MODELLING ENERGY CONSUMPTION AND CARBON DIOXIDE EMISSIONS OF FOSSIL FUELS AND NUCLEAR ENERGY USING LOTKA-VOLTERRA EQUATIONS

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Abstract. This study applied the Lotka-Volterra model to energy consumption and carbon dioxide (CO_2) emissions from 1965 to 2017 in the United States to explore the feasibility of replacing fossil fuels with nuclear energy. Parameter estimations suggested that the consumption of nuclear energy increases the consumption of fossil fuels, thereby increasing CO_2 emissions. Consistent with the arguments in Sovacool (2008) and Lenzen (2008), our results suggested that the mining, milling, conversion, enrichment, fuel fabrication, construction of nuclear plants, nuclear waste treatment, and decommissioning increase the consumption of fossil fuels and hence CO_2 emissions. Utilization of nuclear energy fails to reduce fossil fuel consumption and CO_2 emissions to achieve the environmental protection goals in the United States. By applying the Lyapunov functions to conduct equilibrium analysis, our investigation verified that the consumption of fossil fuels will ultimately be ten-fold the consumption of nuclear energy in the long term. Furthermore, the results of forecast accuracy show that the predictive ability of our proposed Lotka-Volterra model is superior to that of Bass model both in forecasting energy consumption and CO_2 emissions because the Lotka-Volterra model considers how nuclear energy affects the consumption and CO_2 emissions of fossil fuels, while the Bass model does not.
Keywords: *decommissioning, Lyapunov functions, equilibrium analysis, forecast accuracy, CO_2*

Introduction

This study applied the Lotka-Volterra model to explore how the utilization of nuclear energy affects fossil fuel consumption and CO_2 emissions in the United States (US) since the US is the country with the most nuclear power plants. CO_2 emissions generated from burning fossil fuels cause global warming and extreme weather. Monahan et al. (2016) used data from the past 112 years and found that 76% of American national parks have an early arrival of spring. Abatzogloua et al. (2016) demonstrated that rising temperatures have doubled the range of fires in the western US in the past 30 years. Rietbroek et al. (2016) showed that sea warming is one of the most important causes of global sea-level rise. Because global warming affects human life globally, scholars are making efforts to explore the factors that affect CO_2 emissions. Al-Harbi et al. (2020) investigate higher consumption of the greenhouse gas emissions for cooling purposes and traffic activities in four major urban cities in summer compared to winter and higher CO_2 emission accelerate climate change. García-Martosa et al. (2013) stated the continued use of fossil fuels cause increased CO_2 emissions. Besides, Zhang et al. (2019) indicate industrial development led to high carbon emissions in China and Cui et al. (2019) elucidated that fossil fuel combustion, cement and non-fossil singular usage during Chinese industrial plural caused more than quarter of the world total CO_2 to be emitted from China. It is critical to control CO_2 emissions to avoid extreme global warming. Gustavssonab et al. (2011) recovered, refined and transported logging residues to replace fossil fuels and obtain the benefits of CO_2

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reductions. The US has the most nuclear power plants in the world, including 98 operating commercial nuclear reactors at 60 nuclear power plants in 30 states, at the end of 2018, according to the statistics of United States Energy Information Administration. For the purpose of environmental protection, the US was motivated to use nuclear energy to replace fossil fuels. Electricity generation by nuclear power plants does not require fossil fuels, so no CO_2 is emitted during power generation. Consequently, the CO_2 emission of nuclear power is regarded as zero, so more and more countries follow US to adopt nuclear energy to generate electricity. Although the nuclear energy generates steady, reliable, and controllable electricity with much lower carbon emissions than emitted by fossil fuel generation, the true greenhouse gas emissions from the radioactive waste management and nuclear plant constructions are controversial. The United States Energy Information Administration (2012) also emphasized that although nuclear power plants do not consume fossil fuels during their operation, nuclear energy consumes fossil fuels during the entire life cycle of nuclear power plants, from exploration, enrichment, transformation, production and transport of uranium raw material, to the treatment, solidification, transport, and burial of radioactive wastes, as well as decommissioning or undertaking long-term management. The US has accumulated approximately 70,000 metric tonnes of high-level nuclear waste by 2019. The spent high-level nuclear fuel is stored at reactor sites in wet pools to cool off, so that its radiation can be shielded. The absence of a long-term repository for high-level waste and the complicated waste treatment also requires the use of electricity (Alley et al., 2012).

Previous research has estimated how much fossil fuel is needed during the life cycle of nuclear plants. Lenzen (2008) and Sovacool (2008) have estimated the amount of greenhouse gas emissions arising from the consumption of fossil fuels during the entire life cycle of nuclear energy production. Lenzen (2008) estimated that greenhouse gas emissions per kilowatt-hour (kWh) of nuclear energy are equivalent to 65 grams of CO_2. Although nuclear power yields zero CO_2 emissions during heat- and electricity-generation, the extensive system of upstream supply stages requires fossil fuels and nuclear energy production indirectly involves the emission of greenhouse gases. Sovacool (2008) indicated that throughout the lifetime of nuclear energy production, from the construction of a nuclear plant, the implementation of the plant, uranium-mining and concentrating process, through to decommissioning, relies on facilities driven by the energy provided by fossil fuels. The average value of emissions over the lifetime of a nuclear reactor was estimated to be 66 g CO_2/kWh. In addition, Torfs et al. (1998) estimated that the nuclear material, enriched uranium (3.8% U-235), in its extraction, concentration, conversion, manufacturing, and transport steps, directly consumes approximately 10,500 Joules of fossil fuel per milligram of enriched uranium. Nuclear Energy Agency (2012) indicated the emissions stem from the mining and milling of uranium, clean-up of the mine site, the construction, operation and decommissioning of the nuclear power plant and the treatment of low and high-grade ore waste, respectively. The emissions of nuclear power ranges from 3 to 40 g CO_2/kWh. These studies have shown that a large amount of reinforced concrete must be used in the construction of nuclear power plants, explaining why the whole life cycle of nuclear energy consumes large amounts of fossil fuels.

These aforementioned studies demonstrate that nuclear energy production increases the volume growth of fossil fuel consumption when we take the whole life cycle of nuclear power into account. However, the US has tended to utilize nuclear power to

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substitute fossil fuels and lessen CO_2 emissions for more than 50 years, since the Atomic Energy Act of 1954. Because the US consumes the great amount of fossil fuels and emits large volume of CO_2 globally, it is critical to provide tangible evidence of the consumption and the CO_2 emission relationship between fossil fuels and nuclear energy in the US. For this reason, the purpose of this study was to examine whether nuclear energy can take the place of fossil fuels, thereby decreasing CO_2 emissions in the US. This work concentrates on CO_2 emissions and energy consumption in the US as the research sample and empirically investigated whether nuclear energy can substitute fossil fuels. Tsai et al. (2016) have used Lotka-Volterra model to analyze the relationships between the low-carbon energy and fossil fuels in the United States and found that low-carbon energy increases the consumption of fossil fuels. The low-carbon energy includes renewable energy and nuclear energy. However, Tsai et al. (2016) emphasize that mining, milling, conversion, enrichment, waste treatment and decommission of low-carbon energy needs electricity generated by the fossil fuels, but it did not indicate which kind of low-carbon energy increases the fossil fuel consumption. Only nuclear energy deals with the mining, milling, conversion, enrichment, fuel fabrication and decommission, while renewable energy does not. In addition, Lenzen (2008) indicated that the greenhouse gas emissions caused by upstream and downstream processing stages of nuclear life cycle from nuclear plants could not be neglected. Greenhouse gas emissions are exactly higher for the wind turbines and hydroelectricity, but slightly lower for the solar photovoltaic. The conclusion also implies that we may not simply categorize renewable energy into one class while analyzing. Therefore, this research will focus on the analysis of fossil fuels and nuclear energy to simplify our analysis.

Researchers in many fields have applied an S-curve model to explore diffusion of an individual ethnic group (Tsai, 2013a; Tsai, 2013b; Sodero et al., 2017; Lee et al., 2017). However, the S-curve model does not take into account interactions among different groups. As an analogy, the traditional S-curve model also cannot be used to examine the substitution of nuclear energy for fossil fuels. To overcome the drawbacks, many previous studies applied Lotka-Volterra's mathematical model to effectively illustrate the phenomenon of competitive behavior among different groups (Lukas et al., 2017; Kamimura et al., 2006; Tsai et al., 2016; Tsai, 2017; Pac et al., 2018). Tsai and Chen (2020) used the binary Lotka-Volterra model to show that CO_2 emissions in Taiwan and China, where there is a strong dependence on industry and trade, have a significant interactive effect. In this study, for the first time, the forward-looking Lotka-Volterra model was used to quantify the interactive relationship between nuclear energy and fossil fuels in the US to explain the correlation of CO_2 emissions and energy consumption. Furthermore, previous studies ignored the interactive effects of competitive or cooperative subjects and applied a Bass diffusion model to determine the diffusion of products and technology (Fan et al., 2017). Thus, this work also utilizes the Bass model to predict energy consumption and CO_2 emissions of each energy source and compares the prediction ability between the Bass model and the Lotka-Volterra model. We compared the forecast accuracy of the Lotka-Volterra and Bass models and determined whether the Lotka-Volterra model, which considers the substitutive or complementary relations among various energy resources, has a better predictive ability.

This study has three research objectives. The first objective of this study was the determination of whether nuclear energy in the US increased the consumption of fossil fuels, instead of curtailing it. We explored whether it is infeasible for the US

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environmental protection to utilize the nuclear energy instead of fossil fuels and reduce to CO_2 emissions. Second, equilibrium analysis was also conducted to ascertain whether the consumption of fossil fuels and nuclear energy will reach a stable constant level in the long term. Third, this work was motivated to explore the forecast accuracy of our proposed Lotka-Volterra model. The results of this study find that nuclear power plants fail to reduce CO_2 emissions in the US, suggesting that the construction of nuclear power plants, nuclear waste treatment and decommissioning of nuclear power plants consume a large amount of fossil fuels and increase CO_2 emissions. Also, this study for the first time uses equilibrium analysis to find that the fossil fuel consumption in the US is ultimately ten-fold nuclear energy consumption under the incumbent technology. Fossil fuels are still the main sources of power generation and CO_2 emissions. Therefore, reducing CO_2 emissions in the US requires new technologies to improve the efficiency of fossil power generation.

Materials and methods

Lotka-Volterra model of energy consumption

The Lotka-Volterra model combines logic equations and the interaction variables representing other energy sources (Lin, 2013). The consumption relationship between fossil fuels and nuclear energy was analyzed in this work. The following two differential equations represent the interaction between two energy sources:

$$\frac{dX_1}{dt} = (a_1 - b_1X_1 - c_1X_2)X_1 = a_1X_1 - b_1X_1^2 - c_1X_1X_2 \qquad \text{(Eq.1)}$$

and

$$\frac{dX_2}{dt} = (a_2 - b_2X_2 - c_2X_1)X_2 = a_2X_2 - b_2X_2^2 - c_2X_2X_1 \qquad \text{(Eq.2)}$$

where $X_1 \geq 0$ and $X_2 \geq 0$. The terms of X_1 and X_2 represent the consumption of fossil fuels and nuclear energy in every year, respectively; X_1^2 and X_2^2 refer to the self-influence of the same energy source; X_1X_2 and X_2X_1 represent the different energy interactions; $\frac{dX_1}{dt}$ and $\frac{dX_2}{dt}$ denote the annual growth rate of fossil fuels and nuclear energy, respectively.

Since the Lotka-Volterra equation is a continuous model that cannot fit our specific samples at different times, these equations have to be converted to a discrete-time version (Leslie, 1958). The discrete-time format of *Equations 1* and *2* are expressed as follows:

$$X_1(t+1) = \frac{\alpha_1X_1(t)}{1+\beta_1X_1(t)+\gamma_1X_2(t)} \qquad \text{(Eq.3)}$$

and

$$X_2(t+1) = \frac{\alpha_2X_2(t)}{1+\beta_2X_2(t)+\gamma_2X_1(t)} \qquad \text{(Eq.4)}$$

where α_i and β_i represent the logistic parameters of individual energy consumption, and γ_i denotes the magnitude of the impact of one energy source on the growth rate of

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consumption of another energy source. The coefficients in the continuous form of Lotka-Volterra model have relationships with those in the converted discrete-time format (*Equations 3* and *4*). The parameters of Lotka-Volterra model a_i, b_i, c_i can be expressed in *Equations 5-7*.

$$a_i = \ln \alpha_i \quad \text{(Eq.5)}$$

$$b_i = \frac{\beta_i \alpha_i}{\alpha_i - 1} = \frac{\beta_i \ln \alpha_i}{\alpha_i - 1} \quad \text{(Eq.6)}$$

$$c_i = \gamma_i \frac{b_i}{\beta_i} = \frac{\gamma_i}{\beta_i} \frac{\beta_i \, ln\alpha_i}{\alpha_i - 1} = \frac{\gamma_i \ln \alpha_i}{\alpha_i - 1} \quad \text{(Eq.7)}$$

In Equation *7*, γ_i has the same sign as c_i because $\frac{\ln \alpha_i}{\alpha_i - 1}$ is always positive when $\propto_i$ is not equal to one. This means that the sign of γ_i can determine the inter-relationship of two energy sources. Similar to *Equation 7*, coefficients β_i and b_i in *Equation 6* also have the same sign, which represents the self-influence effect. A positive γ_i means that an increase in energy consumption will reduce consumption of a second energy source. Conversely, negative γ_i indicates that the consumption of one kind of energy increases the consumption of another kind of energy. How nuclear energy and fossil fuel consumption affect each other can be explored by determining the sign of γ_i in conjunction with statistical significance.

Lotka-Volterra model of CO_2 emissions

The CO_2 emissions from fossil fuels and CO_2 emission savings from nuclear energy are also analyzed using Lotka-Volterra models in this study after analyzing and investigating energy consumption. We have to define the CO_2 emissions from fossil fuels and CO_2 emission savings from nuclear energy before the model constructions. A zero-sum choice is made by policymakers when adopting either nuclear energy or fossil fuels. The condition is determined by either selecting nuclear energy by abandoning fossil fuels, or *vice versa*. Policymakers choose either nuclear energy, thus giving up fossil fuels, or fossil fuel, thus giving up nuclear energy. The overall CO_2 emissions will be reduced if policymakers use nuclear energy, instead of fossil fuels. Using nuclear energy reduces the same consumption amount of fossil fuels, leading to a net reduction of CO_2 emissions. In this work, we developed a CO_2 emission savings for nuclear energy, which expresses how nuclear energy can reduce CO_2 emissions when nuclear energy is used instead of fossil fuels. The indicator of CO_2 emission savings is defined in *Equation 8*:

$$ES^{Nuclear} = UE^{Fossil\_fuel} \times Consumption^{Nuclear} \quad \text{(Eq.8)}$$

where $ES^{Nuclear}$ represents the CO_2 emissions saving from nuclear energy, which is the reduced emissions arising from the use of nuclear energy to replace fossil fuels. UE^{Fossil_fuels} refers to the CO_2 emissions per unit fossil fuels (Tonnes of carbon/Tonnes of oil equivalent). Because nuclear energy generates electric power without any CO_2 emissions, the CO_2 emission saving from using nuclear energy to replace fossil fuels $ES^{Nuclear}$ is equal to nuclear consumption $Consumption^{Nuclear}$ multiplied by CO_2 generated per unit fossil fuels UE^{Fossil_fuel}. Since $ES^{Nuclear}$ illustrates how nuclear

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energy produces clean-up benefits, policymakers can thus regard $ES^{Nuclear}$ as an indicator of the degree of environmental protection issues at the expense of economic development.

On the other hand, policymakers can also choose to use a certain amount of fossil fuels instead of using nuclear energy. Because fossil fuels emit more CO_2 emissions than nuclear energy, choosing a certain amount of fossil fuels to replace the same amount of nuclear energy results in a net increase in CO_2 emissions. The amount of CO_2 emission due to the use of fossil fuels implies that if policymakers choose fossil fuels to obtain economic benefits, it will eventually lead to enhanced pollution; this can be calculated by *Equation 9*:

$$EC^{Fossil\_fuels} = UE^{Fossil\_fuels} \times Consumption^{Fossil\_fuel} \quad \text{(Eq.9)}$$

where EC^{Fossil_fuels} represents the CO_2 emissions due to fossil fuel use, which increases owing to the replacement of nuclear energy; and UE^{Fossil_fuels} refers to the quantity of CO_2 emissions per unit fossil fuels (Tonnes of carbon/Tonnes of oil equivalent). $Consumption^{Fossil\_fuels}$ denotes the quantity of fossil fuels consumed. As fossil fuels generate electric power with emitting a large amount of CO_2, EC^{Fossil_fuels} is equal to the total fossil fuel consumption $Consumption^{Fossil\_fuels}$ multiplied by the CO_2 generated per unit fossil fuels UE^{Fossil_fuels}. This CO_2 emissions indicator of fossil fuels EC^{Fossil_fuels} explain how fossil fuels produce more CO_2 pollution for economic advantage; therefore, policymakers can thus regard EC^{Fossil_fuels} as an indicator of the degree of economic benefit issues at the expense of environmental protections. After we define the CO_2 emissions from fossil fuels and CO_2 emission savings from nuclear energy. We utilize Lotka-Volterra models to analyze the CO_2 emissions from fossil fuels and CO_2 emission savings from nuclear energy as *Equations10* and *11*:

$$\frac{dY_1}{dt} = (p_1 - q_1Y_1 - r_1Y_2)Y_1 = p_1Y_1 - q_1Y_1^2 - r_1Y_1Y_2 \quad \text{(Eq.10)}$$

and

$$\frac{dY_2}{dt} = (p_2 - q_2Y_2 - r_2Y_1)Y_2 = p_2Y_2 - q_2Y_2^2 - r_2Y_2Y_1 \quad \text{(Eq.11)}$$

where $Y_1 \geq 0$ and $Y_2 \geq 0$. Y_1 and Y_2 denote the annual CO_2 emissions of fossil fuel and annual CO_2 emission savings of nuclear energy, respectively; Y_1^2 and Y_2^2 refer to the self-influence of the same energy source; Y_1Y_2 and Y_2Y_1 represent the interactions between both energy sources; $\frac{dY_1}{dt}$ and $\frac{dY_2}{dt}$ denote the annual growth rate of CO_2 emissions from fossil fuel and CO_2 emission savings from nuclear energy.

Equations 10 and *11* have to be converted to a discrete-time version because these equations are in a continuous format, which cannot fit our samples at different times. The discrete-time format of *Equations10* and *11* are expressed as *Equations 12* and *13*:

$$Y_1(t+1) = \frac{\delta_1 Y_1(t)}{1+\lambda_1 Y_1(t)+\theta_1 Y_2(t)} \quad \text{(Eq.12)}$$

and

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$$Y_2(t+1) = \frac{\delta_2 Y_2(t)}{1+\lambda_2 Y(t)+\theta_2 Y_1(t)} \quad \text{(Eq.13)}$$

where δ_i and λ_i represent the logistic parameters of individual energy sources relative to CO_2 emission indicators, and θ_i denotes the magnitude of the influence of one energy on the CO_2 emissions indicator growth rate of another energy source. The relationships of the coefficients of the Lotka-Volterra model and the ones in the converted discrete-time format (*Equations12* and *13*). The parameters of Lotka-Volterra model p_i, q_i, r_i can be expressed in *Equations 14-16*.

$$p_i = \ln \delta_i \quad \text{(Eq.14)}$$

$$q_i = \frac{\lambda_i \delta_i}{\delta_i - 1} = \frac{\lambda_i \ln \delta_i}{\delta_i - 1} \quad \text{(Eq.15)}$$

$$r_i = \theta_i \frac{q_i}{\lambda_i} = \frac{\theta_i}{\lambda_i} \frac{\lambda_i \ln \delta_i}{\delta_i - 1} = \frac{\theta_i \ln \delta_i}{\delta_i - 1} \quad \text{(Eq.16)}$$

In *Equation 16*, θ_i has the same sign as r_i because $\frac{\ln \delta_i}{\delta_i - 1}$ is always positive when δ_i is not equal to one. This means that the sign of θ_i or r_i reflects the competitive relationship between the two energy sources; the coefficients λ_i and q_i can determine the self-influential effect. Through the determination of the sign and the statistical significance of θ_i, this work examined how the CO_2 emission savings of nuclear energy and CO_2 emissions of fossil fuels, affect each other. In *Equations12* and *13*, Y_1 and Y_2 represent annual CO_2 emissions of fossil fuel and annual CO_2 emission savings of nuclear energy, respectively. A positive θ_1 indicates a competitive relationship and implies that as more nuclear energy is used, less CO_2 emissions are produced by fossil fuels in the US. A positive θ_1 can be an indicator of governmental concern for environmental protection efforts; the value usually represents how policymakers evaluate the cleansing effect of nuclear energy. In contrast, a negative θ_1 indicates that when more nuclear energy is used, more CO_2 emissions are produced by fossil fuels in the US. In this instance, nuclear energy does not result in increased environmental protection.

Equilibrium analysis

When equilibrium is reached, the variables or trajectories do not change over time. In the Lotka-Volterra model, when *Equations 1* and *2* are equal to zero, it represents equilibrium stability. Thus,

$$\frac{dX_1}{dt} = 0 \text{ ,and } \frac{dX_2}{dt} = 0 \quad \text{(Eq.17)}$$

Solving *Equation 17* yields:

$$X_1 = \frac{a_1 - c_1 X_2}{b_1}, and\ X_2 = \frac{a_2 - c_2 X_1}{b_2} \quad \text{(Eq.18)}$$

The intersection of the two lines, $\frac{dX_1}{dt} = 0\ and\ \frac{dX_2}{dt} = 0$, implies an equilibrium point, where the consumption of the two energy sources reaches equilibrium and does not change

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over time. If the equilibrium is unstable, the consumption of nuclear energy or fossil fuels will increase infinitely. The intersection of lines, $\frac{dY_1}{dt} = 0$ and $\frac{dY_2}{dt} = 0$, also implies an equilibrium. The stable values of Y_1 and Y_2 can be solved by *Equations 19* and *20*:

$$\frac{dY_1}{dt} = 0, \text{and } \frac{dY_2}{dt} = 0 \quad \text{(Eq.19)}$$

Solving *Equation 19* yields:

$$Y_1 = \frac{p_1 - r_1 Y_2}{q_1}, and\ Y_2 = \frac{p_2 - r_2 Y_1}{q_2} \quad \text{(Eq.20)}$$

The trajectories of CO_2 emission savings from nuclear energy and CO_2 emissions from fossil fuels moving to equilibrium point demonstrates that the annual emissions of CO_2 generated by fossil fuels will saturate and stop increasing. If the equilibrium is stable, fossil fuels may not increase to generate CO_2 emissions infinitely. This study further utilizes the estimated parameter values in the proposed Lotka-Volterra equation to test the equilibrium point's stability through two criteria, Jacobian matrix eigenvalues at the equilibrium point and the Lyapunov function. We can verify whether the final equilibrium point of energy consumption and CO_2 emission indicators between nuclear energy and fossil fuels is stable by calculating the eigenvalues of Jacobian matrix *A* at the equilibrium point with the method of Tsai and Chen (2020). Hritonenko and Yatsenko (1999) denote the condition that both eigenvalues' real parts are negative will let equilibrium point stable. This investigation examines whether the real parts of the Jacobian matrix's eigenvalues are negative at the equilibrium points to ascertain that the energy consumption and CO_2 emissions trajectories stably reach an equilibrium point. In addition, we applied the Lyapunov function to inspect the nonlinear differential equations' stability. If the value of Lyapunov function is positive and the first order differential of Lyapunov function is negative, the trajectories satisfy the conditions in which energy consumption and CO_2 emissions stably reach an equilibrium point.

Analyses of forecast accuracy

We constructed the Bass model for further comparison with the Lotka-Volterra model to demonstrate the accuracy of forecasts. Energy consumption in the Bass (1969) model are expressed as *Equations 21* and *22*, respectively:

$$\frac{dX_1}{dt} = (g_{X1} + h_{X1} X_1)(m_{X1} - X_1) \quad \text{(Eq.21)}$$

$$\frac{dX_2}{dt} = (g_{X2} + h_{X2} X_2)(m_{X2} - X_2) \quad \text{(Eq.22)}$$

where X_1 and X_2 denote the consumption of fossil fuels and nuclear energy, respectively. By following Bass (1969), we estimated the parameters g_{X1}, h_{X1}, m_{X1}, g_{X2} , h_{X2} , and m_{X2}. Parameters m_{X1} and m_{X2} are defined as the maximum consumption of fossil fuels and nuclear energy, respectively.

Also, we constructed the Bass model for further comparison with the Lotka-Volterra model to demonstrate the accuracy of forecasts. Energy CO_2 indicators in the Bass (1969) model are expressed as *Equations 23* and *24*, respectively.

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$$\frac{dY_1}{dt} = (g_{Y1} + h_{Y1}Y_1)(m_{Y1} - Y_1) \quad \text{(Eq.23)}$$

$$\frac{dY_2}{dt} = (g_{Y2} + h_{Y2}Y_2)(m_{Y2} - Y_2) \quad \text{(Eq.24)}$$

where Y_1 and Y_2 denote the CO_2 emissions of fossil fuels and CO_2 emission savings of nuclear energy, respectively. By following Bass (1969), we estimated the parameters g_{Y1}, h_{Y1}, m_{Y1}, g_{Y2}, h_{Y2}, and $m_{Y2.}$ Parameters m_{Y1} and m_{Y2} are defined as the maximum CO_2 emission of fossil fuels and maximum CO_2 emission savings of nuclear energy, respectively.

By using the training samples from 1965 to 2010, we estimated all the parameters g_{X1}, h_{X1}, m_{X1}, g_{X2}, h_{X2}, m_{X2}, g_{Y1}, h_{Y1}, m_{Y1}, g_{Y2}, h_{Y2}, and m_{Y2} in the Bass and then derived the forecast values of the test period, from 2011 to 2017. The prediction accuracy of our proposed Lotka-Volterra model was compared with the Bass model. This work applies mean absolute percentage error (MAPE) to measure the predictive ability of the Lotka-Volterra model, calculated by:

$$MAPE = \frac{1}{n}\sum_{t=1}^{n}\frac{|Z_t - \hat{Z}_t|}{Z_t} \quad \text{(Eq.25)}$$

where Z_t and $\hat{Z}_t$ are the actual and predicted values, respectively, of energy consumption or CO_2 emission indicators. We followed the criteria proposed by Martin and Witt (1989) to evaluate the predictive ability of our Lotka-Volterra Model and the Bass model into four levels. The forecasting accuracy of a model is “excellent” when MAPE is smaller than 10%; it is “good” when MAPE is between 10% and 20%; and “reasonable” when MAPE is between 20% and 50%. This work compares the forecast accuracy of the Lotka-Volterra and Bass models and determines whether the Lotka-Volterra model, which considers the substitutive or complementary relations among various energy resources, has a better predictive ability.

Materials

This study focused on energy consumption and CO_2 emissions in the US. In 2011, nuclear energy accounted for 47% of low-carbon energy in the US, implying that nuclear energy plays an important role in carbon management. This is why we chose nuclear energy in our investigation, to examine whether nuclear energy reduces CO_2 emissions. The data on energy consumption, from 1965 to 2017, were collected from the 2018 Statistical Review of World Energy, widely recognized as a key source of data on energy markets, published on the BP Public Limited Company website. The consumption of fossil fuel in our study is equal to the sum of gas consumption, coal consumption and oil consumption on the BP Public Limited Company website. According to the methodology definition of BP Public Limited Company, the gas consumption includes derivatives of coal and those consumed in gas-to-liquids transformation. Coal consumption includes only solid fuels, whereas oil consumption includes international aviation, marine bunkers, refinery fuel and inland demand. Data on CO_2 emissions of fossil fuels from 1965 to 2017 were collected from the ICOS Carbon Portal, a research infrastructure to quantify the greenhouse gas balance. The sample period was divided into two parts: the training period from 1965 to 2010, and

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the test period, from 2011 to 2017. The model was constructed by using data from the training period. The integrity of the model can be analyzed by examining the parameters obtained by the model. In addition, accuracy can be tested by comparing predicted and observed values in the test period.

Results

Parameter estimation results

Relationship between consumption of fossil fuels and nuclear energy

To understand interactions between fossil fuels and nuclear energy consumption, we explored whether nuclear energy affects the consumption of fossil fuels. The Lotka-Volterra model estimation results of the interaction between nuclear energy and fossil fuels are shown in *Table 1*. The parameter results in *Table 1* show that γ_1 was -3.32×10^{-4}, which is significantly negative at 10% significance level. Thus, the coefficient of the nuclear impact on fossil fuel c_1 is statistically significant since c_1 is a function of γ_1, $c_1 = \gamma_1 \frac{ln\alpha_1}{\alpha_1 - 1}$. It implies nuclear energy X_2 substantially increases the growth of fossil fuel $\frac{dX_1}{dt}$ from the calculation of *Equation 1*. On the other hand, γ_2 was insignificant, according to the *t*-statistics. It implies that fossil fuel X_1 does not obviously affect the growth of nuclear energy $\frac{dX_2}{dt}$. Therefore, these results signify that nuclear energy consumption can enhance the growth of consumption of fossil fuels, but fossil fuel consumption does not have an obvious impact on the growth of consumption of nuclear energy. The relationship between nuclear energy and fossil fuels is one of commensalism. These results are possibly caused by the fact that the frontend mining, the construction of large-scale nuclear power plants, operation, backend waste treatment and decommissioning phases in nuclear life cycle need a substantial amount of electricity generation, the fabrication of which consumes fossil fuels. The US is the country with the most nuclear power plants to replace fossil fuels with nuclear energy. In contrast to the US expectations, our findings provide the evidence that nuclear power plants fail to reduce CO_2 emissions in the US.

Table 1. *The Lotka-Volterra model's parameter estimation results of energy consumption*

	Coefficient	t-statistics		Calculation value
		Fossil fuels		
α1	1.2463	12.9911 ***	*ai*	0.2202
β1	1.56×10^{-4}	2.3824 **	*bi*	1.39×10^{-4}
γ1	-3.32×10^{-4}	-1.7350 *	*ci*	2.97×10^{-4}
		Nuclear energy		
α2	1.006	7.7466 ***	*ai*	0.0959
β2	0.0011	3.3000 **	*bi*	9.6×10^{-4}
γ2	-4.7×10-5	-0.5191	*ci*	-4.50×10^{-5}

$^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$

In addition, the processes of enriching uranium, treating radioactive waste, and the decommissioning and management of a nuclear plant, consume a considerable amount of fossil fuels. Consistent with the viewpoints in previous studies (Lenzen, 2008;

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Sovacool, 2008), our results emphasize that nuclear energy will increase the growth of fossil fuel consumption when we take the whole life cycle of nuclear power into account, even though the electricity generation of nuclear power plants does not require fossil fuels. Nuclear energy is not the suitable resource to reduce fossil fuel consumption for the environmental protection purpose of the US. These results explain why large amounts of fossil fuels are consumed during the whole life cycle of nuclear energy. In addition, the self-influence coefficient, β_i, was significantly positive, which means that there was a negative force within fossil fuels, or nuclear energy, to suppress its own growth. The growth rate of fossil fuels will be slowed by their own power of suppression.

Relationships between CO_2 emissions of fossil fuels and nuclear energy

The Lotka-Volterra model estimation results of the relationship between the CO_2 emission savings of nuclear energy and CO_2 emissions of fossil fuels is shown in *Table* 2. The parameter results in *Table* 2 demonstrate that θ_1 was -0.0005 and was significantly negative according to the *t*-statistics. The signs of θi and *ci* are the same, so this negative θ_1 suggests that greater CO_2 emission savings of nuclear energy lead to more CO_2 emissions from fossil fuels in the US. However, θ_2 was insignificant, according to the *t*-statistics. CO_2 emissions of fossil fuel do not have significant impact on the CO_2 emissions from nuclear energy in the US. In summary, nuclear energy can increase the growth of CO_2 emissions of fossil fuels, but fossil fuels did not have an obvious impact on the growth of nuclear energy. Therefore, these results signify that the CO_2 emissions relationship between nuclear energy and fossil fuels is one of commensalism. The results suggest that CO_2 emissions savings from the usage of nuclear energy enhance the CO_2 emissions growth from fossil fuels.

Table 2. *The Lotka-Volterra model's parameter estimation results of CO_2 emissions*

	Coefficient	**t-statistics**		**Calculation value**
		Fossil fuels		
δ_1	1.2319	13.1874 ***	p_i	0.2086
λ_1	1.9×10^{-4}	2.2698 **	q_i	1.7×10^{-4}
θ_1	-0.0005	-1.7091 *	r_i	-4.4×10^{-4}
		Nuclear energy		
δ_2	1.1104	8.0010 ***	p_i	0.1047
λ_2	0.0013	2.9714 ***	q_i	0.0012
θ_2	-5.9×10^{-5}	-0.5017	r_i	-5.5×10^{-5}

*p < 0.1, **p < 0.05, ***p < 0.01

Combining the results of *Tables 1* and *2,* nuclear energy contributes to the consumption of fossil fuels in *Equation 1* throughout its product life cycle, leading to an increase in the CO_2 emissions of fossil fuels in *Equation 10*. Both consumption and CO_2 emissions indicators exhibited a similar relationship, whereby nuclear energy enhanced fossil fuel growth and fossil fuels exerted no effect on nuclear energy. Because it is not feasible for nuclear energy to replace fossil fuels to generate electric power, the "carbon-free" nuclear energy is not an effective energy resource to reduce CO_2 emissions in the US. Lenzen (2008) indicated that the most of the greenhouse gas

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emissions are caused in processing stages upstream and downstream in nuclear life cycle from nuclear plants. Sovacool (2008) illustrates that the nuclear generate greenhouse gas emissions from frontend, construction, operation, backend and decommissioning phases and greenhouse emission intensity in the frontend and decommissioning phases is larger than those in the other phases of the nuclear life cycle. The viewpoints of Lenzen (2008) and Sovacool (2008) concurred with the empirical results of parameter estimations in our proposed Lotka-Volterra model.

Equilibrium analysis results

Jacobian matrix at the equilibrium point of energy consumption

The X-axis and Y-axis in *Figure 1* represent nuclear energy and fossil fuel consumption, respectively. The values of the trajectory in 1965 start from area IV: ($X_1 < \frac{a_1 - c_1 X_2}{b_1}$ and $X_2 < \frac{a_2 - c_2 X_1}{b_2}$) and transit to area I: ($X_1 < \frac{a_1 - c_1 X_2}{b_1}$ and $X_2 > \frac{a_2 - c_2 X_1}{b_2}$). From 1979 to 1983 fossil fuel consumption decreased continually: $\frac{dX_1}{dt} < 0$, during the initial phase of using of nuclear energy. However, fossil fuel consumption increased substantially and moved into area I in 2007. This implies that nuclear energy reduced fossil fuel consumption only during the early stages of nuclear plant operation, but enhanced fossil fuel consumption during the middle and late stages because waste treatment, management, and decommissioning of nuclear plants require a lot of electricity, which was generated from fossil fuels.

The real parts of the eigenvalues of the Jacobian matrix $\boldsymbol{A}$ at the equilibrium point were -0.3087 and -0.1423. The negative real parts of eigenvalues indicate that the orbits computed using our Lotka–Volterra equations satisfy the Hritonenko and Yatsenko (1999) stability conditions. By applying the eigenvalues of the Jacobian matrix at the equilibrium point, our investigation verified that the annual consumption of fossil fuels finally reaches a long-term equilibrium point 1990.00 million tonnes oil equivalent, approximately ten times the equilibrium point of nuclear consumption 193.18 million tonnes oil equivalent. Fossil fuels of 1,945.88 million tonnes oil equivalent were consumed in 2010, which will increase by 2.27% by approximately 2075.

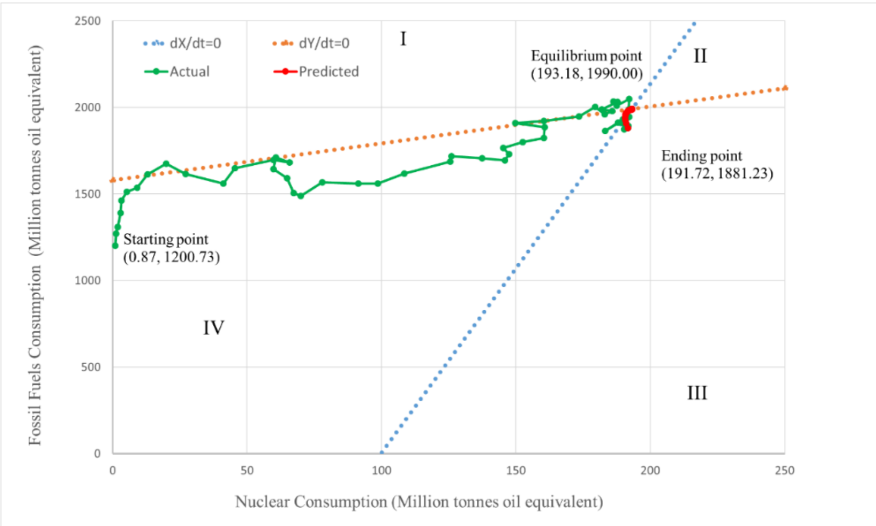

Figure 1. *Phase diagram for the consumption of annual fossil fuel and nuclear energy*

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Lyapunov analysis of energy consumption

The Lyapunov stability equilibrium analysis established that $V(x') = 1.0229 \times 10^7 > 0$, $\dot{V}(x') = -3.9973 \times 10^7 < 0$, demonstrating that the trajectory satisfied the conditions for a stable equilibrium point at approximately 2071, with fossil fuel consumption ultimately being ten-fold the consumption of nuclear energy. *Figure* 2 depicts actual and forecasted consumption of fossil fuels and nuclear energy from 1965 to 2017 and the consumption forecast of fossil fuels and nuclear energy subsequent to 2018. Fossil fuel consumption decreased with the increased use of nuclear energy from 1979 to 1983. From 1983 to 2007, the use of nuclear energy accelerated the consumption of fossil fuels because the construction, management and decommissioning of nuclear plants require a lot of electricity generated from fossil fuels. From 2007 to 2009, the decreasing consumption of nuclear energy from 192 to 190 million tonnes oil equivalent led to a reduction of fossil fuel consumption from 2,049 to 1,873 million tonnes of oil equivalent. The trajectory of fossil fuel consumption was positively related to nuclear energy consumption; there is no obvious evidence that nuclear energy can replace fossil fuels.

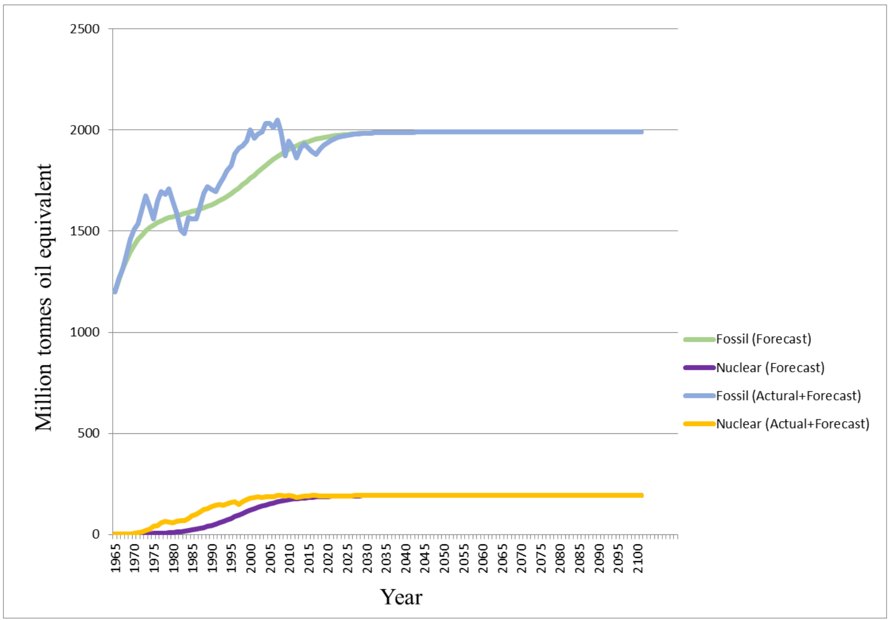

Figure 2. *Time-series consumption of fossil fuels and nuclear energy*

Jacobian matrix at the equilibrium point of CO_2 emissions

The X-axis and Y-axis in *Figure* 3 represent the CO_2 emission saving of nuclear energy and the CO_2 emissions of fossil fuels, respectively. The trajectory starts in 1965 from area IV ($Y_1 < \frac{a_1 - c_1 Y_2}{b_1}$ and $Y_2 < \frac{a_2 - c_2 Y_1}{b_2}$) and change to area I ($Y_1 < \frac{a_1 - c_1 Y_2}{b_1}$ and $Y_2 > \frac{a_2 - c_2 Y_1}{b_2}$). From 1979 to 1983, CO_2 emissions of fossil fuel decreased continually: $\frac{dY_1}{dt} < 0$, during the initial stage of using of nuclear energy. However, fossil fuel CO_2 increased substantially and changed to area I in 2007. The use of nuclear energy accelerated the CO_2 emissions of fossil fuels. Our investigation verified that CO_2 emission of fossil fuels finally reaches a long-term equilibrium point 1,623.56 million

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tonnes of carbon, approximately ten times the equilibrium point of nuclear CO_2 emission savings 156.52 million tonnes of carbon.

The real parts of eigenvalues of the Jacobian matrix $\boldsymbol{A}$ at the equilibrium point were -0.4322 and -0.2074. The negative real parts of eigenvalues indicate that the trajectories of our Lotka–Volterra equations satisfy the Hritonenko and Yatsenko (1999) stability conditions. Although the CO_2 emissions of fossil fuels and CO_2 emissions-savings of nuclear energy were 1,438.19 and 147.53 million tonnes of carbon in 2017, respectively, the CO_2 emissions of fossil fuels and CO_2 emission savings of nuclear energy would finally converge to their equilibrium point in the future, at 1,623.56 and 156.52 million tonnes of carbon, respectively.

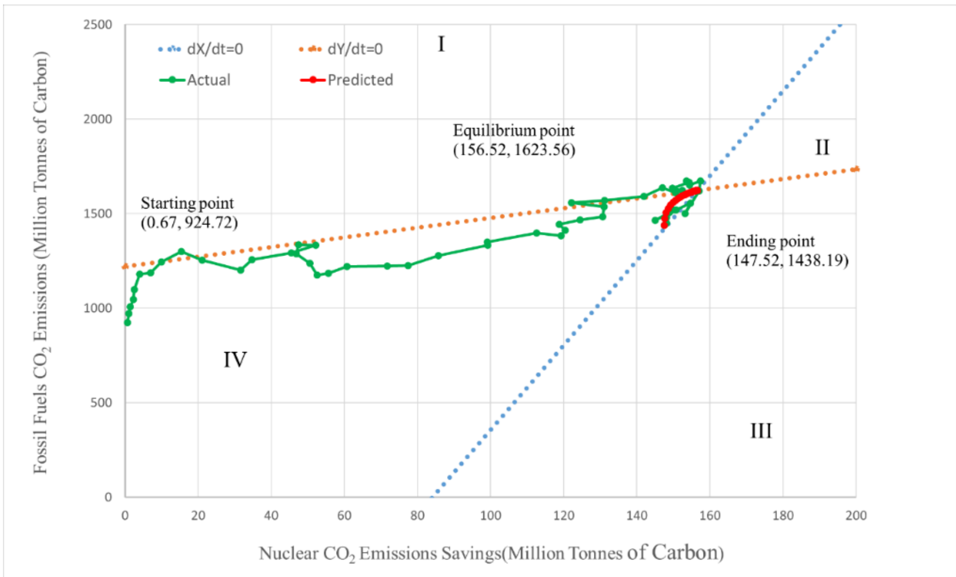

***Figure 3.** Phase diagram for the fossil fuel CO_2 emission and the nuclear CO_2 emission savings*

Lyapunov analysis results of CO_2 emissions

The Lyapunov stability equilibrium analysis established that $V(x') = 4.8424 \times 10^6 > 0$, $\dot{V}(x') = -2.6585 \times 10^7 < 0$, demonstrating that the trajectory satisfied the stability conditions of its equilibrium by approximately 2075. The fossil fuel CO_2 emissions will ultimately be ten-fold the CO_2 emission savings of nuclear energy. *Figure* 4 depicts actual and forecasted CO_2 emissions of fossil fuels and CO_2 emission savings of nuclear energy from 1965 to 2017 and the consumption forecast of fossil fuels and nuclear energy subsequent to 2018. Fossil fuel CO_2 emissions decreased with the increasing use of nuclear energy from 1979 to 1983. From 1983 to 2007, the use of nuclear energy accelerated the CO_2 emission of fossil fuels because the construction, waste management, and decommissioning of nuclear plants require a lot of electricity generated from fossil fuels. Combining the results of fossil fuel CO_2 emissions with nuclear consumption, decreasing the consumption of nuclear energy from 192 to 190 million tonnes oil equivalent led to the reduction of CO_2 emissions from 1,673 to 1,500 million tonnes of carbon from 2007 to 2009. This supports the conclusion that in the long run, using nuclear energy will increase fossil fuel consumption and thus increase CO_2 emissions, even though the use of nuclear energy in the short term can reduce CO_2 emissions.

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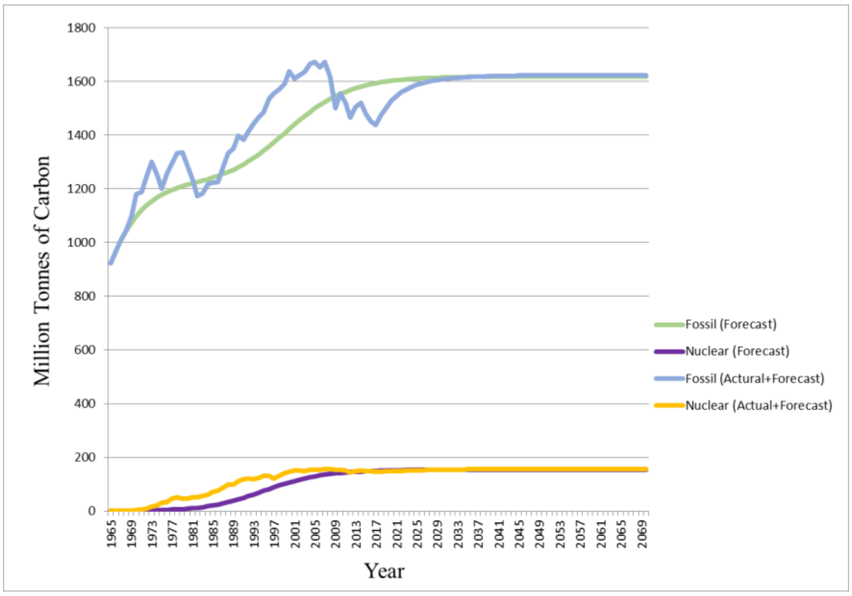

Figure 4. *Time-series CO_2 emissions of fossil fuels and CO_2 emission savings of nuclear energy*

Results of forecast accuracy analysis

We then applied the parameter values to our Lotka-Volterra model to predict the consumption of fossil fuels and nuclear energy in the test period, using the Lotka-Volterra and Bass models (*Fig. 5a* and *b*). Predicted consumption of the Lotka-Volterra model were extremely close to the actual consumption of fossil fuels and nuclear energy. In contrast, the predicted consumption of the Bass model was far from the actual consumption of fossil fuels and nuclear energy. Because our proposed Lotka-Volterra model sets the negative signs before interaction items in *Equation 2*, negative interaction parameter c_i in *Table 1* denotes that the consumption of fossil fuel increased the consumption of nuclear energy. However, the Bass model does not consider the enhance of fossil fuels on nuclear energy consumption, so the Bass model underestimated the nuclear clear consumption in test period. This can explain why the forecasted error of our proposed Lotka-Volterra model is much smaller than the Bass model in predicting nuclear energy consumption.

Figure 6a depicts the actual and predicted values using the Lotka-Volterra and Bass model for the CO_2 emissions of fossil fuels and nuclear energy, respectively, during the test period. *Figure 6b* shows that the forecast CO_2 emission savings predicted by the Lotka-Volterra model is closer to the actual CO_2 emission savings of nuclear energy than the values predicted by the Bass model. Because the Bass model does not consider the enhance of fossil fuels CO_2 emission on nuclear energy CO_2 emission savings, the Bass model underestimated the nuclear CO_2 emission savings in test period.

Table 3 summarizes the forecast accuracy of fossil fuel and nuclear energy consumption and CO_2 emissions indicators during the test period. Graphs stagnation of the Lotka-Volterra predicted value caused by the fact that the error rate of the prediction value of Lotka-Volterra model is lower than 8% as shown in *Table 3*. It implies the prediction is already very close to the actual value. However, the difference between actual value and predicted value is relatively small, leading a smooth prediction curve and no corresponding trend can be seen. Particularly, *Figures 5* and *6* also exhibits the

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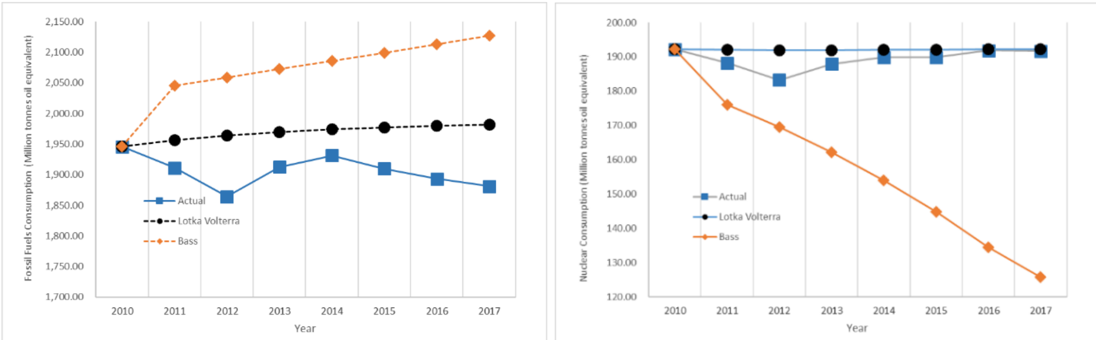
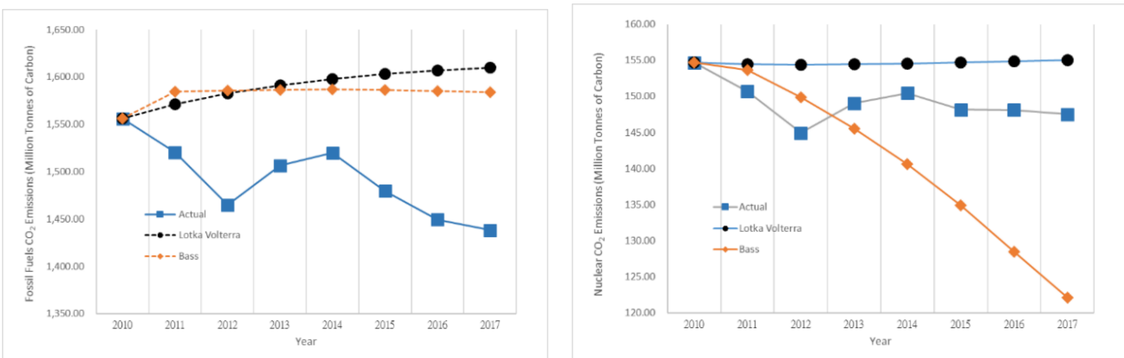
prediction of the Bass model. Due to the large error rate of Bass value, the predicted value of Lotka-Volterra model in *Figures 5* and *6* looks more rigid at a certain level.



(a) Fossil fuel (b) Nuclear energy

Figure 5. *The consumption trajectory for fossil fuel (a) and nuclear energy (b)*



(a) Fossil fuel (b) Nuclear energy

Figure 6. *The trajectory of fossil fuel CO_2 emission (a) and nuclear CO_2 emission savings (b)*

Table 3. *Forecast accuracy of fossil fuel and nuclear energy*

Consumption	Lotka-Volterra	Bass
Fossil fuel	3.77%	9.79%
Nuclear energy	1.66%	19.22%
CO_2 emission indicators		
CO_2 emissions of fossil fuel	7.62%	6.98%
CO_2 emission savings of nuclear energy	4.21%	7.66%

In the course of the test period, the MAPEs of the predicted consumption of the Lotka-Volterra model for fossil fuels were 3.77%, whereas the result was 1.66% for nuclear energy. All MAPEs of the predicted values, derived from the Lotka-Volterra model, were lower than 10%, indicative of an excellent predictive accuracy (Martin and Witt, 1989). The results demonstrate the reliability of our Lotka-Volterra model in predicting energy consumption. However, the MAPEs of the predicted consumption of the Bass model were 9.79% for fossil fuels and 19.22% for nuclear energy within the test periods. The MAPEs of the predicted consumption forecast by our Lotka-Volterra

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model were lower than those forecast by the Bass model during the test period. Because the Bass model does not consider the enhance of fossil fuels on nuclear energy consumption, the Bass model underestimated the nuclear clear consumption in test period. This explains why our proposed Lotka-Volterra model outperforms the Bass model in predicting the nuclear consumption.

Table 3 also denote that the MAPEs of the predicted CO_2 emissions from fossil fuels and the savings of CO_2 emission with nuclear energy, derived from our Lotka-Volterra model, were 7.62% and 4.21%, respectively, over the test period. All of the MAPEs of the values predicted by the Lotka-Volterra model were lower than 10%, indicative of an excellent predictive accuracy. The analytical results demonstrated the reliability of our prediction with Lotka-Volterra model in CO_2 emissions. In contrast, the MAPEs of the predicted CO_2 emissions of the Bass model were 6.98% and 7.66%, from fossil fuels and nuclear energy, respectively, throughout the test period. The MAPE difference of the predicted CO_2 emissions generated from fossil fuels between Lotka-Volterra and Bass models were no more than 1%, but the MAPE of the predicted CO_2 emissions savings of nuclear energy forecasted by the Lotka-Volterra model was lower than that of the CO_2 emissions savings forecasted by the Bass model by more than 3%.

The predictions of the CO_2 emissions and consumption of fossil fuels and nuclear energy with Lotka-Volterra model, were excellent, according to the criteria of Martin and Witt (1989). The analytical results demonstrated the trustworthiness of energy consumption prediction with the Lotka-Volterra model, and the MAPE of the Bass model was larger than 10%, indicative of a good, but not excellent, predictive ability. Except for the CO_2 emissions due to fossil fuels, the analytical results demonstrated that the forecast accuracy of the Lotka-Volterra model was superior to that of the Bass model. This work proved the dynamic interactions between fossil fuel and nuclear energy, thereby explaining the CO_2 emissions and predicting future energy consumption in the US.

Discussion

Regarding the long-term CO_2 emission calculation for the two energy production ways, nuclear power generation relies on nuclear fission without greenhouse gas emissions, while fossil fuel power generation relies on fuel combustion with greenhouse gas emissions. The greenhouse gas emissions are mainly CO_2 emissions. In order to compare the two energy under the consistent basis, we deducted the total emissions of fossil fuel power generation from fuel combustion. Our comparison of fossil fuels and nuclear energy are based on the long-term greenhouse gas emissions from the frontend mining, construction, operation, backend waste treatment to decommissioning phases.

For fossil fuels, Hondo (2005) reveals life cycle greenhouse gas emission of coal-fired, oil-fired, liquefied natural gas-fired and liquefied natural gas combined cycle power generation. There are 3.6, 32, and 52.9 gCO_2e/kWh in the construction, operation and methane leakage phases, respectively for coal-fired power generation. There are 2.3, 35.2, and 0.3 gCO_2e/kWh in the construction, operation and methane leakage phases, respectively for oil-fired power generation. There are 2.9, 117.7, and 9.1 gCO_2e/kWh in the construction, operation and methane leakage phases, respectively for liquefied natural gas-fired power generation. There are 2.7, 100.9, and 7.7 gCO_2e/kWh in the construction, operation and methane leakage phases, respectively for liquefied natural gas combined cycle power generation. Since fossil fuels are

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composed by coal-fired, oil-fired, liquefied natural gas and liquefied natural gas combined cycle, there are in average 2.875, 71.45, and 17.5 gCO_2e/kWh in the construction, operation and methane leakage phases, respectively for fossil fuels.

For nuclear energy, Sovacool (2008) reveals nuclear fuel cycle, and indicates the quantity CO_2 footprint per kWh at every stage. There are at least 0.58 gCO_2e/kWh, at most 118 gCO_2e/kWh, in average 25.09 gCO_2e/kWh in the frontend phase, including mining, milling, conversion, enrichment, fuel fabrication and transportation. Then, there are at least 0.27 gCO_2e/kWh, at most 35 gCO_2e/kWh, in average 8.2 gCO_2e/kWh in the construction phase, including all materials and energy input for building the facility. Additionally, there are at least 0.1 gCO_2e/kWh, at most 40 gCO_2e/kWh, in average 11.58 gCO_2e/kWh in the operating phase, including maintenance, cooling and fuel cycles, backup generators during outages and shutdowns. Moreover, there are at least 0.4 gCO_2e/kWh, at most 40.75 gCO_2e/kWh, in average 9.2 gCO_2e/kWh in the backend phase, including fuel processing, conditioning, reprocessing, interim and permanent storage. Lastly, there are at least 0.01 gCO_2e/kWh, at most 54.5 gCO_2e/kWh, in average 12.01 gCO_2e/kWh in the decommissioning phase, including deconstruction of facility and land reclamation. From Sovacool (2008), we could observe that the CO_2 emission intensity in the frontend and decommissioning phases is larger than those in the other phases. Nuclear energy totally causes long-term CO_2 emissions at least 1.36, gCO_2e/kWh in average 66.08 gCO_2e/kWh, and at most 288.25 gCO_2e/kWh. CO_2 emissions of the nuclear energy seem no less than fossil fuels CO_2 emissions 91.8 gCO_2e/kWh if fossil fuels and nuclear energy are compared based on the long-term greenhouse gas emissions from the frontend mining, construction, operation, backend waste treatment to decommissioning phases. Under the technology in our sample period from 1965 to 2017, our findings indicate nuclear life cycle requires electricity generated from fossil fuels so as to emit incremental CO_2.

Conclusion

This study assessed energy consumption and CO_2 emissions in the US and examined the relationship between fossil fuels and nuclear energy. We determined whether nuclear energy can replace fossil fuels, thereby reducing CO_2 emissions in the US. Our results show that nuclear energy increased the consumption of fossil fuels, rather than deterring the use of fossil fuels. Uranium mining, concentration, conversion, manufacturing, transportation, and the disposal of radioactive waste, including curing, transportation, landfill, the construction and management of treatment plants, and decommissioning and long-term management of nuclear power plants, all consume a large amount of traditional fossil fuels. Therefore, the use of nuclear energy inevitably contributes to a growth in the consumption of fossil fuels and concomitant CO_2 emissions. Nuclear energy is not the suitable resource to reduce fossil fuel usage and CO_2 emissions for the environmental protection and public health purpose of the US. Our results regarding the relationship between nuclear energy and fossil fuels are in agreement with those of previous studies. While the use of nuclear energy may not emit CO_2 during electricity generation, the use of nuclear energy increases fossil fuel consumption throughout the entire life cycle of nuclear power, from the construction of the plant until its decommissioning, and thereby further increases CO_2 emissions. This result verifies that from the construction of a nuclear plant until its decommissioning,

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nuclear power plants increase fossil fuels consumption, which explains the difficulty of the CO_2 emission reductions in the US.

In addition, we find that nuclear energy consumption decreased fossil fuels in a short run from 1979 to 1983, but nuclear energy consumption positively increased fossil fuel consumption and CO_2 emission in the long run. The results of equilibrium analysis show the consumption of fossil fuels and nuclear energy will reach a stable and constant level in the long term. The consumption of fossil fuels will ultimately be ten-fold the consumption of nuclear energy. This implies that nuclear energy reduced fossil fuel consumption only during the early stages of nuclear plant operation, but enhanced fossil fuel consumption during the middle and late stages because waste treatment, management, and decommissioning of nuclear plants require a lot of electricity, which was generated from fossil fuels. Fossil fuels are still the main sources of power generation and CO_2 emissions. Finally, this work explored the forecast accuracy of our Lotka-Volterra model and compared the forecast accuracy of the Lotka-Volterra model with the Bass model in predicting the amount of energy consumed and CO_2 emission indicators of these energy sources. Our estimations of forecast accuracy showed that the Lotka-Volterra model, which considers the substitutive or complementary relations among various energy sources, generally performed better than the Bass model in predicting the consumption and CO_2 emission indicators of fossil fuels and nuclear energy. To sum up, reducing CO_2 emissions in the US requires new technologies to improve the efficiency of fossil power generation. Nowadays, the importance of renewable energy production needs to be emphasized as well. The power demand of nuclear waste management could be supplied from renewable sources and this can modify the whole CO_2 emission. However, this paper dose not investigate the feasibility of renewable energy to replace fossil fuels to generate electricity. Future studies can further explore the consumption relationships among fossil fuels, renewable energy and nuclear energy to examine the feasibility of renewable energy to replace fossil fuels to reduce CO_2 emissions.

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