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Comparing the Substitution of Nuclear Energy or Renewable Energy for Fossil Fuels between the United States and Africa

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Abstract: This study explores the differences in energy consumption between the highly economically developed United States and economically underdeveloped Africa. This study conducted the parameter estimation and equilibrium analysis of a Lotka–Volterra model to investigate the short-term and long-term relations of different types of energy, respectively. The parameter estimation results show that nuclear energy consumption increases the consumption of fossil fuels in the United States but decreases fossil fuel consumption in Africa. This implies that Africa can replace fossil fuels with nuclear energy in the short run. Given the current state of energy consumption, the results of the equilibrium analysis indicate that the United States' nuclear and fossil fuel consumption will reach a stable long-term equilibrium. However, Africa will experience significant fluctuations in nuclear and fossil fuel consumption, and both nuclear and fossil fuel consumption will eventually be depleted. The highly economically developed United States arranges energy consumption in an environmentally friendly way and reshapes economies to achieve sustainability, so its long-term energy consumption is more stable than economically underdeveloped Africa. Accuracy analysis results show that the nuclear or renewable energy consumption predicted by the Lotka–Volterra model is more accurate than that of a Bass model since the Lotka–Volterra model considers energy interactions.

Keywords: renewable energy; nuclear energy; Africa; developing countries; predictive ability

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1. Introduction

The environmental Kuznets curve indicates that environmental protection decreases with economic growth under a certain national income level, while environmental protection conversely increases with economic growth as the national income accumulates over a certain level. From the perspective of the environmental Kuznets curve, at early stages of economic development, the economy is prioritized over environmental protection, but as the economy develops, environmental protection is prioritized over the economy to a certain extent [1–3]. To examine the environmental Kuznets curve, this work focuses on the highly economically developed United States and economically underdeveloped Africa. We explore whether the United States practices environmental protection by means of the proper design of energy circularity and whether Africa ignores environmental deterioration to consume energy for the purpose of economic development. For the first time, this study examined differences in the short-term and long-term relationships between fossil fuels and nuclear energy and the relationship between fossil fuels and renewable energy in developing and developed countries using a Lotka–Volterra model since the parameter estimation and equilibrium analysis of the Lotka–Volterra model can be used to elucidate short-term and long-term energy relationships [4].

Global carbon emissions have been increasing along with the expansion of the economy. Since 1980, the concentration of carbon dioxide in the atmosphere has gradually risen [5]. Many countries have become aware of this serious issue. A study conducted on 29 OECD countries from 1992 to 2018 investigated the impact of carbon emissions and the process of reducing them [6]. The study found that the carbon intensity of OECD countries showed a declining trend, but the convergence was slow. The main factors contributing to this trend were economic development, energy structure, and energy efficiency [6]. Among these factors, energy efficiency was found to be the most important. To transition into a low-carbon economy, the deep decarbonization of an energy system, including improving the utilization of non-fossil energy and developing renewable energy sources, is required [6]. The proper implementation of a low-carbon economy is necessary to ensure economic growth while maintaining the use of carbon dioxide [7]. Previous studies on global warming and abnormal climate phenomena found that the energy used for electricity generation results in carbon dioxide (CO_2) emissions and greenhouse effects [8–10]. To slow down CO_2 emissions and generate cleaner electricity, previous studies have suggested the usage of clean energy to replace fossil fuels [11–13]. Previous studies have regarded nuclear energy or renewable energy as clean energy that can be used to generate electricity and have proposed using clean energy to replace fossil fuels. Both BRICS countries (including the Federative Republic of Brazil, the Russian Federation, the Republic of India, the People's Republic of China, and the Republic of South Africa) and developed European nations have made resolute decisions to explore alternatives and trends in the new energy market in order to develop low-carbon economies [14–16]. Nguyena et al. [17] described the goals and potentials of renewable energy development in Vietnam. Hoang et al. [18] illustrated that the COVID-19 pandemic has accelerated development policies of renewable energy infrastructure to provide sustainable resources of power generation. However, the key factors determining the new energy market are capital and technology, and the development trends of different types of new energy sources, such as biomass energy, tidal energy, hydrogen energy, geothermal energy, nuclear energy, solar energy, and wind energy, vary among countries [19]. These trends also reflect the significant differences in substitutability within the new energy market among various countries [14]. Currently, nuclear energy, solar energy, wind energy, and biomass energy have become the most widely used and consumed new energy sources [20–22]. For this reason, this study explores the impact of nuclear energy or renewable energy on fossil fuel consumption.

The electricity generated by nuclear power plants does not require fossil fuels and does not produce CO_2 during its power generation process, so nuclear energy is considered to produce zero CO_2 emissions [23–25]. In contrast, previous studies have argued that the entire lifecycle of a nuclear power plant wastes a large amount of electricity [26–29]. At first, raw uranium materials are explored, enriched, transformed, and transported to nuclear power plants. Then, the radioactive waste from nuclear electricity generation needs to be treated, solidified, and buried. Finally, nuclear power plants need to be decommissioned. These studies explained why the whole life cycle of nuclear energy needs to consume great amounts of fossil fuels. Furthermore, some scholars have debated the idea that nuclear energy decreases the consumption of fossil fuels, with studies indicating the radiation risks of nuclear energy [30–32]. Bowen et al. [33] studied the price decline of the United States' energy stocks after the Three Mile Island incident. Fields and Janjigian [34] indicated abnormal negative returns of the United States' energy stocks after the Chernobyl accident and found that the stock price of nuclear energy declined. To resolve arguments about the relations between fossil fuels and nuclear energy, this work was intended to examine the short-term nuclear energy substitution of fossil fuels using the parameter estimation of the Lotka–Volterra model.

Additionally, previous research has discussed the feasibility of using renewable energy to replace fossil fuels. Betzer et al. [35] showed that after the Fukushima disaster, non-renewable energy stocks slightly declined but renewable energy stocks increased by more than 20%. Investors regard renewable energy as an alternative to nuclear energy and have purchased a large number of renewable energy stocks, leading to a substantial price rise for renewable stocks. Ferstl et al. [36] interpreted the impact of the 311 earthquakes on energy stocks in Japan, the United States, France, and Germany. After the nuclear disaster triggered by the Great East Japan Earthquake, these countries have been accelerating the use of renewable energy and implementing electricity tariff systems. Consequently, the stock prices of renewable energy have increased. Academic fields have long paid attention to the renewable power infrastructure that the United States has developed. Due to the lack of utility grids and a large power infrastructure in Africa, renewable energy for small-scale, decentralized installations is an appropriate power solution. Compared with the traditional large-scale power plants that need to build high-voltage transmission lines, the construction costs required for renewable energy may be relatively small, which could lead to the construction of solar and wind power plants to engage in electricity generation in Africa. Since Africa has the aforementioned features, the academic field has gradually been paying attention to the replacement of fossil fuels with nuclear and renewable energy. Thus, the second purpose of this paper was to examine the substitution of renewable energy for fossil fuels using the parameter estimation of the Lotka–Volterra model.

The third purpose of this study was to utilize equilibrium analyses of the Lotka–Volterra model to examine differences in the long-term trajectories of different energy resources between the United States and Africa. Chen and Pao [15] emphasized that economic growth can enhance a circular economy, under which energy and resources are recycled in an environmentally friendly way to reshape economies to achieve energy sustainability. Pao and Chen [16] found evidence that a circular economy would use recyclable raw materials and reduce CO_2 emissions in the European Union. The highly economically developed United States has the knowledge and technology to reshape economies to achieve energy sustainability, and long-term energy consumption is likely to be stable under the advanced arrangement of a circular economy. In Africa, however, the proportion of nuclear energy consumption is much lower than that of fossil fuels. Currently, South Africa has the only two nuclear reactors in the African continent, though about 20% of the world's uranium reserves are in Africa. With growing electricity demands, economically underdeveloped Africa tends to consume nuclear energy and fossil fuels to generate electricity without the advanced design of a circular economy. For this reason, the third purpose of this work was to compare differences in the long-term energy consumption trajectories of the United States and Africa.

Historical data on annual energy consumption from 1965 to 2021 were collected and applied to our proposed binary Lotka–Volterra model. By utilizing the Lotka–Volterra model to determine the relationship between fossil fuels, nuclear energy, and renewable energy, the impact factors across different types of energy sources were identified via the statistical significance of the estimated parameters. The equilibrium stability between two types of energy was also analyzed with the estimated parameters, assuming that energy technology does not change in the future. Additionally, a Bass model was constructed in our study to examine whether our Lotka–Volterra model could outperform it because the Bass model ignores interactive competitive or cooperative effects [37–39]. We were motivated to prove whether our proposed Lotka–Volterra model could more accurately predict energy consumption than the Bass model. The results of the equilibrium analysis showed that long-term energy consumption was predicted to be more stable in the United States than in Africa. This suggests that the United States, with its high level of national income, applies the circular economy concept to energy consumption in contrast to Africa, which does not, consistent with the environmental Kuznets curve. Our accuracy analysis results showed that nuclear or renewable energy consumption predicted by the Lotka–Volterra model is more accurate than that of the Bass model since the Lotka–Volterra model considers energy interactions.

2. Methodology

2.1. Lotka–Volterra Model of Energy Consumption

The Lotka–Volterra model considers the interaction between two species [40,41]. In this work, the consumption relationship analysis of the two different types of energy was divided into two pairs. The first pair consisted of fossil fuels and nuclear energy, and the second pair comprised fossil fuels and renewable energy. These paired Lotka–

Volterra model analyses were applied to different regions, the United States and Africa, via differential Equations (1) and (2), respectively, for each pair.

$$\frac{\mathrm{d}X_1}{\mathrm{dt}} = (a_1 - b_1X_1 - c_1X_2)X_1 = a_1X_1 - b_1X_1^2 - c_1X_1X_2 \tag{1}$$

and

$$\frac{\mathrm{d}X_2}{\mathrm{dt}} = (a_2 - b_2X_2 - c_2X_1)X_2 = a_2X_2 - b_2X_2^2 - c_2X_2X_1 \tag{2}$$

where $X_1 \geq 0$ and $X_2 \geq 0$; X_1 and X_2 represent the annual consumption of different energy types; $\frac{\mathrm{d}X_1}{\mathrm{dt}}$ and $\frac{\mathrm{d}X_2}{\mathrm{dt}}$ represent annual energy growth rates; X_1^2 and X_2^2 represent increasing and decreasing tendencies of energy growth, respectively; and X_1X_2 and X_2X_1 denote interactions with each other. Parameter a_i denotes the impact of ith energy on ith energy growth. Parameter b_i denotes the acceleration of the impact of ith energy on ith energy growth. If parameter b_i is positive, the impact of ith energy on ith energy growth decreases with time. Parameter c_i denotes the impact of the other energy source on energy growth, which indicates the substitution of a different energy source. Parameter c_i in the Lotka–Volterra model is used to analyze the interactions between different energy sources.

Since the Lotka–Volterra equation is a continuous model that could not fit our sample data, this work converted the equation into a discrete-time version [26,42]. The discrete-time formats of Equations (1) and (2) are denoted as Equations (3) and (4), respectively.

$$X_1(t+1) = \frac{\alpha_1X_1(t)}{1 + \beta_1X_1(t) + \gamma_1X_2(t)} \tag{3}$$

and

$$X_2(t+1) = \frac{\alpha_2X_2(t)}{1 + \beta_2X_2(t) + \gamma_2X_1(t)} \tag{4}$$

where α_i, β_i and γ_i are the coefficients. The coefficients in continuous Lotka–Volterra Equations (1) and (2) can be calculated through discrete-time Lotka–Volterra Equations (3) and (4) using the following Equations (5) to (7).

$$a_i = ln\alpha_i \tag{5}$$

$$b_i = \frac{\beta_i\alpha_i}{\alpha_i - 1} = \frac{\beta_i ln\alpha_i}{\alpha_i - 1} \tag{6}$$

$$c_i = \gamma_i\frac{b_i}{\beta_i} = \frac{\gamma_i}{\beta_i}\frac{\beta_i ln\alpha_i}{\alpha_i - 1} = \frac{\gamma_i ln\alpha_i}{\alpha_i - 1} \tag{7}$$

The sign of γ_i in Equation (7) is the same as c_i because $\frac{\ln\alpha_i}{\alpha_i - 1}$ is always positive when $\alpha_i \neq 1$. The sign of γ_i expresses the marginal effect of one energy source on another energy source. The sign of β_i in Equation (7) is the same as b_i because $\frac{\ln\alpha_i}{\alpha_i - 1}$ is always positive when $\alpha_i \neq 1$. Through the sign and statistical significance of γ_i, we can judge how nuclear and renewable energy consumption affect fossil fuels. This work examined the energy consumption relationships in the United States and Africa by repeating the simulations from Equations (1) to (7), in which X_1 represents the annual consumption of fossil fuels and X_2 represents the annual consumption of nuclear and renewable energy in the first and second pairs, respectively.

2.2. Equilibrium Stability Analysis

When reaching equilibrium points, trajectories do not change over time. Lotka–Volterra model Equations (1) and (2) are equal to zero when the equilibrium stability described by Equation (8) is reached.

$$\frac{dX_1}{dt} = 0,\ and\ \frac{dX_2}{dt} = 0 \tag{8}$$

Solving Equation (8) yields four equilibrium points—(X_1, X_2) = (0, 0), ($\frac{a_1}{b_1}$, 0), and (0, $\frac{a_2}{b_2}$)—and the cross points of the two lines—$\frac{dX_1}{dt} = 0$ and $\frac{dX_2}{dt} = 0$—as shown in Equation (9):

$$X_1 = \frac{a_1 - c_1 X_2}{b_1}, \quad and\ X_2 = \frac{a_2 - c_2 X_1}{b_2} \tag{9}$$

This shows that the consumption trends of two energy types reach stable states and do not change over time. Next, this work utilized the eigenvalues of a Jacobian matrix to examine equilibrium stability. The negative real parts of a Jacobian matrix were required to prove the equilibrium stability of our Lotka–Volterra equations. Additionally, this work chose Lyapunov functions to examine equilibrium stability. Positive Lyapunov functions and the negative first differentials of Lyapunov functions were required to prove the equilibrium stability of our Lotka–Volterra equations.

2.3. Predictive Ability Analysis

This work constructed the Bass model [43] expressed as Equation (10) for comparison with the Lotka–Volterra model in order to demonstrate forecast performance.

$$\frac{dX_i}{dt} = (g_{Xi} + h_{Xi} X_i)(m_{Xi} - X_i) \tag{10}$$

Given that X_i is consumption at year t, we estimated g_{Xi}, h_{Xi}, and m_{Xi}. Parameter m_{Xi} is defined as the maximum size of this energy consumption. This work estimated all the parameters in the Bass and Lotka–Volterra models from training sample data ranging from 1965 to 2014 and calculated the forecast values during the test period from 2015 to 2021.

The mean absolute percentage error (MAPE) was utilized to measure the predictive ability of the Lotka–Volterra model. The MAPE can be calculated by $MAPE = \frac{1}{n}\sum_{t=1}^{n} \frac{|Z_t - \hat{z}_t|}{Z_t}$, where Z_t and $\hat{z}_t$ are the actual and predicted values, respectively, of energy consumption. According to Martin and Witt [44], the predictive ability of a model is "excellent" when the MAPE is smaller than 10%, the predictive ability is "good" when the MAPE is between 10% and 20%, and the predictive ability is "reasonable" when the MAPE is between 20% and 50%.

3. Sample and Data

In 2017, the consumption of fossil fuels in the United States and Africa accounted for 16.18% and 3.56% of the total world energy use, respectively. In the United States, fossil fuels accounted for 82.25%, while nuclear and renewables represented 8.58% and 4.24%, respectively. In Africa, fossil fuels accounted for 89.92%, while nuclear and renewables represented 0.8% and 1.22%, respectively. As more fossil fuels are consumed, more CO_2 is emitted; therefore, this study focused on examining whether the use of clean energy, nuclear and renewable energy, reduces fossil fuel usage. Accordingly, sample data on energy usage in the United States and Africa from 1965 to 2021 were collected from the 2023 Statistical Review of World Energy published on the BP company website. We used training period data from 1965 to 2014 to construct the models and test period data from 2015 to 2021 to conduct the forecast accuracy analysis.

4. Empirical Results

4.1. Coefficient Estimation Results

4.1.1. Relationships between Fossil Fuels and Nuclear Energy in the United States

To deeply understand the interactions between fossil fuel and nuclear energy consumption, this study considered nuclear energy and renewable energy to explore which factor affects the consumption of fossil fuels in the United States and Africa. The Lotka–Volterra model estimation results of the consumption of nuclear and fossil fuels in the United States are shown in Table 1. The parameter results of pair one showed that γ_1 was significantly negative and γ_2 was insignificant according to the t-statistics. As mentioned above, the signs of γ_i and c_i were found to be equal. Therefore, nuclear energy stimulates the growth of fossil fuels, but fossil fuels do not affect the growth of nuclear energy. A possible reason for this is that electricity is consumed during uranium mining, nuclear power plant operations, landfill treatment, and decommissioning; the United States is a developed nation that has the most nuclear power plants of any country in the world, and many of the United States' power plants have been decommissioned in recent years. Under a scenario with no alternative energy sources, the long-term management of the United States' nuclear power plants requires a lot of electricity, which increases the consumption of fossil fuels. The arguments of previous studies [26–28] coincide with our results regarding the relationship between nuclear energy and fossil fuels. The United States' nuclear power plants may not emit CO_2 from electricity generation, but they still increase fossil fuel consumption from uranium mining to nuclear power plant decommissioning. The Paris Agreement promises carbon reductions, but the United States suffers from a lack of sufficient alternative energy sources. The pressure and difficulty of carbon reduction may cause the United States to withdraw from the Paris Agreement. The United States imports a great amount of energy to achieve its economic development. Because the United States is not overexploiting energy minerals within the United States, the United States still protects the environment, consistent with the environmental Kuznets curve theory. Here, coefficient β_1 (and b_1) of fossil fuel consumption was found to be significantly positive, indicating that the self-growth coefficient b_1 is limited due to saturation and is the dominant factor limiting the growth rate. The coefficient of nuclear energy β_2 was found to be positive as well, indicating a decreasing nuclear energy growth rate. The growth rate of these two types of energy sources will be slowed by growth pressures.

Table 1. Coefficients of fossil fuels versus nuclear energy and fossil fuels versus renewable energy in the United States.

Pair one	Fossil			Nuclear	
	Coefficient	*t*-Statistic		Coefficient	*t*-Statistic
α_1	1.243940	13.313824 ***	α_2	1.105225	8.284798 ***
β_1	0.000154	2.415522 **	β_2	0.001030	3.844238 **
γ_1	−0.000306	−1.696481 *	γ_2	−0.000046	−0.554438 *
Adjusted R^2	0.950505		Adjusted R^2	0.994220	
Pair two	**Fossil**			**Renewable**	
	Coefficient	*t*-Statistic		Coefficient	*t*-Statistic
α_1	1.108970	26.972427 ***	α_2	0.979189	8.450911 ***
β_1	0.000067	2.389635 **	β_2	0.000882	0.948305
γ_1	−0.000225	−0.654088	γ_2	−0.000062	−0.837827
Adjusted R^2	0.947048		Adjusted R^2	0.799433	
	Pair one			**Pair two**	
	Fossil	Nuclear		Fossil	Renewable
a_i	0.218284	0.100049		0.103432	−0.021030
b_i	0.000138	0.000980		0.000064	0.000891
c_i	−0.000274	−0.000044		−0.000213	−0.000063

Note: *, **, and *** denote the significance of the *p*-value at the 0.1, 0.05, and 0.01 levels, respectively.

4.1.2. Relationships between Fossil Fuels and Renewable Energy in the United States

Table 1 also shows the results of pair two, renewable energy and fossil fuel. Table 1 exhibits that γ_1 and γ_2 were both found to be insignificantly negative, suggesting no significant relationships between renewable energy and fossil fuels. Table 1 confirms that there is no obvious relation between renewable energy and fossil fuels. Our empirical results show that renewable energy has no impact on fossil fuels but nuclear energy does. These empirical results suggest that nuclear energy significantly influences the growth of fossil fuels and that renewable energy has no significant effect on fossil fuels. These results shown in Table 1 explain why the whole life cycle of nuclear energy needs to consume great amounts of fossil fuels in the United States. The construction of large-scale nuclear power plants requires lots of concrete and steel, the fabrication of which necessitates the use of lots of fossil fuels.

4.1.3. Relationships between Fossil Fuels and Nuclear Energy in Africa

Table 2 shows the energy consumption trends of two different sources in Africa. The parameter results of pair one showed that γ_1 was positive, γ_2 was negative, and both were significant according to the *t*-statistics. Nuclear energy was found to reduce the growth of fossil fuels, and fossil fuels were found to increase the growth of nuclear energy. A prey–predator interaction was found between fossil fuels and nuclear energy in Africa. The self-coefficient β_1 of fossil fuel consumption was insignificantly negative, indicating that the major suppression force is nuclear energy. However, coefficient β_2 was significantly positive, which means that self-growth coefficient b_1 was also positive. This means that the consumption of nuclear energy is limited by itself, although fossil fuels are an enhancement force.

Table 2. Coefficients of fossil fuels versus nuclear energy and fossil fuels versus renewable energy in Africa.

Pair one	Fossil			Nuclear	
	Coefficient	*t*-Statistic		Coefficient	*t*-Statistic
α_1	1.051173	89.372333 ***	α_2	1.630882	6.406432 ***
β_1	−0.000046	−0.674886	β_2	0.416840	3.213824 ***
γ_1	0.013378	2.246280 **	γ_2	−0.001775	−2.524072 **
Adjusted R^2	0.997634		Adjusted R^2	0.952987	
Pair two	**Fossil**			**Renewable**	
	Coefficient	*t*-Statistic		Coefficient	*t*-Statistic
α_1	1.068860	87.860238 ***	α_2	1.023909	51.700878 ***
β_1	0.000725	3.641271 ***	β_2	0.000270	0.061292
γ_1	−0.008547	−3.312911 ***	γ_2	−0.000074	−0.223302
Adjusted R^2	0.997888		Adjusted R^2	0.992614	
	Pair one			**Pair two**	
	Fossil	Nuclear		Fossil	Renewable
a_i	0.049907	0.489121		0.066593	0.023628
b_i	−0.000045	0.323175		0.000701	0.000266
c_i	0.013047	−0.001376		−0.008266	−0.000073

Note: **, and *** denote the significance of the *p*-value at the 0.05, and 0.01 levels, respectively.

4.1.4. Relationships between Fossil Fuels and Renewable Energy in Africa

In Table 2, the parameter results of pair two, fossil fuel and renewable energy, show that γ_1 was significantly negative and γ_2 was insignificant according to the *t*-statistics. Because the signs of γ_i and c_i were equal, the results suggest that renewable energy can enhance the growth of fossil fuel consumption. The results also imply that the construction of solar and wind power plants to engage in renewable power generation in Africa still needs a great amount of electricity, which will increase the consumption of fossil fuels. Neither Africa nor the United States can rely on renewable energy to replace fossil fuels at the current stage. The self-coefficient coefficient β_1 of fossil fuel consumption was found to be significantly positive, indicating that fossil fuel consumption growth has decreased with time in Africa. On the other hand, renewable energy growth was shown to be controlled by neither fossil fuels nor itself.

4.2. Equilibrium Analysis Results

This study further explored the equilibrium stability of pair one, nuclear and fossil fuels in the United States since we found obvious correlations between the two energy types. This work utilized the eigenvalues of the Jacobian matrix to examine equilibrium stability. This work computed the negative real parts of the Jacobian matrix of the Lotka–Volterra equations for the pairs of nuclear and fossil fuel consumption in the United States. This work additionally used Lyapunov functions to examine equilibrium stability. This work computed the positive Lyapunov functions and the negative first differentials of the Lyapunov functions to prove the equilibrium stability. Figure 1 depicts the consumption trajectories of fossil fuels and nuclear energy in the United States. The trajectories were found to start in 1965 and rise with simultaneous increases in nuclear energy and fossil fuel consumption. The intersecting point of the two straight lines, which are two linear functions ($a_1 - b_1X_1 - c_1X_2 = 0$, and $a_2 - b_2X_2 - c_2X_1 = 0$), is the equilibrium point. Fossil fuel and nuclear energy consumption reached 1811.57 and 176.75 million tons of oil equivalent in 2021, respectively, and were not over the saturation boundaries. As our proposed Lotka–Volterra equations were shown to satisfy the stable conditions proposed by Hritonenko and Yatsenko [45], the annual consumption of fossil fuels and nuclear energy approached 1964.18 and 190.57 million tons of oil equivalent, respectively.

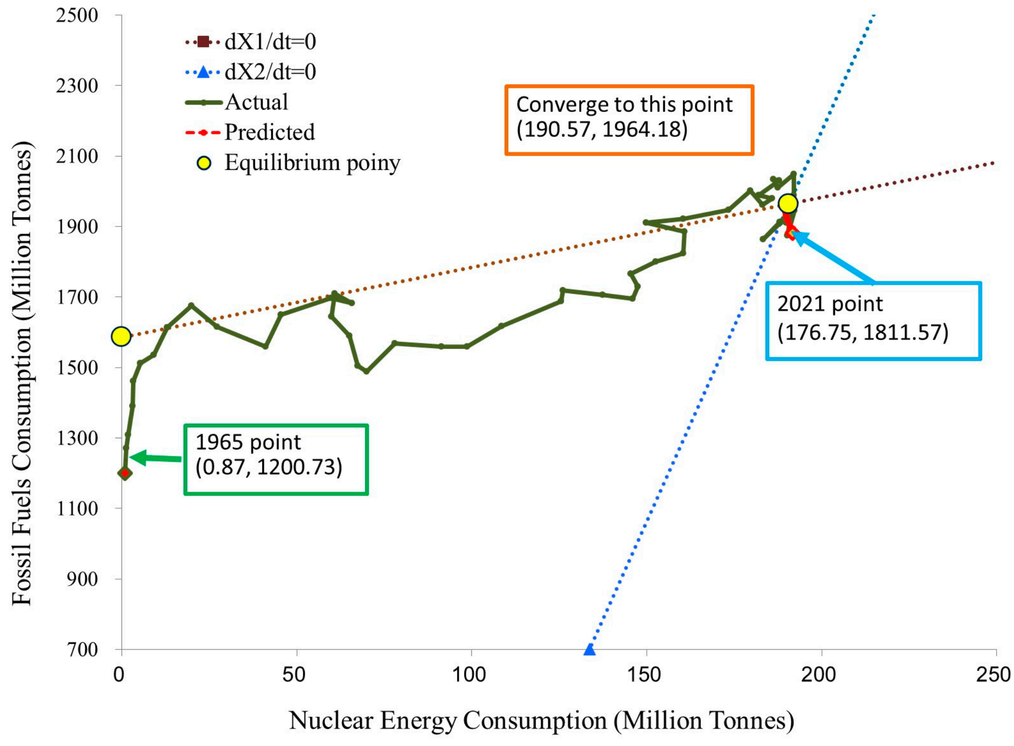

Figure 1. Trajectories of energy consumption in the United States.

The x-axis and y-axis in Figure 1 represent nuclear energy and fossil fuel consumption in the United States, respectively. During the period from 1979 to 1983, the coordinate point, the values in 1979, of the trajectories started from $X < dX_2/dt$ and $Y < dX_1/dt$ to $X < dX_2/dt$ and $Y > dX_1/dt$ because fossil fuel consumption continually decreased, i.e., $dX_1/dt < 0$, while nuclear energy increased over time, i.e., $dX_2/dt > 0$. However, fossil fuel consumption inversely increased after 1983, which implies that nuclear energy cannot entirely replace fossil fuels; the whole world continued using these two energy types. The annual consumption of these two energy types was found to converge to long-term equilibria of 190.57 and 1964.18, respectively. This suggests that in the long term, the adoption of nuclear energy raises fossil fuel consumption.

Due to the significant relationship of pair one, fossil fuels and nuclear energy in Africa, this study further analyzed their equilibria. The x-axis and y-axis in Figure 2 represent nuclear energy and fossil fuel consumption in Africa, respectively. The fossil fuel trajectories started in 1965 and moved in the rising direction. Africa does not have many countries that fully exploit their commercial, manufacturing, and industrial potential, so energy consumption is much lower in Africa than anywhere else in the world due to a lack of infrastructure, production, and activities. Africa did not develop nuclear power until 1984, so there are currently not enough available data on nuclear power generation in Africa. When we used the existing data and estimated parameters a_1, b_2, and c_2 in Table 2 to simulate the future trajectories of nuclear power generation in Africa, the simulated trajectories of fossil fuel and nuclear energy were found to greatly fluctuate, as shown in Figure 2. Africa prioritizes the economy over environmental protection and fails to utilize energy as efficiently as the United States. In addition, technological improvements and industrialization evolutions have caused substantial changes in electricity generation. Consequently, energy consumption fluctuation in Africa is much greater than that in the United States.

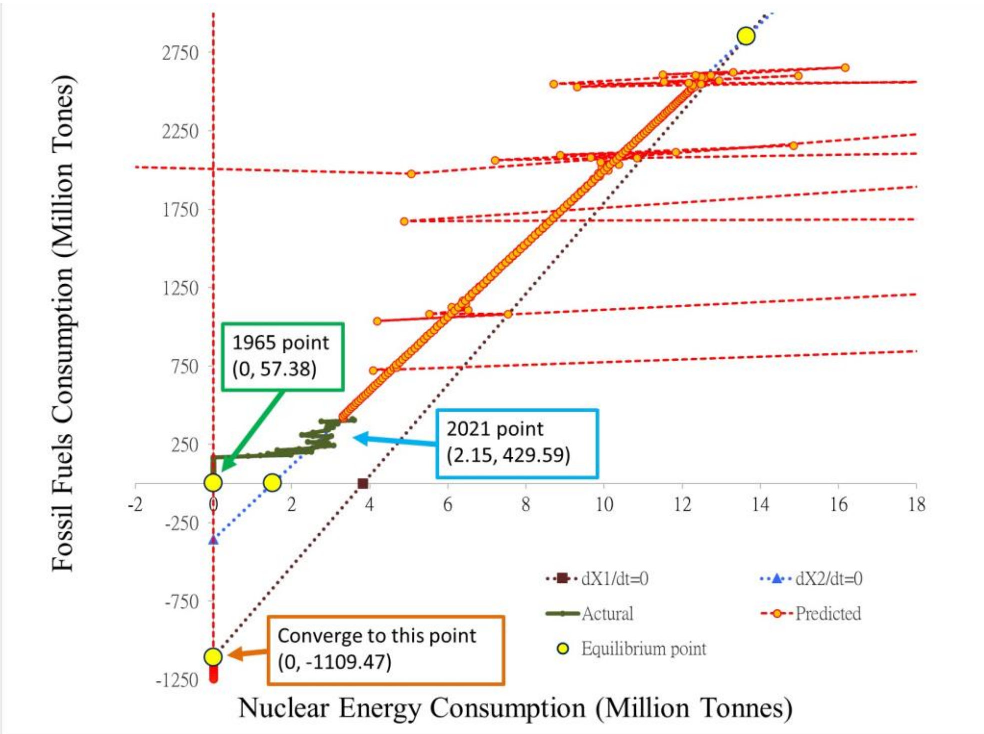

Figure 2. Trajectories of energy consumption in Africa.

Currently, the proportion of nuclear energy is much lower than that of fossil energy in Africa at its current initial stage of economic development. African countries, especially South Africa, have provided tax incentives to encourage enterprises to use more green energy and less fossil energy, which has led to substantial increases in nuclear power use. Developing countries in Africa have substantially increased both nuclear power and fossil fuel power station use during their industrialization evolutions. Africa is inclined to develop its economy at the cost of environmental damage and uranium overexploitation. When we used the small available amount of African nuclear energy data, we estimated parameters a_1, b_2, and c_2 in order to conduct the equilibrium analysis; African fossil fuel and nuclear energy consumption were found to eventually converge to an equilibrium point of -1109 million tons of oil equivalent and zero tons of oil equivalent, respectively. This work further computed the negative real parts of the Jacobian matrix of the Lotka–Volterra equations, the positive Lyapunov functions, and the negative first differentials of Lyapunov functions for the pairs of nuclear and fossil fuel consumption in Africa. The equilibrium analysis results showed that Africa's long-term energy sources will be depleted as they converge to an equilibrium point where nuclear energy consumption is zero and fossil fuel consumption is negative. This suggests that Africa's fossil fuel and uranium consumption will increase in the future if Africa continues to inefficiently consume energy without circular energy knowledge and technology. Consistent with the environmental Kuznets curve theory, the United States engages in energy consumption in a more environmentally friendly way than Africa, so the United States' long-term trajectories are more stable than Africa's.

4.3. Forecast Accuracy Analysis Results

This section presents the forecast accuracy analysis results for the test period. Figures 3 and 4 depict the United States' and Africa's fossil fuel consumption trajectories for pair one, respectively. Figures 3 and 4 show that the values predicted using the proposed Lotka–Volterra model were closer to the actual values in comparison with the values predicted with the Bass model in the United States and Africa, respectively. This suggests that our proposed Lotka–Volterra model outperforms the traditional Bass model in forecasting the trajectories of fossil fuel consumption because our proposed Lotka–Volterra model takes the interactions between different energy types into account.

Figures 5 and 6 depict the United States' and Africa's nuclear consumption trajectories for pair one, respectively. Figures 5 and 6 show that the values predicted using the proposed Lotka–Volterra model were closer to the actual values in comparison with the values predicted with the Bass model in the United States and Africa, respectively. This suggests that our proposed Lotka–Volterra model outperforms the traditional Bass model in forecasting nuclear energy consumption trajectories because our proposed Lotka–Volterra model takes the interactions between different energy types into account.

Figures 7 and 8 depict the United States' and Africa's renewable consumption trajectories for pair two, respectively. Figures 7 and 8 show that the values predicted using the proposed Lotka–Volterra model were closer to the actual values in comparison with the values predicted with the Bass model in the United States and Africa, respectively. This suggests that our proposed Lotka–Volterra model outperforms the traditional Bass model in forecasting renewable energy consumption trajectories because our proposed Lotka–Volterra model takes the interactions between different energy types into account.

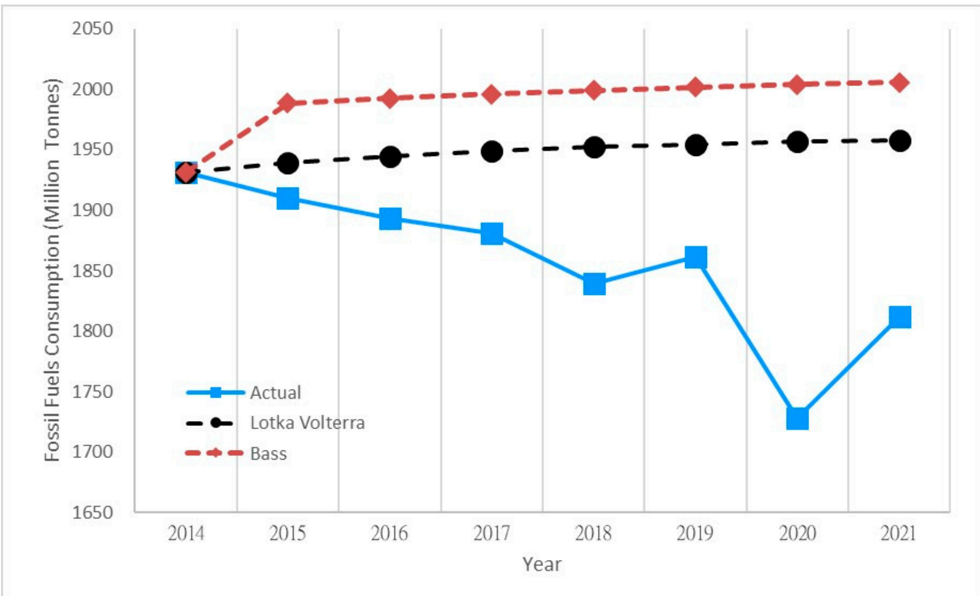

Figure 3. The United States' fossil fuel consumption trajectories.

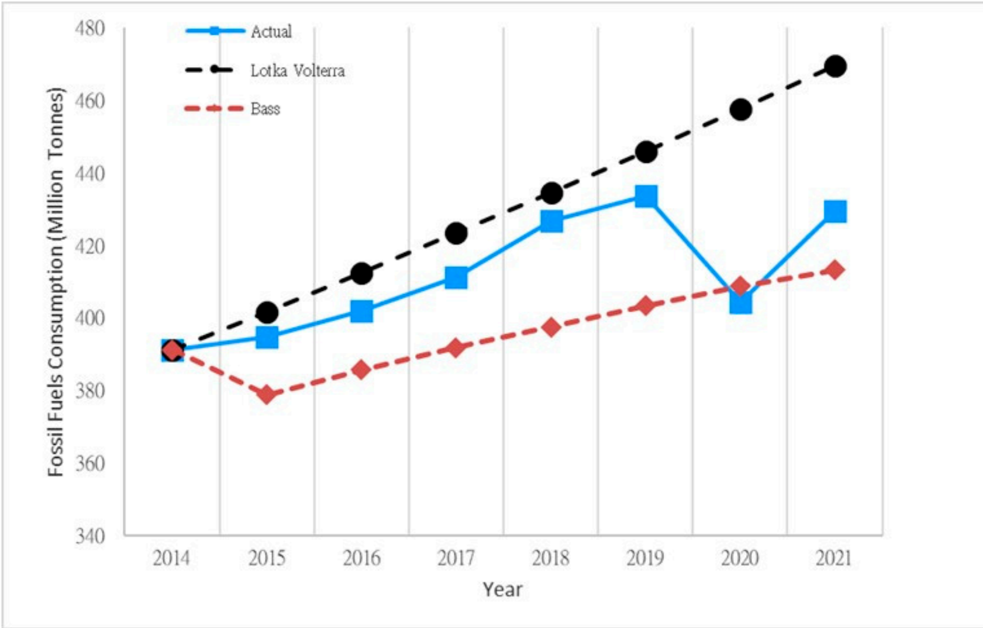

Figure 4. Africa's fossil fuel consumption trajectories.

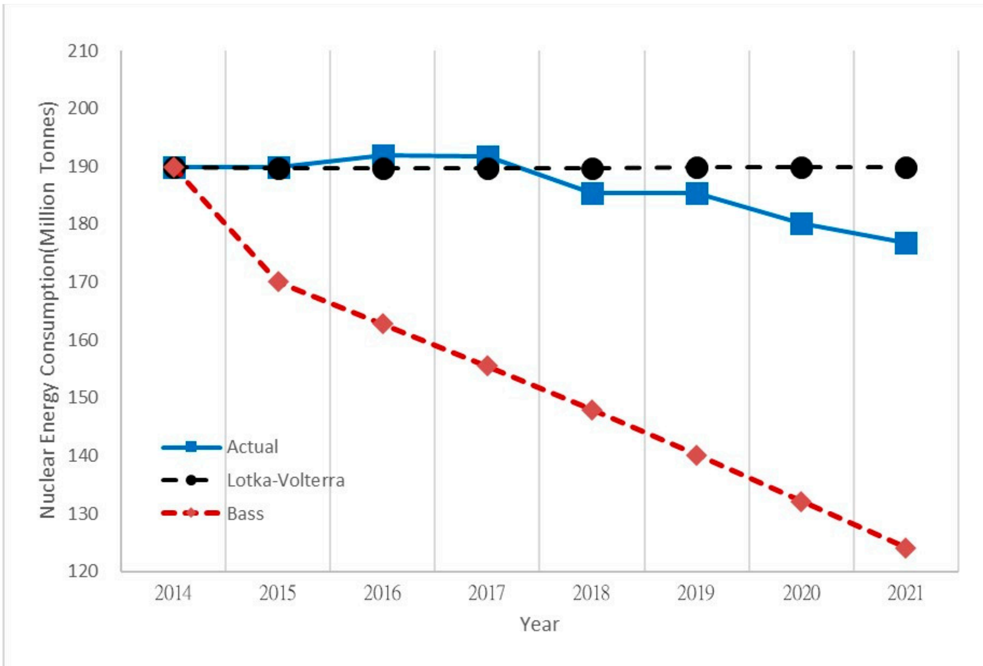

Figure 5. The United States' nuclear consumption trajectories.

Table 3 summarizes the MAPE results in the United States and Africa in the test period. The MAPEs of the proposed Lotka–Volterra model for the first pair of fossil fuels and nuclear energy were 5.75% and 3.70%, respectively, in the United States. Both MAPEs were lower than 10%, displaying excellent prediction according to the criteria of Martin and Witt [4]. For both fossil fuel and nuclear consumption in the United States, the nuclear prediction MAPEs of our proposed Lotka–Volterra model were much smaller than the MAPEs of the Bass model because the Lotka–Volterra model considers the consumption correlation between fossil fuels and nuclear energy. The MAPEs of the proposed Lotka–Volterra model for the first pair of fossil fuels and nuclear energy were 4.92% and 21.02%, respectively, in Africa. Our proposed Lotka–Volterra model predicted nuclear energy consumption more accurately than the Bass model because our proposed Lotka–Volterra model takes the relationships between different energy types into account. For the second pair of fossil fuels and renewable energy, the renewable energy MAPEs were 25.73% and 4.04% in the United States and Africa, respectively, in our proposed Lotka–Volterra model, while the renewable energy MAPEs were 27.11% and 16.24% in the United States and Africa, respectively, in the Bass model. In both the United States and Africa, the MAPE of the renewable energy prediction of our proposed Lotka–Volterra model was smaller than the MAPE of the Bass model. Our proposed Lotka–Volterra model was found to predict renewable energy consumption more accurately than the Bass model because our proposed Lotka–Volterra model considers the consumption correlation between fossil fuels and nuclear energy.

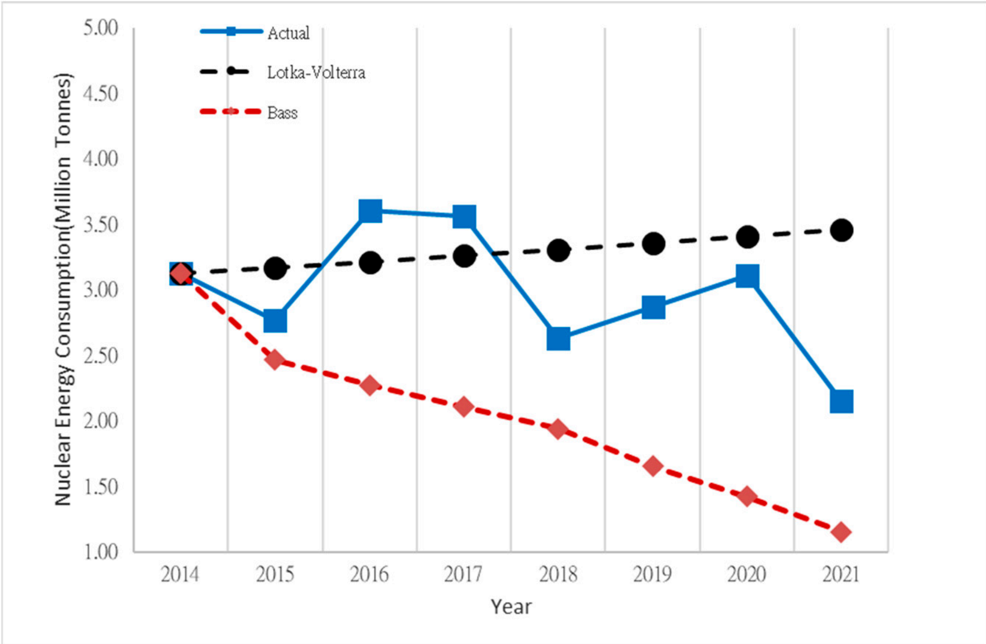

Figure 6. Africa's nuclear consumption trajectories.

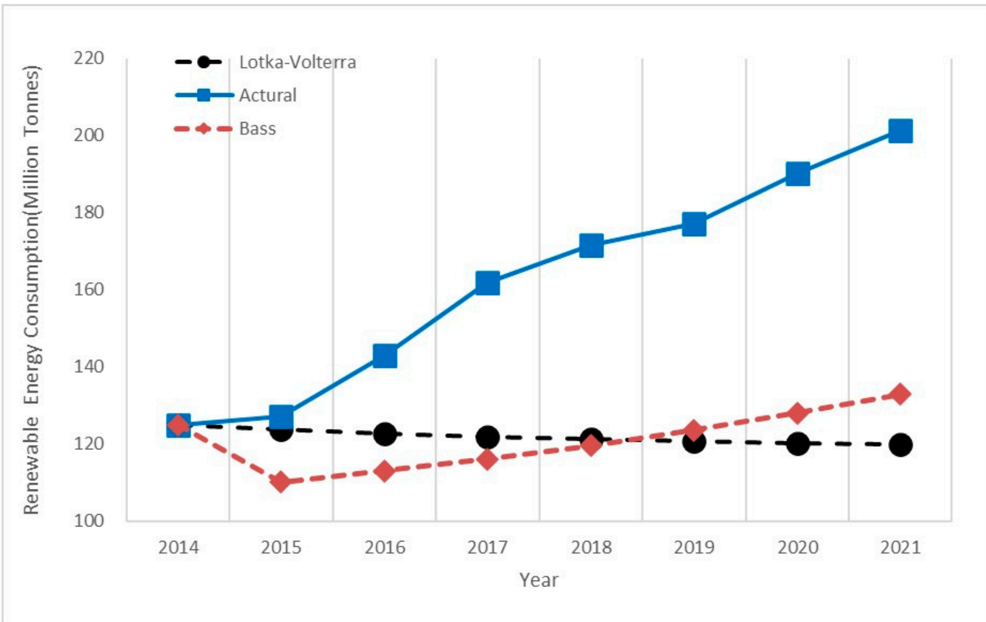

Figure 7. The United States' renewable consumption trajectories.

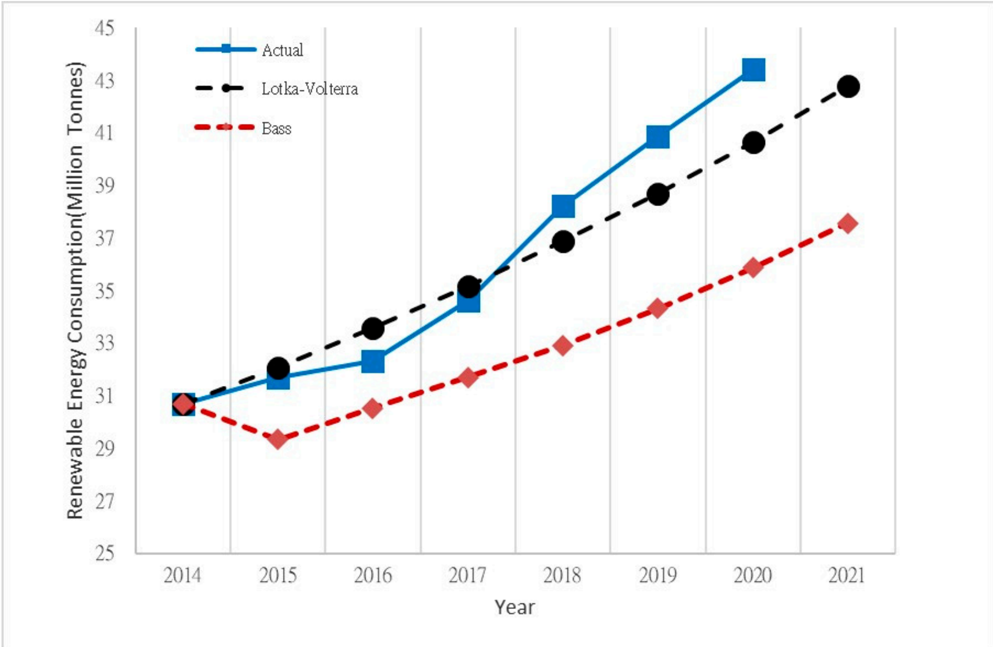

Figure 8. Africa's renewable consumption trajectories.

Table 3. Forecast accuracy (MAPE) of the Lotka–Volterra model and the Bass model in the test period (2015~2021).

	United States		**Africa**	
	Lotka–Volterra	**Bass**	**Lotka–Volterra**	**Bass**
Pair one				
Fossil Fuels	5.75%	8.33%	4.92%	4.66%
Nuclear Energy	3.70%	22.53%	21.02%	42.27%
Pair two				
Fossil Fuels	6.95%	8.33%	12.92%	4.66%
Renewable Energy	25.73%	27.11%	4.04%	16.24%

5. Conclusions

The purpose of this study was to examine the differences in the relationship between fossil fuels and nuclear energy and the relationship between fossil fuels and renewable energy in developing and developed countries. This study chose fossil fuel, nuclear energy, and renewable energy consumption in the United States and Africa as its research objects. The parameter estimation results show that nuclear energy enhances the consumption of fossil fuels in the United States and that nuclear energy reduces the consumption of fossil fuels in Africa in the short run. In the United States, the whole life cycle of nuclear power plants contains multiple steps from uranium searching to landfill treatment and decommissioning that may increase fossil fuel consumption, coinciding with the viewpoints of previous research [27–29].

Regarding long-term energy consumption relations, given the current state of energy consumption, the results of the equilibrium analysis indicated that the United States' nuclear and fossil fuel consumption will remain at a stable long-term equilibrium; however, Africa will experience significant fluctuations in nuclear and fossil fuel consumption, and both nuclear and fossil fuel consumption will eventually be exhausted. These results suggest that the United States has the knowledge and technology to recycle energy and resources in an environmentally friendly way and to reshape economies to achieve energy sustainability. Under the assumption that there will be no structural changes in electricity generation in the United States, the equilibrium analysis and Lyapunov functions show that United States' energy types will converge to an equilibrium point in the long run if there are no breakthroughs in energy substitution.

In contrast, the results of Africa show that nuclear energy reduces the consumption of fossil fuels in the short run. African countries, especially South Africa, have provided tax incentives to encourage enterprises to use more green energy and less fossil energy, which has led to the substantial substitution of nuclear power for fossil fuel electricity generation. The current proportion of nuclear energy is much lower than that of fossil energy in Africa, and African nuclear power is at an initial stage of development. Given the current state of energy consumption, the results of the equilibrium analysis indicate that Africa will experience significant fluctuations in future nuclear and fossil fuel consumption. Africa is predicted to ultimately increase fossil fuel and nuclear energy consumption in the long run. The results suggest that developing countries in Africa substantially increase power demand during industrialization evolutions at the cost of environmental damage and uranium overexploitation. Africa's long-term energy consumption was found to more greatly fluctuate than the United States', which is possibly caused by the fact that Africa cannot utilize energy as efficiently as the United States, consistent with the implication of the environmental Kuznets curve theory.

This study further found that renewable energy is unable to replace fossil fuels for power generation in both the United States and Africa. Neither Africa with its developing economies nor the United States with its mature industrialization can rely on renewables to replace fossil fuels at the current stage. Finally, accuracy analysis was used to investigate whether our proposed Lotka–Volterra model could outperform the traditional Bass model in predicting energy consumption. We found that the values predicted using the proposed Lotka–Volterra model were closer to the actual values in comparison with the values predicted with the Bass model in the United States and Africa. All of the forecasting error rates of the values predicted with our proposed Lotka–Volterra model for fossil fuels in both regions were much lower than those of the traditional Bass model in the United States. In both the United States and Africa, the forecasting error rates of the nuclear or renewable energy prediction of our proposed Lotka–Volterra model were much smaller than that of the Bass model. The aforementioned parameter estimation results revealed significant relations between fossil fuels and nuclear energy in both the United States and Africa, and fossil fuels were also found to be significantly affected by renewable energy in Africa. As a result, our proposed Lotka–Volterra model, which considers the interactions between different energy types, is more suitable for forecasting than other models without interactive factor consideration. A limitation of this study is our assumption that future electricity technology will remain unchanged. Future research can explore breakthroughs in electricity technology to predict energy consumption trends.

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