coal-to-methanol, methanol-to-olefin and coal-to-oil technologies and has mastered strategic alternative technologies in both transportation fuels and chemical products. For example, in mining, the Bulianta Coal Mine of the Shenhua group of China has, since 2017, adopted a working face that is 8 m high. One working face can recover 1.2 million tons of coal within 48 months, and the recovery rate is as high as 98%. The energy production diversity will continue to increase, because the Chinese government attaches great importance to the development of no fossil energy. According to data released by the International Energy Agency (IEA), in 2017 alone, China spent $132 billion on clean energy systems, which is more than that spent by the US and EU combined. China's onshore wind power represented approximately 35% of the world's total in 2017, and the average utilization hours of wind power in China were 1948 h, which is an increase of 203 h. However, compared with the developed countries in the world, China's share of renewable energy is still relatively low, and the energy production diversity of 75% of EU countries is higher than this level [134]. China's energy dependence will also continue to increase, because China is undergoing an energy transformation, and the demand for oil and natural gas has greatly increased. In 2017, China's dependence on foreign oil grew to 72.3%. However, with the promotion of the Belt and Road Initiative, China Petroleum has cooperated with other countries and has achieved more international cooperation. Hence, the market liquidity of oil will continue to improve.

The economic sustainability forecasting results in Figure 5 indicate that the economic vulnerability index and the energy price index will show a downward trend for a long time, and GDP per capita will rise in both the short and the long term. First, China's economic vulnerability index will continue to decrease, because China's ability to withstand rising oil prices and large fluctuations will gradually increase as China's energy diversification level increases and a series of strategies to delay oil consumption growth are implemented. Second, China's energy product price index fluctuates unsteadily and rises in the short term. However, overall, it is lower than the historical energy price index, mainly because China's energy price reform process is slow [135]. In 2015, China's "Several Opinions of the Central Committee of the Communist Party of China and the State Council on Promoting the Reform of the Price Mechanism" noted that, by 2017, China's competitive areas and links were basically liberalized, and by 2020, the market-determined price mechanism will be basically improved. With the implementation of a series of policies, China's energy prices will be reduced in the long run. GDP per capita will grow at a rate of 6.63% in the short term, from 2017 to 2020, which is close to the predictions of 6.67% by Pao (2012) [44] and 6.5% by Yuan [136]. Since 2008, China's total GDP has

surpassed that of Japan, becoming the world's second largest economy. However, from the perspective of per capita GDP, China remains far behind developed countries. In the long run, China's GDP per capita growth will decrease by approximately 4.7% in 2030.

The environmental sustainability forecasting results in Figure 6 show that, from 2017 to 2030, China's per capita wastewater discharge, per capita sulfur dioxide emissions, and per capita NOx emissions all showed a downward trend, and the forest coverage will rise. Specifically, in the short term, from 2017 to 2021, the average deceleration rates of the three are 1.5%, 1%, and 1%, respectively. In the long run, by 2030, the rate of decline will increase to 2%, 1.5% and 1.5%, respectively. The main reason is the implementation of the "Water Pollution Prevention Action Plan" (Water 10 Articles 2015), "Fire Power Plant Air Pollutant Emission Standards" (2011), "Atmosphere Ten Articles" (2015) and other policies introduced by the Chinese government in recent years. Using Beijing as an example, in 2017, Beijing's "good days" were 226 days, an increase of 28 days, compared with 2016. It had 23 "heavy pollution days", which was 16 days fewer than in 2016. In 2017, the concentration of sulfur dioxide in Beijing was "single digit", which is much better than the national standard (60 $\mu g/m^3$). Forests are not only related to national ecological security but are also the main content of China's sustainable development in the new era. On October 18, 2017, Chinese president, Xi Jinping, in the report of the 19th National Congress, noted that, to adhere to the harmonious coexistence of man and nature, it is necessary to establish and practice the concept of green water and green hills, which is the concept of Jinshan and Yinshan. The president also noted that it is important to adhere to the basic national policy of conserving resources and protecting the environment. According to the forecast of this paper, China's forest coverage rate is expected to maintain a growth rate of 1.6% in 2017–2020, achieving 23.06% in 2020. After 2020, the growth rate will increase to 2%. By 2030, forest coverage will exceed 28%, and China's rate will match the world's average level.

The technical sustainability forecasting results in Figure 7 show that, in 2017–2030, China's clean power generation ratio and investment in fixed assets of energy industry will increase, and electricity distribution efficiency and energy consumption per unit GDP will decline. In the short term, from 2017 to 2021, the clean power generation ratio and investment in the fixed assets of the energy industry will increase by 1.86% and 1%, respectively. In addition, by 2030, the growth rate will rise to 2% and 1.5%, respectively. In the short term, from 2017 to 2021, electricity distribution efficiency and energy consumption per unit GDP will decrease by 0.5% and 5%, respectively. In the long term, electricity distribution efficiency will increase to 0.4% by 2030, and the rate of energy consumption per unit GDP will decrease by 5.5%. In sum, the proportion of clean energy generation is increasing faster than the fixed asset investment of the energy industry, and the energy consumption per unit GDP is decreasing faster than the loss rate of distribution. By 2030, the proportion of non-fossil energy in China will grow to approximately 20%, and the energy consumption per unit GDP will be reduced to 0.27%. This is because, given an increasingly serious energy crisis, energy development or energy efficiency enhancement has become a key component of energy security strategies. China has proffered clear requirements for improving energy efficiency in the China Energy 13th Five-Year Plan and the China Energy Security Development Strategy.

5.3.2. Prediction Results and Analysis of ESSI

The exponential smoothing-GM(1,1) hybrid prediction model was selected in Section 5.2, using the predicted values of each indicator for the energy supply sustainability, measured in Section 5.3.1. It also refers to the two different forecasting approaches for energy supply sustainability in Section 4.1. We calculated the forecast energy supply sustainability index, $ESSI_1^*$, by weighting the forecast index value of each indicator, and we determined the forecast energy supply sustainability index, $ESSI_2^*$, directly from ESSI, as shown in Figure 8. In this paper, China's energy supply sustainability is not only predicted for the short term, from 2017 to 2020, but also for the long term, from 2020 to 2030.

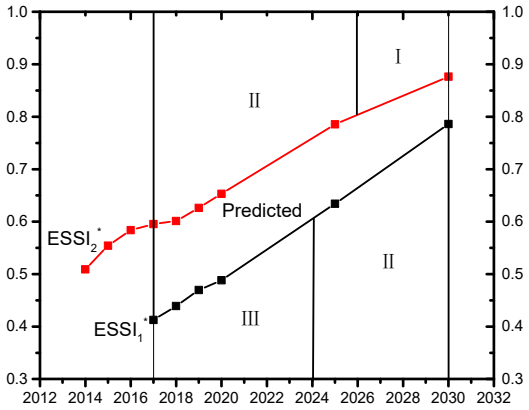

Figure 8. Forecasting results for China's energy supply sustainability.

Figure 8 clearly shows that the forecasting results for China's energy supply sustainability from 2017 to 2020 by scheme 1 is far from its actual value in 2016. From this result, it can be judged that scheme 2 is more accurate in predicting the sustainability of China's energy supply. Therefore, using the forecast result $ESSI_2^*$ of scheme 2 as a reference, this paper conducts a detailed analysis of the development trend of the sustainable level of energy supply in China in the short and long term. In the short term, the sustainable level of the energy supply in China will increase steadily from 2017 to 2020, with an average annual increase of 3.23%, but at level II in the short term. This is because China's energy supply sustainability starting point is low, and many unsustainable factors remain. In particular, China's resource endowment characteristics make it difficult for it to change its coal-based energy structure in the short term. Coal will represent approximately 60% of China's total energy supply by 2020, which will lead to a low diversification of the energy supply, a high degree of external dependence and a high degree of environmental pollution in China.

The Chinese government has implemented many measures to support the development of renewable energy, although in the short term, there are problems relating to inadequate absorption and a lag in technology. Compared with other developed countries, China has a lower proportion of renewable energy. Moreover, China's scientific and technological progress has a low starting point and a strong lag. Most of China's energy is heavily dependent on imports [137], which will seriously affect the sustainable level of China's energy supply in the short term. Denmark is the country with the safest and most sustainable energy in the Organization for Economic Cooperation and Development. Denmark has reduced its dependence on foreign energy sources to zero and achieved full self-sufficiency. The country's commitment to energy efficiency, long-term taxes on energy fuels, electricity and carbon dioxide, and incentives for cogeneration (CHP) and wind turbines are all worth learning from [138]. The Chinese government will also further implement a series of policy measures to improve China's energy supply structure and improve its sustainability level. China's "Revolutionary Strategy for Energy production and consumption (2016–2030)" clearly notes that, by 2030, the proportion of natural gas and no fossil energy in China's energy consumption will increase to 35%. By then, the proportion of coal supply will decrease to approximately 42%, which is close to Britain's level in 2014. Therefore, beginning in 2026, China's energy supply sustainability will be greatly improved. $ESSI_2^*$ will be higher than 0.8, and the level of sustainability of China's energy supply will be upgraded to the safe level (level I). By 2030, $ESSI_2^*$ will be increased to 0.8765.

6. Conclusions

Energy supply is the core issue relating to energy security. The sustainability of energy supplies is an important issue in the field of energy security, especially given increasing global warming and various environmental problems caused by fossil fuel combustion. The sustainability of energy supplies has become a common global demand of humans. The sustainability of the energy supply is more significant than that of the actual energy supply, as it focuses more on the equity of energy

supply and environmental sustainability. Some scholars have noted the environmental aspects of energy security, and some organizations have raised the issue of sustainable energy development. However, the sustainability of energy supplies has not been studied in depth. In-depth research on the sustainability of energy supplies is in accordance with the social requirements and the law of scientific development. It is of great significance to further deepen research in the field of energy security and to promote the sustainable development of energy supplies in countries or regions. On the basis of the research on energy security and sustainability by the relevant organizations and scholars, this paper creatively proffers a definition of energy supply sustainability, defines it and proffers the corresponding impact indicator system. Furthermore, the measurement method of the sustainability level of the energy supply, based on the entropy method, and the combined forecasting method of the energy supply sustainability level, based on exponential smoothing-GM(1,1), are proposed. Finally, using China as an example, this paper evaluates and predicts the sustainable level of the energy supply in China by using the above methods, which proves the validity of this method.

First, the comprehensive evaluation results show that the reserve and production ratio, the production diversity and the clean energy power generation ratio rank as the top three factors for energy supply sustainability. This conclusion is in accordance with international standards for sustainable energy development. By comparing previous studies, it is found that countries with a stable energy supply, a high degree of diversification, a low degree of external dependence and a suitable development of clean energy, such as the Netherlands and Germany [19], have a lower energy risk. From the perspective of dimensions, energy reliability, energy efficiency and environmental sustainability rank in the top three, and economic sustainability ranks fourth. This conclusion is in accordance with China's reality and fully reflects that energy reliability is the basic guarantee of energy supply sustainability. Energy efficiency and environmental sustainability are key issues for a sustainable energy supply in China. The equity of the energy supply in China is relatively strong; therefore, the weight of this dimension is the lowest.

Comparing experiments on exponential smoothing, the GM(1,1) single model and the exponential smoothing-GM(1,1) hybrid model, it is ultimately found that the exponential smoothing-GM(1,1) hybrid model has the lowest RMSE and MAPE for predicting the sustainable level of the energy supply in China. The results are only 2% of the MAPE and 0.0278 of the RMSE, with the highest accuracy. The experimental results showed that the exponential smoothing-GM(1,1) hybrid model was not only suitable for the prediction of the energy supply sustainability in the future but also suitable for the prediction of various impact indicators relating to energy supply sustainability in the future.

The forecasting results show that, in the short term, from 2017 to 2020, China's coal-based energy structure will be difficult to change, and the proportion of renewable energy is low. Therefore, many unsustainable factors remain in China's energy supply system. The level of sustainability is low, at level II. In the long run, with the diversification of China's energy supply and the energy technology progress, the sustainable level of China's energy supply will be greatly improved. By 2030, the sustainable level of China's energy supply will be raised to 0.8765, attaining level I. However, compared with Sweden and other countries with high levels of energy security and strong sustainability, China continues to have a large gap, because China has outdated low-carbon emissions and energy efficiency policies. There is no universal solution to all countries' energy problems. We should further integrate China's energy characteristics and social development process to formulate real-time sustainable solutions for the promotion of a sustainable energy supply and sustainable social development.

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