

Toward a sustainable energy system in China: Status and influencing factors

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Abstract

This paper focused on the endogenous and exogenous factors that affect China's sustainable energy system (SES). 19 Endogenous factors, from economic sustainability dimension, social sustainability dimension, environmental sustainability dimension and energy security dimension assessed China's SES by entropy method-analytic hierarchy process-criteria importance through intercriteria correlation method (EM-AHP-CRITIC). We used urbanization, foreign direct investment and industrialization as exogenous variables and explored the extent of their long-term and short-term impacts on China's SES by autoregressive distributed lag-error correction (ARDL-ECM) model.

Keywords

Sustainable energy system, endogenous variables, exogenous variables, EM-AHP-CRITIC method, ARDL-ECM model

Introduction

As the largest developing country, China is the world's largest energy producer and consumer and the world's largest carbon emitter. In 2018, CO₂ emissions in China reached 10.313 billion tons (World bank, 2021). In addition, global warming and severe domestic air pollution are forcing

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the energy system in China to transform from current fossil fuel-based to clean energy-based (Bolwig et al., 2019), and finally, a sustainable energy system (SES) (Li and Taihigh, 2020). The SES is critical to the success of China's long-term sustainable development goals.

As more attention paid to energy security and climate change, SES has attracted global attention. Sustainable energy is one of the guiding principles of sustainable development strategy on human energy consumption (UN. Secretary General, 1987; Sáez-Martínez et al., 2016). The concept of sustainable energy was first formally proposed by Munasinghe (1994), who believed that sustainable energy development could finally be realised through implementing a series of energy management policies from either the supply side or demand side. After that, Santoyo-Castelazo and Azapagic (2014) expanded energy sustainability into a three-dimensional concept with environmental, economic and social aspects. The International Organization for Standardization (ISO) developed a sustainability initiative involving energy use, clean water, pollution, and other issues (Antunes et al., 2014). Energy sustainability has become a guiding concept, including economy, environment, technology, security, and other aspects (Munasinghe, 1994; Santoyo-Castelazo and Azapagic, 2014; Sáez-Martínez et al., 2016). In general, research on SES has experienced three evolutions in different periods: from the year 1974 to 1985, focusing on energy security and taking economic benefits into account; from the year 1986 to 1998, focusing on economic benefits and environmental performance, taking energy security into account; and after the year 1999, focusing on energy security, as well as social-economic benefits and environmental performance (Despeisse et al., 2012). A meaningful way to achieve the SES is the energy transition (Bolwig et al., 2019; Chen et al., 2019). In the past 20 years, scholars (Benasla et al., 2019; Bolwig et al., 2019; Gales et al., 2007; Hong et al., 2019) conducted energy transition-related research and formed a conceptual understanding of this topic (Chen et al., 2019). For example, Liu et al. (2021) and Li et al. (2021a, 2021b) predicted short-term renewable energy generation. Safari et al. (2019) qualitatively analyzed the role of natural gas in the decarbonization process of the energy system by taking Iran, Norway, the United Kingdom and India as examples. Nawab et al. (2019) quantified the energy-water nexus to manage ecological assets to a more sustainable solution from a consumption-based approach. However, environmental and social costs in the transition process are slowing the global energy transition process (Sareen and Haarstad, 2018). For example, Wei and Chen (2020) took Guangzhou city as an example and found that only technological advancement in the building and transportation infrastructure exceeds the pace of the average urban economy, could the energy and carbon footprints of new planned projects be reduced.

To the best of our knowledge, currently there are no standardized methods available for assessing the sustainability of energy system (Maxim, 2014), and researchers usually tailor their methods to specific goals (Angelis-Dimakis et al., 2012). We summarize the typical literature shown in Table 1. With the transformation of the power system as a research goal, existing researchers (Dorini et al., 2011; Gujba et al., 2010; Jeswani et al., 2011; Maxim, 2014; May and Brennan, 2006; Rovere et al., 2010; Santoyo-Castelazo and Azapagic, 2014; Stamford and Azapagic, 2012) conducted in-depth studies on the process of replacing traditional energy by renewable energy in specific countries or regions. These studies usually focused on the economic and environmental impacts of the transition (Gujba et al., 2010; Jeswani et al., 2011), and some studies also took social impacts (May and Brennan, 2006; Santoyo-Castelazo and Azapagic, 2014) and technological level (Dorini et al., 2011; Maxim, 2014; Rovere et al., 2010) into consideration. World Economic Forum (2020) built an energy transition matrix from the global perspective focusing on energy access and security, environmental sustainability, economic development and growth. Some scholars regarded SES as a target and evaluated the level of sustainable energy development from the environmental, technological, and economic dimensions (ESMAP, 2018; Fang et al., 2018; Iddrisu and Bhattacharyya, 2015).

Table 1. Summary of representative literature on the sustainable energy system (SES).

Reference	Dimensions				Other dimensions	Methods used
	Environmental	Economic	technological	Social		
(May and Brennan, 2006)	✓	✓		✓		Not applied
(Gujba et al., 2010)	✓	✓				Life cycle assessment (LCA) and economical costing
(Rovere et al., 2010)	✓	✓	✓	✓		Data envelopment analysis
(Dorini et al., 2011)	✓	✓	✓			Compromise programming
(Jeswani et al., 2011)	✓	✓				LCA
(Stamford and Azapagic, 2012)	✓	✓	✓			LCA
(Maxim, 2014)	✓	✓	✓	✓		Weighted multi-criteria decision analysis (MCDA)
(Santoyo-Castelazo and Azapagic, 2014)	✓	✓	✓			MCDA and Scenario analysis
(Strantzali et al., 2017)	✓	✓	✓			MCDA
(Iddrisu and Bhattacharyya, 2015)	✓	✓	✓	✓	Institutional	A ratio between zero and one
(Vera and Langlois, 2007)	✓	✓	✓			Not applied

Since energy sustainability evaluation usually needs to incorporate elements of environmental, social, economic and technological aspects, multi-standard decision (MSDA) (Maxim, 2014; Santoyo-Castelazo and Azapagic, 2014; Strantzali et al., 2017) analysis is widely used in SES evaluation, with the combination of other approaches such as grey relational analysis (Strantzali et al., 2017), entropy method (EM) (Fang et al., 2018), and analytic hierarchy process (AHP) method (Solangi et al., 2019).

Not seeking the specific energy transition process, we, in this paper from the status quo of China's sustainable energy development, focus on the endogenous and exogenous factors that affect the sustainability of China's energy system. Endogenous factors are applied to construct China's SES model and to evaluate the sustainability of China's energy system from economic, social, environmental, and national energy security dimensions. Furthermore, the autoregressive

distributed lag-error correction (ARDL-ECM) model is used to analyze the impact of external factors. Exogenous factors are independent of those within the SES evaluation indicator system. They do not directly but indirectly influence SES through related endogenous factors. Existing studies focus on the nexus between carbon emissions and urbanization, foreign direct investment (FDI) and industrialization (Ding and Li, 2017; Franco et al., 2017; Li et al., 2021a, 2021b; Zhang and Zhou, 2016). Based on the existing research and data availability, we mainly select three variables, namely urbanization, FDI, and industrialization, as independent variables to investigate their impacts on SES in China.

The rest parts of this paper are arranged as follows. Section 2 introduces the current situation of China's SES. The method is described in Section 3, and in Section 4 the main results are given and discussed. Conclusions in Section 5 end the paper.

Investigation on the status quo of SES in China

Energy reserve status

According to BP (2020), primary energy is relatively rich in China, and the reserves of oil, natural gas, and coal are among the highest in the world. At the end of 2019, proved reserves of oil, natural gas, and coal in China ranked 14th, 6th, and 4th of the world total, respectively. As the population grows in China, energy exploration and mining technology improvement cannot meet the growing energy demand (Fang et al., 2018). From 1990 to 2005, the reserves-to-production (R/P) of oil in China dropped from 15 to 11, followed by a regrowing trend since 2006 and reached 18.7 in 2019. R/P of natural gas in China has shown a continuous downward trend since 1990 (65.3). In 2019 the ratio was 47.3, a decrease of 27.57% compared to 1990 but a slight increase due to shale gas production from 2015. Compared with oil and natural gas energy, China's coal resources are relatively prosperous. In 2019, the R/P of coal was 37, higher than oil and slightly lower than natural gas. However, compared to the world's R/P coal (132) ratio, coal in China is still meagre.

Energy supply

China has formed a relatively complete energy production and supply system, including coal, oil, natural gas, and renewable energy (hydropower, nuclear power, wind power, and solar power). According to the National Bureau of Statistics of China (NBS, 2021), the total primary energy production in China in 2019 was 3.97×10^9 tons of standard coal (tsc), an increase of 5% compared to the previous year (Figure 1(a)). In 2019, and raw coal production was 2.73×10^9 tsc, increased by 6% than 2018. Crude oil production was 2.74×10^8 tsc with a 1.5% increase compared to 2018. The output of natural gas was 2.34×10^8 tsc, which was 10% higher than in 2018. The interannual variation of different energy varieties was differentiated. For example, the total energy production experienced continuous growth until 2015 and then declined in 2016, then increased again in these recent years. In terms of different types, raw coal production declined in 2014, reached a lower value in 2016, and rebounded in the past three years. Crude oil production fell below 3×10^8 tsc from 2016 but increased slightly in 2019. Natural gas exploration and development continued to increase, and therefore, its total production has continued to increase. Hydropower, nuclear power, wind power and solar power were growing continuously during the observation period.

Energy consumption

According to the NBS (2021) preliminary statistics, the total energy consumption was 4.86×10^9 tsc in 2019, increasing 5% over the previous year. Among them, coal consumption accounted for 57.7% of total energy consumption, with a 2% increase compared to the previous year. Consumption of natural gas, hydropower, nuclear power, wind power, and solar power accounted for 23.4% of total energy consumption, increasing 10.9% compared to 2018. Since 2010, the total energy consumption has continued to rise, and in 2019 the total energy consumption increased by 41% compared with 2010. The proportion of coal consumption had a downward trend, with 72.7% in 2010 and falling to 57.7% in 2019. Nevertheless, it is still China's primary energy source in the short term (Figure 1(b)). Compared with other countries' primary energy consumption structure globally, coal has a prominent position in China's primary energy consumption structure (BP, 2020). The proportion of clean energy consumption (natural gas plus renewable energy) in total energy consumption increased from 9% in 2010 to 23.4% in 2019. From the energy efficiency perspective, China's energy consumption per 10,000 yuan of GDP in 2019 dropped by 2.6% compared to the previous year.

Energy trade and external dependence

In 2019, China imported 5.06×10^8 tons of crude oil and exported 8.1×10^5 tons, increasing 113% and -73% respectively compared with 2010, resulting in a continued increase of net imports. China imported 6.8×10^7 tons of natural gas (approximately 9.46×10^{10} cubic meters) in 2017, a year-on-year increase of 28.3% compared to 2010. At the same time, the export was 2.44×10^6 tons (about 3.5×10^9 cubic meters), down 1.7% year-on-year compared to 2010. So the dependence on natural gas continued to rise. China imported 2.9×10^8 tons of coal in 2019 with an increase of 83%, while coal exports dropped significantly by 68% compared to 2010.

According to the current status of domestic primary energy production and consumption and future development trends, the increasing dependence on energy imports poses a threat to the sustainable development of China's energy system.

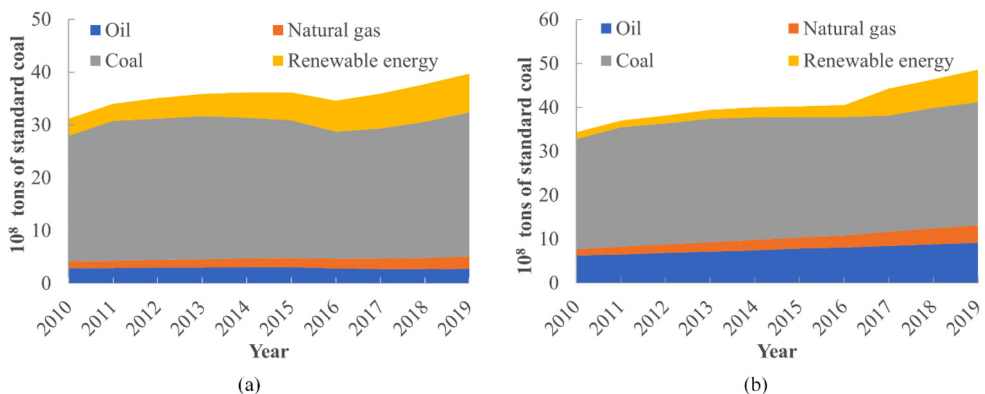


Figure 1. China's primary energy production and composition (a) and primary energy consumption and composition (b) from 2010 to 2019. Renewable energy includes hydropower, nuclear power, wind power and solar power.

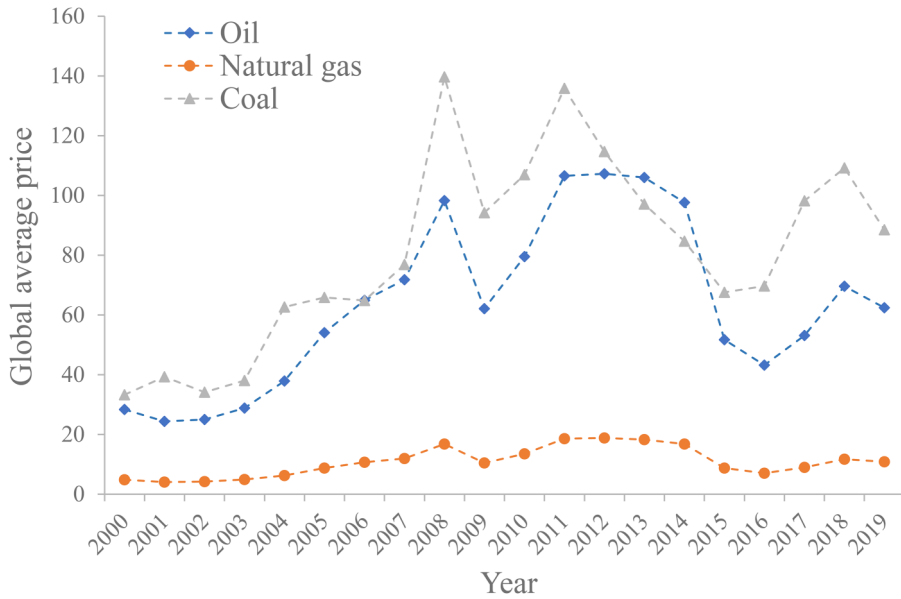


Figure 2. Global primary energy price. The unit for the spot price of oil in US dollars per barrel, natural gas in US dollars per million Btu, and coal in US dollars per ton. Global oil price is the average spot price of Dubai, Brent, Nigerian Forcados and West Texas Intermediate. Global natural gas price is the average price of the OECD. The global coal price is the average price of Northwestern Europe, the Appalachian spot coal price index in Central America, Japan steam spot CIF price, China Qinhuangdao spot price, and Japan coking coal import CIF and the Asian market price.

Energy prices

As shown in Figure 2, global crude oil price, natural gas price, and coal price illustrated momentum upward. Crude oil price rose from an average of 28.37 US dollars per barrel (US\$/ barrel) in 2000 (the average price of Dubai, Brent, Nigerian Forcados and West Texas Intermediate) to 62.4 US\$/ barrel in 2019, an average annual growth rate of 4%. The natural gas price represented by the OECD countries CIF price was increasing steadily, from 4.83 US dollars per million British thermal units (US\$/MBtu) in 2000 to 10.82 US\$/ MBtu in 2019, an increase of 124%. Global coal price rose from US\$33.24 per ton (t) in 2000 to 88.49 US\$/t in 2019. The rising energy prices is a full manifestation of the increasingly acute contradiction between energy supply and demand.

Environmental pressure

China's environmental protection pressure has gradually increased with the rapid growth of total energy consumption and the continuous increase of CO₂ emission (Yu et al., 2018a; Zhou et al., 2020). In 2010, China's total energy consumption was 3.12×10^9 tsc, and the total CO₂ emissions were about 8.47 billion tons (World Bank, 2021). Researchers predicted that carbon emissions would be peaked around 2022 to 2028 (Yu et al., 2018a; Yu et al., 2018b), with 11.21–11.56 Gt CO₂ (Yu et al., 2018a). Considering that 18 of the 20 most polluted cities globally are in China (Lozano Gracia and Soppelsa, 2019), premature deaths and diseases caused by air pollution threaten the realization of sustainable development.

Methodology

Constructing SES evaluation indexes

SES requires the overall consideration of economy, society, environment and energy security. Economic sustainability provides a solid foundation for the SES. Economic competitiveness improves sustainable energy use from “open source” and “cutting expenditure”. “Open source” requires to provide more capital and technology to ensure the sustainable development of energy from the perspective of enhancing supply capacity. “Cutting expenditure” requires improving energy efficiency and reducing energy intensity. Social sustainability manifests in the improvement of living standards and education levels. Environmental sustainability provides material and environmental support for the realization of an SES. It is an essential prerequisite for sustainable energy development. Energy security indicates the degree to which energy supply satisfies demand.

Combining with the status quo of sustainable energy development in China, we construct a comprehensive evaluation index system for China’s sustainable energy system (see Table 2), composed of a target layer, a dimension layer, and an indicator layer. The target to achieve SES in China is specified in the dimension layer, which is decomposed to economic, social, environmental, and national energy security. Nineteen indicators are given in the indicator layer, and they reflect the implementation effects of different dimensions in terms of quantity and degree of change. The definition, quantification, coding, and direction of each indicator are shown in Table 2.

Evaluating the sustainability of China’s energy system

We adopt the idea of combining objective and subjective empowerment to determine the weights of indexes. The entropy method (EM) is used to determine the weights of the indicators at the indicator layer, and the subjective methods (Analytic Hierarchy Process (AHP)) and the objective method (CRITIC method) are used to obtain the weights at the dimension level. The principle of Lagrangian extremum is then applied to weight the optimal combination.

Determining the weight of each index in the indicator layer. We use the EM to determine the weight of each index in the indicator layer. Due to different dimensions of the indicators, direct use of the original data produces misleading results. Therefore the original data is standardized according to Equation (1) and (2) for positive and negative indicators, respectively.

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

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

Where x'_{ij} is the indicator after dimensionless processing, $\max(x_{ij})$ and $\min(x_{ij})$ are the maximum and minimum values of the indicator x_{ij} , respectively. We add 1 to each standardized value to eliminate 0 among standardized indicators, as shown in Equation (3):

$$x^*_{ij} = 1 + x'_{ij} \quad (3)$$

Table 2. China's SES evaluation indexes and their weights by different methods.

Target	Dimension	Coding	Indicator	Direction	EM	AHP	CRITIC	AHP-CRITIC
SES in China	Economic sustainability	SES11	GDP per capita	+	0.065	0.172	0.162	0.170
		SES12	The proportion of tertiary industry	+	0.049			
		SES13	Energy export cost as a percentage of export value	+	0.055			
			SES14	Energy import cost as a percentage of import value	-	0.022		
		Social sustainability	SES15	Oil price	-	0.060		
			SES21	Engel coefficient	-	0.030	0.103	0.158
			SES22	Total dependency ratio	-	0.066		
			SES23	The proportion of education expenditure	+	0.042		
			SES24	Technological advances	+	0.072		
		Environmental sustainability	SES31	Carbon intensity	-	0.050	0.183	0.244
			SES32	Carbon emissions from electricity production	-	0.050		
			SES33	Percentage of forest area	+	0.055		
			SES34	Environmental taxes	+	0.074		
		Energy security	SES41	Oil reserve ratio	+	0.036	0.542	0.435
	SES42		Energy efficiency	+	0.042			
	SES43		Energy substitution	+	0.053			
	SES44		The proportion of renewable energy power generation	+	0.060			
		SES45	Per capita primary energy use	-	0.069			
		SES46	Share of net energy imports in total energy consumption	-	0.050			

Note: The sign "+" is a positive indicator, for which the higher value shows better SES. While "-" is a negative indicator whose impact on SES is negative with a higher value.

We then normalize the shifted data by Equation (4),

$$y_{ij} = \frac{x_{ij}^*}{\sum_{i=1}^n x_{ij}^*} \quad (4)$$

and calculate the information entropy and redundancy of the indicator j by Equation (5) and (6).

$$e_j = -\frac{1}{\ln n} \sum_{i=1}^n y_{ij} \ln y_{ij} \quad (5)$$

$$g_j = 1 - e_j \quad (6)$$

Finally, the weight of each indicator is determined as in Equation (7).

$$w_j = \frac{g_j}{\sum_{j=1}^m g_j} \quad (7)$$

Calculating the weight of each dimensional layer element. We use a subjective method AHP and an objective method CRITIC, to obtain weights of dimension-level indicators. The results from these two methods are then combined from the below-mentioned process.

Firstly, from the normalized matrix $(Y(y_{ij}))_{mn}$ of the indicator layer, we construct the n^{th} order non-negative positive definite matrix $(Z(g_{ij}))_{mn}$.

Secondly, reorganize the objective weight ω_1 from the CRITIC method with the subjective weight ω_2 from the AHP method to obtain the weight matrix $W(\omega_1, \omega_2)^T$. Calculate the second-order symmetric matrix H from matrix Z and matrix W by Equation (8):

$$H = W^T Z W \quad (8)$$

Thirdly, calculate the maximum eigenvalue λ_{\max} of the symmetric matrix H and the vector-matrix M by the normalization of the corresponding eigenvectors, and use Equation (9) to obtain the weight matrix ω^* of the optimal combination weighting method.

$$\omega^* = W^T M \quad (9)$$

Finally, using the weight of each indicator at the dimension level and indicator level, we calculate the weighted average of all indicators to get the score of China's SES for each year.

Analyzing the influence of exogenous factors on SES

The exogenous factors affecting the SES are independent of the SES evaluation indicators. Therefore, exogenous factors do not directly affect the availability of SES. We mainly focus on three variables: urbanization, foreign direct investment (*FDI*), and industrialization to study their external impact on the SES. The salient feature of urbanization is the shift of population from rural to urban areas, resulting in a decrease in the number of people employed in agriculture, while an increase in the number of employees in the secondary and tertiary industries. This continuously expands economic activities, so as energy consumption. On the other hand, urbanization changes people's lifestyles, which positively contributes to energy efficiency. Therefore, we propose two hypotheses:

H1a: The progress of urbanization has a positive contribution to China's SES.

H1b: The progress of urbanization slows the improvement towards China's SES

Since 2001, China has gradually integrated into the international industrial transfer system. By 2018, China ranked the second among countries (regions) in attracting foreign investment in the world, attracting US\$138.1 billion in foreign investment, a year-on-year increase of 1.5% (MOC, 2019). The process of undertaking industrial transfer increases energy consumption, which may negatively impact social and environmental development (Iamsiraroj and Ulubaşoğlu, 2015; Reiter and Steensma, 2010), thereby affecting sustainable energy system. On the other hand, however, FDI positively affects technology upgrading and job creation (Asiedu, 2006; Hans Martin and Anguelov, 2018), which promote the SES. So *FDI* is considered to play an essential role in the sustainable development of developing countries (Aust et al., 2020), and we assume that:

H2: FDI contributes to the sustainable development of China's ES.

China is at the peak of industrialization, with invested mountains of energy (Liu and Bae, 2018). Although the proportion of high-energy-consuming industries has reduced due to adjustment of China's industrial structure in recent years, the industrial sector still accounts for a large proportion of the industrial structure (Lin and Zhu, 2017), so the decline in energy consumption will be in the short term not apparent. So we assume that

H3: Industrialization hinders SES in China.

We use the ratio of urban population to total population to quantify urbanization, denoted by *UR*. *FDI* stands for foreign direct investment, and the ratio of manufacturing output value to GDP quantified the level of industrialization, expressed by *IND*. When evaluating the exogenous factors affecting China's SES, we expand China's SES value calculated by the evaluation index system by 100 times to make the dimensions of each variable consistent, and use their logarithmic value for analysis. The descriptive statistics of all variables are in Table 3.

Existing studies focusing on the relationship of multiple time series variables mostly use vector auto regression (VAR) and vector error correction model (VECM) models. These two models require time series to be single integers of the same order. We analyze the impact of *UR*, *FDI*, and *IND* on SES in China using the autoregressive distributed lag (ARDL) model. Compared with the traditional cointegration model, the ADRL model has the following advantages: firstly, it does not require strict stationarity of the sequence, and does not require that all variables have the same single integer order; secondly, it does not test by the method of the simultaneous equation, and the dynamic error model derived from the ARDL method integrates both short-term dynamics and long-term equilibrium information; finally, ARDL model is suitable for sample estimation with a smaller volume.

We assume that *UR*, *FDI* and *IND* have a long-term equilibrium relationship with China's SES, as shown in Equation (10)

$$\ln SES = \alpha_0 + \alpha_1 \ln UR_t + \alpha_2 \ln FDI_t + \alpha_3 \ln IND_t + \varepsilon_t \quad (10)$$

Where ε_t is for random error, $\alpha_1, \alpha_2, \alpha_3$ is the long-term elasticity of the impact of *UR*, *FDI*, and *IND* on the *SES*, respectively.

According to Equation (10), the dynamic unrestricted error correction model (UECM), shown in Equation (11), can be derived from the ARDL model,

$$\begin{aligned} \Delta \ln SES_t = & \beta_0 + \beta_1 \Delta \ln UR_t + \beta_2 \Delta \ln FDI_t + \beta_3 \Delta \ln IND_t + \sum_{i=1}^p \gamma_i \ln SES_{t-i} \\ & + \sum_{j=0}^q \delta_j \ln UR_{t-j} + \sum_{k=0}^r \theta_k \ln FDI_{t-k} + \sum_{l=0}^s \vartheta_l \ln IND_{t-l} + \mu_t. \end{aligned} \quad (11)$$

where Δ is the first-order difference of the sequence, which is an independently distributed residual item. Perform the F-test on the UECM to determine whether there is a long-term equilibrium relationship between variables.

After determining the long-term equilibrium relationship between UR , FDI , and IND and SES , the ARDL(p, q, r, s) model is used to construct this relationship using Equation (12):

$$\ln SES = \rho_0 + \sum_{i=1}^p \rho_i \ln SES_{t-i} + \sum_{j=0}^q \rho_j \ln UR_{t-j} + \sum_{k=0}^r \rho_k \ln FDI_{t-k} + \sum_{l=0}^s \rho_l \ln IND_{t-l} + \tau_t \quad (12)$$

Equation (13) is transformed into a long-term relationship:

$$\ln SES_t = \delta_0 + \delta_1 \ln UR_t + \delta_2 \ln FDI_t + \delta_3 \ln IND_t + v_t \quad (13)$$

In reality, due to various reasons, the short term may deviate from the long-term equilibrium track. Based on ARDL (p, q, r, s), an error correction model (ECM), shown in Equation (14), is constructed to analyze the short-term dynamic changes of variables,

$$\begin{aligned} \Delta \ln SES_t = & \emptyset_0 + \sum_{i=1}^{p-1} \emptyset_i \Delta \ln SES_{t-i} + \sum_{j=0}^{q-1} \emptyset_j \Delta \ln UR_{t-j} + \sum_{k=0}^{r-1} \emptyset_k \Delta \ln FDI_{t-k} \\ & + \sum_{s=0}^{s-1} \emptyset_s \Delta \ln IND_{t-s} + ECM(-1) + \tau_t. \end{aligned} \quad (14)$$

Among them, $ECM(-1)$ is for the error. When the long-term equilibrium relationship deviates, the error can play a callback role. The $ECM(-1)$ coefficient represents the correction error's speed to the model callback, and it is generally a negative number. After the ARDL model is constructed, the cumulative sum of recursive residuals (CUSUM) and the cumulative sum of squared recursive residuals (CUSUMSQ) are for the stability test of parameters in the model.

Main results

Weights of indicators

The index weights obtained from the EM-AHP-CRITIC method are shown in Table 2. Arranged the values obtained by EM method, top five indicators are environmental taxes ($SES34$), technological advances ($SES24$), per capita primary energy use ($SES45$), Total dependency ratio ($SES22$) and GDP per capita ($SES11$), and two of which belong to the social sustainability dimension, another three are, respectively, for the environmental sustainability dimension, energy security and economic sustainability dimension.

The ranking in the dimensional level obtained by the AHP method shows that energy security contributes the greatest to SES in China, and the weights of the energy security dimension (0.542)

Table 3. Descriptive statistics for all variables in the ARDL model.

Statistics	<i>lnSES</i>	<i>lnUR</i>	<i>lnFDI</i>	<i>lnIND</i>
Average	3.677	3.01	6.577	3.799
Median	3.670	3.732	6.803	3.820
Max	3.766	4.087	7.336	3.863
Minimum	3.623	3.274	4.189	3.679
Standard deviation	0.039	0.239	0.743	0.058
Skewness	0.835	-0.178	-1.865	-0.985
Kurtosis	2.947	1.665	5.976	2.583

are much greater than the value of the environmental sustainability dimension (0.183), and the economic sustainability (0.172), while the social sustainability dimension (0.103) has the smallest weight. The values obtained by the CRITIC method are different from the AHP method (see column 8 of Table 2). However, the weights of dimensions in descending order obtained by the two methods show no difference: energy security, environmental sustainability, economic sustainability, and social sustainability. The different weights values indicate the importance of the combination of subjective and objective empowerment methods. The Lagrangian extreme value optimization method (see column 9 of Table 2) balances the values of the weights when the subjective weighting method or the objective weighting method is used alone.

Results for China's SES

Based on the above-identified EM-AHP-CRITIC method, the results of China's SES are shown in Figure 3. Since 1990, the score of China's SES showed an upward but fluctuated trend till 2007. After 2008, the score increased significantly due to the improvement of the energy security dimension. The value of the environmental sustainability dimension did not fluctuate significantly, while the score of the social sustainability dimension continued to grow from 1990 to 2018. The energy security dimension declined from 2001 to 2005 and increased after 2006. The values in the economic sustainability dimension increased before in 2017 and slightly decreased after that. In general, the contribution of the energy security dimension is the highest

In the economic sustainability dimension (see in Figure 4(a)), the indicator *SES11* contributed the most. The value of this indicator increased, which indicated that the increase in per capita income significantly improved the sustainability of China's ES. The contribution of the indicator *SES14* was the smallest and with a downward trend, reflecting the reduced impact of energy import costs on economic sustainability. The indicator *SES15*'s contribution to the dimension of economic sustainability fluctuated the most. From 1990 to 2000, *SES15* had a relatively high contribution to the economic dimension, but after 2001, it fluctuated. The contribution rates of the indicators *SES12* and *SES13* to the economic sustainability dimension showed a small range of fluctuations.

In the social sustainability dimension (see Figure 4(b)), the contribution of the indicator *SES23* showed a downward trend, from a contribution rate of 32.9% in 1990 to 12.7% in 2018. On the other hand, the contribution rate of the indicator *SES24* increased, with an increase of 44.1% in 2018 compared to 1990, indicating that technological progress played an increasingly important role in social sustainability. Change of indicator *SES22*'s contribution to the social sustainability dimension was similar to *SES24*. The contribution of indicator *SES21* to the social sustainability dimension was stable.

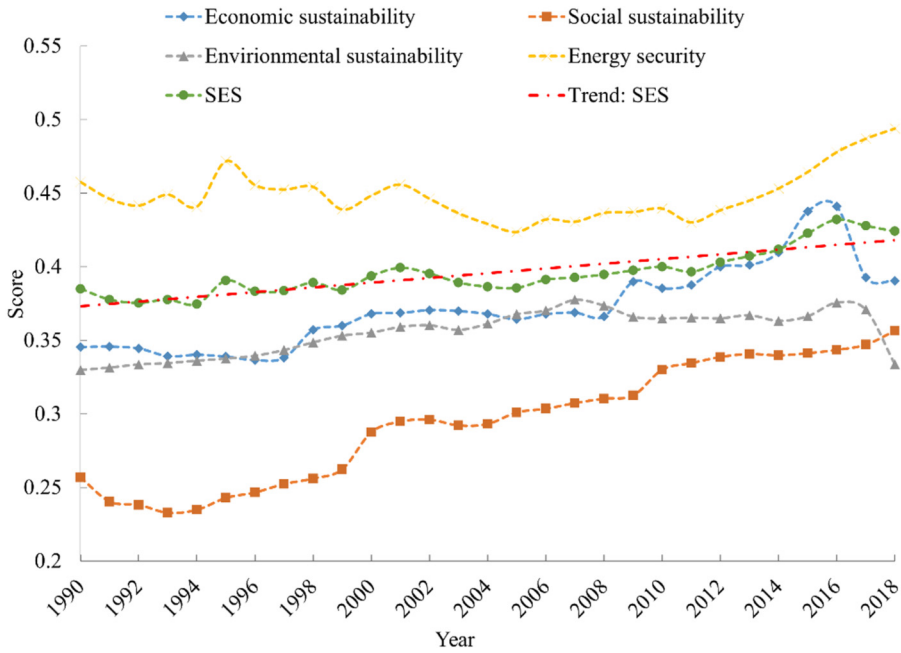


Figure 3. The scores of China's SES and its four dimensions from 1990 to 2018.

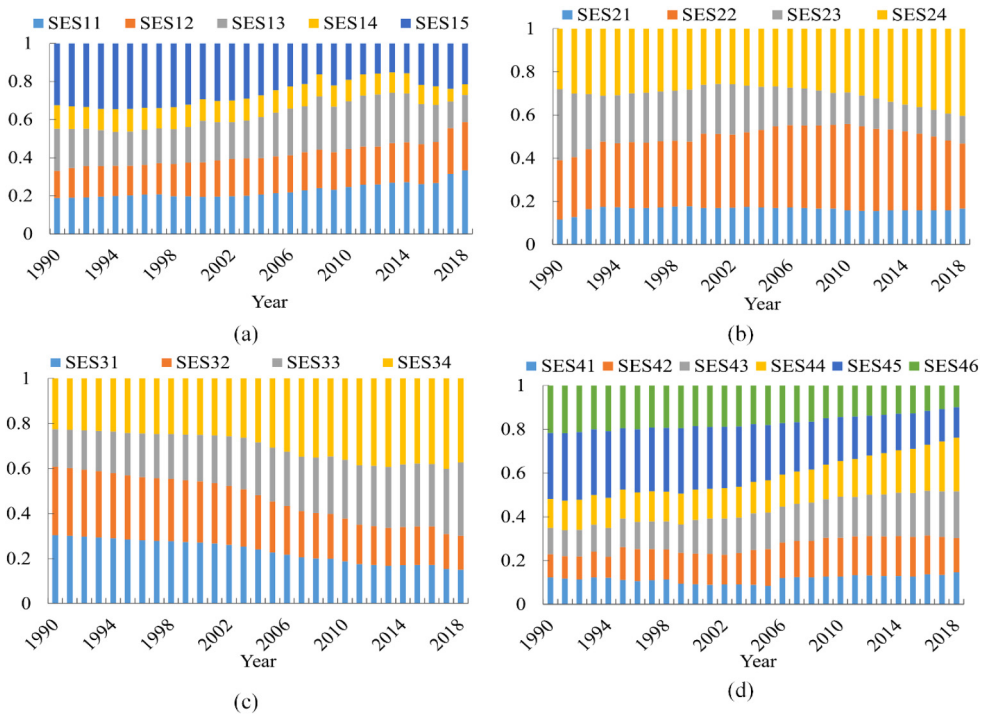


Figure 4. Inter-annual change in the contribution rate of each indicator in different dimensions.

In the dimension of environmental sustainability (Figure 4(c)), the contribution of indicator *SES34* increased the most, with an increase of 1.7% between 1990 and 2018. The contribution of indicators *SES31* and *SES32* showed a downward trend, but indicator *SES33* increased.

In the dimension of national energy security (see Figure 4(d)), the contribution of indicator *SES45* illustrated a downward trend, dropping from 30.2% in 1990 to 14% in 2018. Contributions of both indicators *SES44* and *SES43* showed trends upward. In 2018, the contribution of indicator *SES44* was as high as 24.5%. The contribution of indicator *SES42* was stable.

Exogenous factors of China's SES

We performed the DF-GLS unit root test as shown in Table 4. The original sequence of *lnFDI* was significant at a 10% significance level, and was the stationary sequence $I(0)$. *lnSES*, *lnUR*, and *lnIND* were not stationary series, but their first-order difference series were significant at a 10% significance level, and they were all first-order single integers. We selected the maximum lag order third-order and used the ARDL model for the marginal cointegration test. Each variable in the model rejected the null hypothesis at the 10% significance level, indicating that *lnSES*, *lnUR*, *lnFDI* and *lnIND* had a long-term cointegration equilibrium relationship. Therefore we studied the impact of *UR*, *FDI* and *IND* on China's SES.

According to the principle of minimum standard deviation, a model that does not contain a trend term was selected to estimate ARDL (3,0,2,1) in both the long and short term. The results were in Table 5. In the long run, *FDI* and *IND* significantly affected China's SES in opposite directions, while *UR* had a positive but insignificant impact on SES. Therefore, we rejected H1a and H1b; that was, the increase of *UR* in China in the long term did not significantly impact SES. We accepted the original hypothesis H2 because the coefficient of SES and *FDI* was positive at a 5% significant level, indicating that the long-term FDI improved China's energy sustainability. While studies from Ahmad and Du (2017) and Graham and Krugman (1995) believed that FDI had a minor role in the economic growth of a country, neither to the sustainable energy system. Mwilima (2003) and Kumar and Pradhan (2002) were in line with our result that FDI contributed to SES by stimulating economic growth. One possible explanation was that the Chinese government strictly guided the industries that FDI can enter in China. The introduction of FDI can effectively avoid monopoly and improve the energy efficiency of regulated industries, resulting in an improved SES.

Contrary to the effects of *FDI*, *IND* decreased China's SES for a long time at 1% significance, showing the reverse relationship between the secondary industry and SES development. Comparing the absolute values of the coefficients of *IND* and *FDI* on SES, which was 0.389 and 0.03 respectively, we found that the domestic industrial structure had a much more significant effect on China's

Table 4. DF-GLS unit root test results.

Variable	T statistics	First-order difference variable	T statistics
<i>lnSES</i>	-0.293	$\Delta lnSES$	-4.542***
<i>lnUR</i>	-1.437	$\Delta lnUR$	-1.791*
<i>lnFDI</i>	-1.616*	$\Delta lnFDI$	-4.932***
<i>lnIND</i>	-1.383	$\Delta lnIND$	-3.008***
Inspection form		F statistics	P-value
Trending item		$F(4) = 8.463$	0.008***

*** means significant at the 1% level; ** means significant at the 5% level; * means significant at the 10% level.

Table 5. Parameter estimation of ARDL model.

For long-run:			
Variable	Coefficient	Standard deviation	T value
<i>lnUR</i>	0.005	0.059	0.820
<i>lnFDI</i>	0.030	0.040	3.247**
<i>lnIND</i>	-0.389	0.023	-16.334***
TREND	2.149	0.002	46.303***
C	0.005	0.246	0.820
For short-run:			
Variable	Coefficient	Standard deviation	T value
Δ <i>lnSES</i>	0.512	0.196	2.607**
Δ <i>lnUR</i>	0.008	0.036	0.229
Δ <i>lnFDI</i>	0.064	0.021	3.091***
Δ <i>lnIND</i>	-0.478	0.102	-4.647***
ECM(-1)	-1.803	0.280	-6.447***

*** means significant at the 1% level; ** means significant at the 5% level; * means significant at the 10% level.

SES than *FDI*. This aligns with the states that domestic firms better understand the domestic market than *FDI* (Graham and Krugman, 1995).

The coefficient estimation results of the short-term ECM model showed that UR coefficients had a positive but insignificant impact on China's SES, while *FDI* and *IND* both had significant influence, from the positive and negative direction, respectively. The error correction coefficient was -1.803 at a 1% significance level. The absolute value of the error correction term reflected the speed of the adjustment towards the long-run equilibrium.

Robustness test

To ensure the robustness of our results, we tested the stability of the ARDL model. Here we chose the CUSUM and CUSUMSQ to test the stability of the model, and the results were shown in Figure 5. The red and green solid lines in Figure 5 represented the upper and lower bounds at a 5% significance level. The fluctuation values of CUSUM and CUSUMSQ were shown as the solid blue line. Thus, the constructed ARDL (1,1,0,1) model coefficients were stable at the 5% significance level.

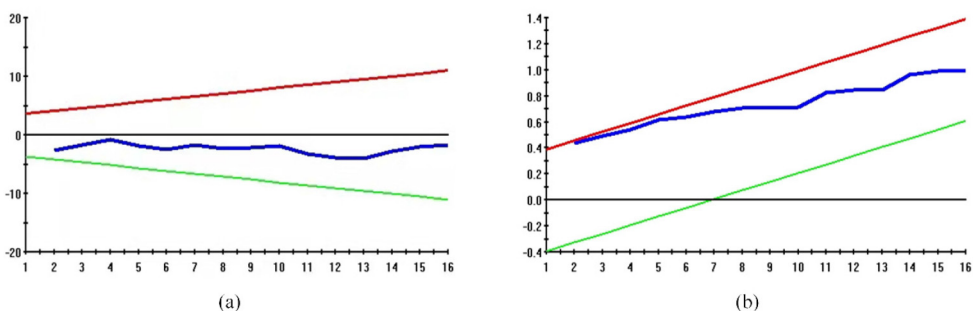


Figure 5. Results for recursive cumulative sum of residuals (CUSUM) (a) and recursive cumulative sum of squared residuals (CUSUMSQ) test (b).

Conclusions

This Paper analysed the endogenous and exogenous factors of SES for China. First, we evaluated China's SES situation from the aggregated economic, social, environmental, and energy security dimensions with 19 endogenous factors using the EM-AHP-CRITIC model from 1990 to 2018. China's SES showed a significant upward trend since 1990, which was mainly due to the improved energy security. Energy structure adjustment plays a crucial role in realising China's SES because energy security is related to the transition to low-carbon energy, such as renewable energy generation. And then, the ARDL-ECM model was used to analyze the long-run and short-run impact of urbanization, foreign direct investment and industrialization on China's SES. The results of the ARDL-ECM model indicated urbanization in China in the long term and short-run had positively related to SES, but not statistically significant. On the other hand, the foreign direct investment did well to China's SES, which might be related to China's introduction of foreign investment has improved the energy efficiency of relevant industries. On the other hand, the over-reliance of the national economy on the secondary industry worsen China's SES, as illustrated by the significant negative effect of industrialization on China's SES. In addition, the absolute value of the impact of industrialization and foreign direct investment on China's SES showed that the domestic industrial structure had a much more significant effect on China's SES than foreign direct investment.

We believed that evaluating the factors affecting the sustainability of China's energy system can provide theoretical support for the formulation of energy development plans and the implementation of carbon emission reduction policies for China and other countries. The above results implied that the development dividends brought by urbanization could not significantly promote the sustainable use of energy. Future policies should focus on improving people's lifestyles and advocating low-carbon life. China has become the world's second-largest recipient of foreign direct investment. Since the adjustment of the domestic industrial structure has a significantly higher increase in China's SES than that of foreign direct investment, the Chinese government should continuously optimize its industrial layout to control the total energy consumption through production, trade, transportation, and consumption, and improve energy conservation and energy use efficiency to adjust the energy consumption structure. While from the supply side, China must rely on technological progress to accelerate renewable energy development such as solar, wind, and biomass energy, aiming to promote the diversification of energy production structures and ultimately establish China's sustainable energy structure.

Considering the regional differences in China, one potential research direction of our manuscript is to compare the sustainability of energy systems at different development levels in China from the perspective of Chinese urban agglomerations or east, middle and west regions. Another way is by combining IPAT decomposition methods to focus on the influence mechanism of exogenous factors on China's SES.

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Supplemental material

Supplemental material for this article is available online.

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