

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

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(Received 17<sup>th</sup> Oct 2021; accepted 23<sup>rd</sup> Dec 2021)

**Abstract.** This study applied the Lotka-Volterra model to energy consumption and carbon dioxide (CO<sub>2</sub>) 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<sub>2</sub> 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<sub>2</sub> emissions. Utilization of nuclear energy fails to reduce fossil fuel consumption and CO<sub>2</sub> 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<sub>2</sub> emissions because the Lotka-Volterra model considers how nuclear energy affects the consumption and CO<sub>2</sub> emissions of fossil fuels, while the Bass model does not.

**Keywords:** *decommissioning, Lyapunov functions, equilibrium analysis, forecast accuracy, CO<sub>2</sub>*

## Introduction

This study applied the Lotka-Volterra model to explore how the utilization of nuclear energy affects fossil fuel consumption and CO<sub>2</sub> emissions in the United States (US) since the US is the country with the most nuclear power plants. CO<sub>2</sub> 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. Abatzoglou 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<sub>2</sub> 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<sub>2</sub> emission accelerate climate change. García-Martosa et al. (2013) stated the continued use of fossil fuels cause increased CO<sub>2</sub> 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<sub>2</sub> to be emitted from China. It is critical to control CO<sub>2</sub> emissions to avoid extreme global warming. Gustavsson et al. (2011) recovered, refined and transported logging residues to replace fossil fuels and obtain the benefits of CO<sub>2</sub>

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<sub>2</sub> is emitted during power generation. Consequently, the CO<sub>2</sub> 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<sub>2</sub>. Although nuclear power yields zero CO<sub>2</sub> 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<sub>2</sub>/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<sub>2</sub>/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

substitute fossil fuels and lessen CO<sub>2</sub> 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<sub>2</sub> globally, it is critical to provide tangible evidence of the consumption and the CO<sub>2</sub> 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<sub>2</sub> emissions in the US. This work concentrates on CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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

environmental protection to utilize the nuclear energy instead of fossil fuels and reduce to CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> emissions. Therefore, reducing CO<sub>2</sub> 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:

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

and

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

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:

$$X_1(t+1) = \frac{\alpha_1 X_1(t)}{1 + \beta_1 X_1(t) + \gamma_1 X_2(t)} \quad (\text{Eq.3})$$

and

$$X_2(t+1) = \frac{\alpha_2 X_2(t)}{1 + \beta_2 X_2(t) + \gamma_2 X_1(t)} \quad (\text{Eq.4})$$

where  $\alpha_i$  and  $\beta_i$  represent the logistic parameters of individual energy consumption, and  $\gamma_i$  denotes the magnitude of the impact of one energy source on the growth rate of

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.

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

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

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

In Equation 7,  $\gamma_i$  has the same sign as  $c_i$  because  $\frac{\ln \alpha_i}{\alpha_i - 1}$  is always positive when  $\alpha_i$  is not equal to one. This means that the sign of  $\gamma_i$  can determine the inter-relationship of two energy sources. Similar to Equation 7, coefficients  $\beta_i$  and  $b_i$  in Equation 6 also have the same sign, which represents the self-influence effect. A positive  $\gamma_i$  means that an increase in energy consumption will reduce consumption of a second energy source. Conversely, negative  $\gamma_i$  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  $\gamma_i$  in conjunction with statistical significance.

### Lotka-Volterra model of CO<sub>2</sub> emissions

The CO<sub>2</sub> emissions from fossil fuels and CO<sub>2</sub> 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<sub>2</sub> emissions from fossil fuels and CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> emissions. In this work, we developed a CO<sub>2</sub> emission savings for nuclear energy, which expresses how nuclear energy can reduce CO<sub>2</sub> emissions when nuclear energy is used instead of fossil fuels. The indicator of CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> emissions per unit fossil fuels (Tonnes of carbon/Tonnes of oil equivalent). Because nuclear energy generates electric power without any CO<sub>2</sub> emissions, the CO<sub>2</sub> emission saving from using nuclear energy to replace fossil fuels  $ES^{Nuclear}$  is equal to nuclear consumption  $Consumption^{Nuclear}$  multiplied by CO<sub>2</sub> generated per unit fossil fuels  $UE^{Fossil\_fuel}$ . Since  $ES^{Nuclear}$  illustrates how nuclear

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<sub>2</sub> 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<sub>2</sub> emissions. The amount of CO<sub>2</sub> 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:

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

where  $EC^{Fossil\_fuels}$  represents the CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub>,  $EC^{Fossil\_fuels}$  is equal to the total fossil fuel consumption  $Consumption^{Fossil\_fuels}$  multiplied by the CO<sub>2</sub> generated per unit fossil fuels  $UE^{Fossil\_fuels}$ . This CO<sub>2</sub> emissions indicator of fossil fuels  $EC^{Fossil\_fuels}$  explain how fossil fuels produce more CO<sub>2</sub> 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<sub>2</sub> emissions from fossil fuels and CO<sub>2</sub> emission savings from nuclear energy. We utilize Lotka-Volterra models to analyze the CO<sub>2</sub> emissions from fossil fuels and CO<sub>2</sub> emission savings from nuclear energy as Equations 10 and 11:

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

and

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

where  $Y_1 \geq 0$  and  $Y_2 \geq 0$ .  $Y_1$  and  $Y_2$  denote the annual CO<sub>2</sub> emissions of fossil fuel and annual CO<sub>2</sub> 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<sub>2</sub> emissions from fossil fuel and CO<sub>2</sub> 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 Equations 10 and 11 are expressed as Equations 12 and 13:

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

and

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

where  $\delta_i$  and  $\lambda_i$  represent the logistic parameters of individual energy sources relative to CO<sub>2</sub> emission indicators, and  $\theta_i$  denotes the magnitude of the influence of one energy on the CO<sub>2</sub> 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 (*Equations 12 and 13*). The parameters of Lotka-Volterra model  $p_i$ ,  $q_i$ ,  $r_i$  can be expressed in *Equations 14-16*.

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

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

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

In *Equation 16*,  $\theta_i$  has the same sign as  $r_i$  because  $\frac{\ln \delta_i}{\delta_i - 1}$  is always positive when  $\delta_i$  is not equal to one. This means that the sign of  $\theta_i$  or  $r_i$  reflects the competitive relationship between the two energy sources; the coefficients  $\lambda_i$  and  $q_i$  can determine the self-influential effect. Through the determination of the sign and the statistical significance of  $\theta_i$ , this work examined how the CO<sub>2</sub> emission savings of nuclear energy and CO<sub>2</sub> emissions of fossil fuels, affect each other. In *Equations 12 and 13*,  $Y_1$  and  $Y_2$  represent annual CO<sub>2</sub> emissions of fossil fuel and annual CO<sub>2</sub> emission savings of nuclear energy, respectively. A positive  $\theta_1$  indicates a competitive relationship and implies that as more nuclear energy is used, less CO<sub>2</sub> emissions are produced by fossil fuels in the US. A positive  $\theta_1$  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  $\theta_1$  indicates that when more nuclear energy is used, more CO<sub>2</sub> 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:

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

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

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:

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

The trajectories of CO<sub>2</sub> emission savings from nuclear energy and CO<sub>2</sub> emissions from fossil fuels moving to equilibrium point demonstrates that the annual emissions of CO<sub>2</sub> generated by fossil fuels will saturate and stop increasing. If the equilibrium is stable, fossil fuels may not increase to generate CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> indicators in the Bass (1969) model are expressed as *Equations 23* and *24*, respectively.



$$\frac{dy_1}{dt} = (g_{Y1} + h_{Y1}Y_1)(m_{Y1} - Y_1) \quad (\text{Eq.23})$$

$$\frac{dy_2}{dt} = (g_{Y2} + h_{Y2}Y_2)(m_{Y2} - Y_2) \quad (\text{Eq.24})$$

where  $Y_1$  and  $Y_2$  denote the CO<sub>2</sub> emissions of fossil fuels and CO<sub>2</sub> 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<sub>2</sub> emission of fossil fuels and maximum CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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

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  $\gamma_1$  was  $-3.32 \times 10^{-4}$ , 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  $\gamma_1$ ,  $c_1 = \gamma_1 \frac{\ln \alpha_1}{\alpha_1 - 1}$ . 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,  $\gamma_2$  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<sub>2</sub> emissions in the US.

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

|                | Coefficient            | t-statistics |       | Calculation value      |
|----------------|------------------------|--------------|-------|------------------------|
| Fossil fuels   |                        |              |       |                        |
| $\alpha_1$     | 1.2463                 | 12.9911 ***  | $a_i$ | 0.2202                 |
| $\beta_1$      | $1.56 \times 10^{-4}$  | 2.3824 **    | $b_i$ | $1.39 \times 10^{-4}$  |
| $\gamma_1$     | $-3.32 \times 10^{-4}$ | -1.7350 *    | $c_i$ | $2.97 \times 10^{-4}$  |
| Nuclear energy |                        |              |       |                        |
| $\alpha_2$     | 1.006                  | 7.7466 ***   | $a_i$ | 0.0959                 |
| $\beta_2$      | 0.0011                 | 3.3000 **    | $b_i$ | $9.6 \times 10^{-4}$   |
| $\gamma_2$     | $-4.7 \times 10^{-5}$  | -0.5191      | $c_i$ | $-4.50 \times 10^{-5}$ |

\*  $p < 0.1$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

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;

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,  $\beta_i$ , 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<sub>2</sub> emissions of fossil fuels and nuclear energy*

The Lotka-Volterra model estimation results of the relationship between the CO<sub>2</sub> emission savings of nuclear energy and CO<sub>2</sub> emissions of fossil fuels is shown in Table 2. The parameter results in Table 2 demonstrate that  $\theta_1$  was -0.0005 and was significantly negative according to the *t*-statistics. The signs of  $\theta_i$  and  $c_i$  are the same, so this negative  $\theta_1$  suggests that greater CO<sub>2</sub> emission savings of nuclear energy lead to more CO<sub>2</sub> emissions from fossil fuels in the US. However,  $\theta_2$  was insignificant, according to the *t*-statistics. CO<sub>2</sub> emissions of fossil fuel do not have significant impact on the CO<sub>2</sub> emissions from nuclear energy in the US. In summary, nuclear energy can increase the growth of CO<sub>2</sub> 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<sub>2</sub> emissions relationship between nuclear energy and fossil fuels is one of commensalism. The results suggest that CO<sub>2</sub> emissions savings from the usage of nuclear energy enhance the CO<sub>2</sub> emissions growth from fossil fuels.

**Table 2.** The Lotka-Volterra model's parameter estimation results of CO<sub>2</sub> emissions

|                | Coefficient           | t-statistics |       | Calculation value     |
|----------------|-----------------------|--------------|-------|-----------------------|
| Fossil fuels   |                       |              |       |                       |
| $\delta_1$     | 1.2319                | 13.1874 ***  | $p_i$ | 0.2086                |
| $\lambda_1$    | $1.9 \times 10^{-4}$  | 2.2698 **    | $q_i$ | $1.7 \times 10^{-4}$  |
| $\theta_1$     | -0.0005               | -1.7091 *    | $r_i$ | $-4.4 \times 10^{-4}$ |
| Nuclear energy |                       |              |       |                       |
| $\delta_2$     | 1.1104                | 8.0010 ***   | $p_i$ | 0.1047                |
| $\lambda_2$    | 0.0013                | 2.9714 ***   | $q_i$ | 0.0012                |
| $\theta_2$     | $-5.9 \times 10^{-5}$ | -0.5017      | $r_i$ | $-5.5 \times 10^{-5}$ |

\*  $p < 0.1$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

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<sub>2</sub> emissions of fossil fuels in Equation 10. Both consumption and CO<sub>2</sub> 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<sub>2</sub> emissions in the US. Lenzen (2008) indicated that the most of the greenhouse gas

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.

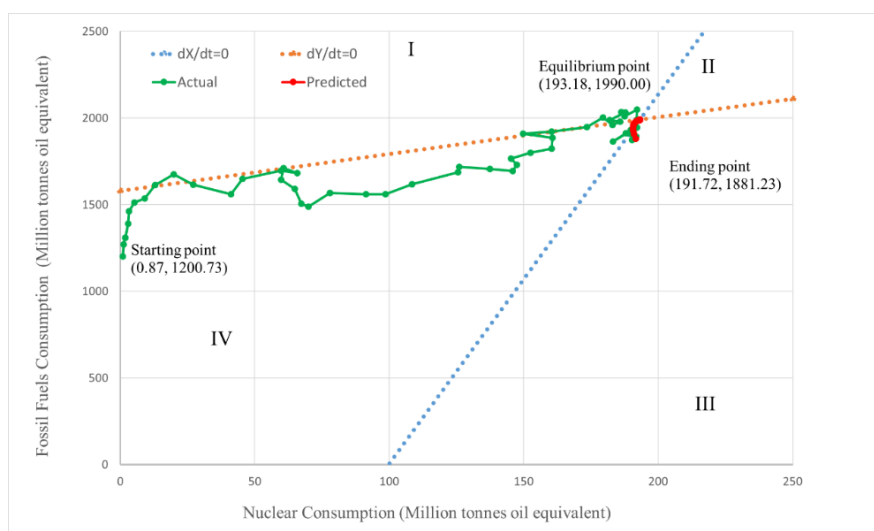
## Equilibrium analysis results

### 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 **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

### 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.



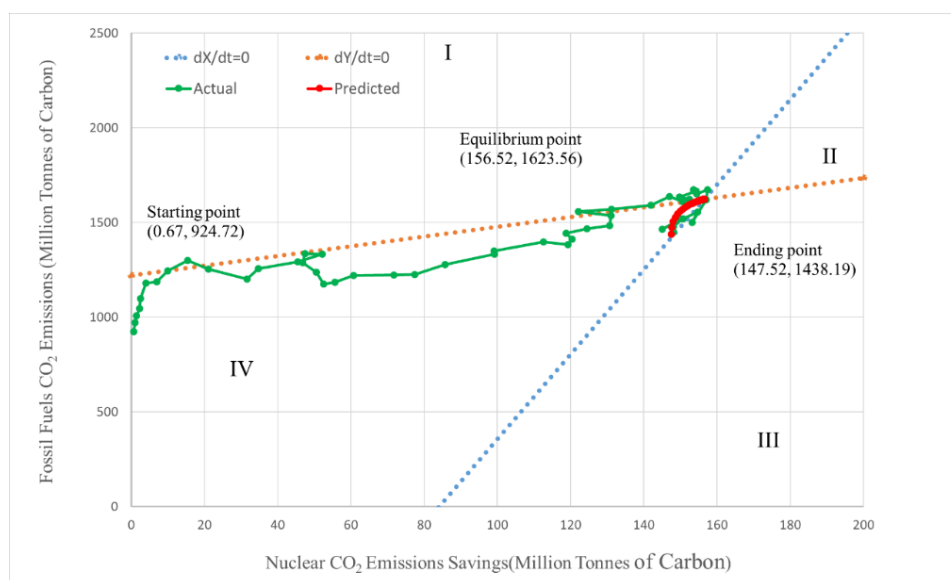
**Figure 2.** Time-series consumption of fossil fuels and nuclear energy

### Jacobian matrix at the equilibrium point of CO<sub>2</sub> emissions

The X-axis and Y-axis in *Figure 3* represent the CO<sub>2</sub> emission saving of nuclear energy and the CO<sub>2</sub> 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<sub>2</sub> emissions of fossil fuel decreased continually:  $\frac{dy_1}{dt} < 0$ , during the initial stage of using of nuclear energy. However, fossil fuel CO<sub>2</sub> increased substantially and changed to area I in 2007. The use of nuclear energy accelerated the CO<sub>2</sub> emissions of fossil fuels. Our investigation verified that CO<sub>2</sub> emission of fossil fuels finally reaches a long-term equilibrium point 1,623.56 million

tonnes of carbon, approximately ten times the equilibrium point of nuclear CO<sub>2</sub> emission savings 156.52 million tonnes of carbon.

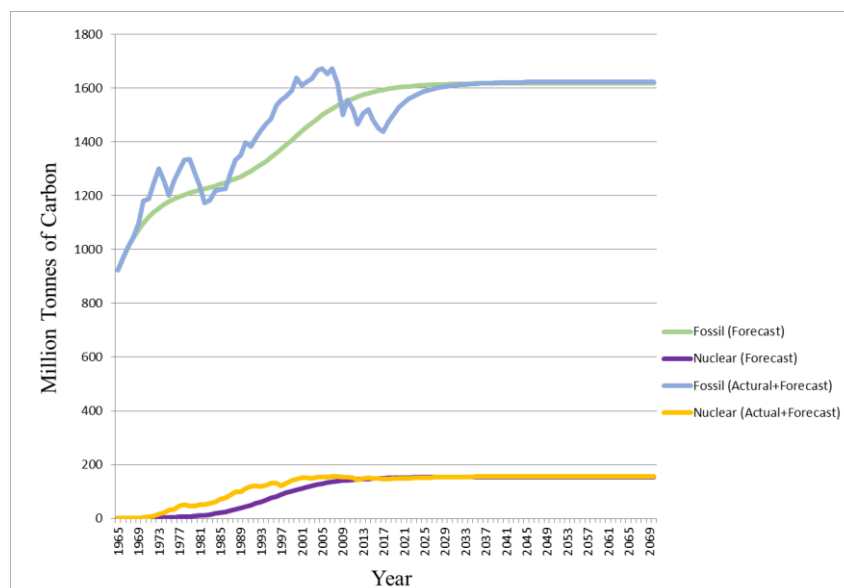
The real parts of eigenvalues of the Jacobian matrix **A** at the equilibrium point were -0.4322 and -0.2074. The negative real parts of eigenvalues indicate that the trajectories of our Lotka–Volterra equations satisfy the Hritonenko and Yatsenko (1999) stability conditions. Although the CO<sub>2</sub> emissions of fossil fuels and CO<sub>2</sub> emissions-savings of nuclear energy were 1,438.19 and 147.53 million tonnes of carbon in 2017, respectively, the CO<sub>2</sub> emissions of fossil fuels and CO<sub>2</sub> 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<sub>2</sub> emission and the nuclear CO<sub>2</sub> emission savings

### Lyapunov analysis results of CO<sub>2</sub> 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<sub>2</sub> emissions will ultimately be ten-fold the CO<sub>2</sub> emission savings of nuclear energy. Figure 4 depicts actual and forecasted CO<sub>2</sub> emissions of fossil fuels and CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> emissions with nuclear consumption, decreasing the consumption of nuclear energy from 192 to 190 million tonnes oil equivalent led to the reduction of CO<sub>2</sub> 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<sub>2</sub> emissions, even though the use of nuclear energy in the short term can reduce CO<sub>2</sub> emissions.



**Figure 4.** Time-series CO<sub>2</sub> emissions of fossil fuels and CO<sub>2</sub> emission savings of nuclear energy

### Results of forecast accuracy analysis

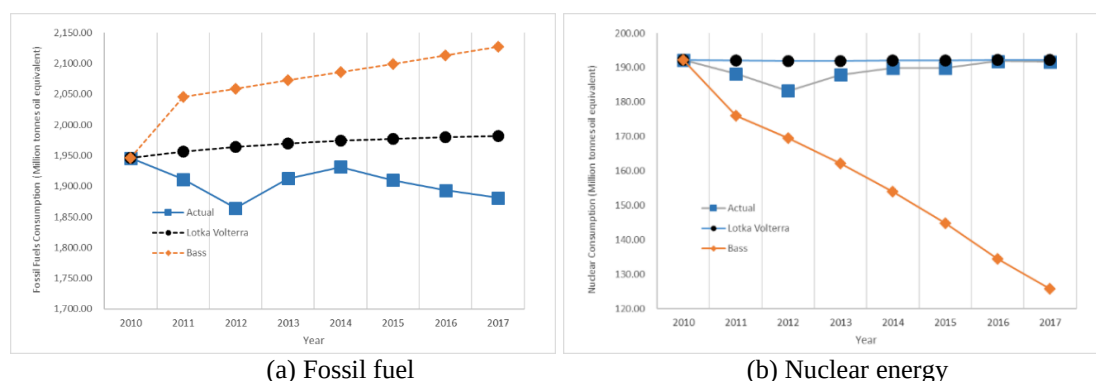
We then applied the parameter values to our Lotka-Volterra model to predict the consumption of fossil fuels and nuclear energy in the test period, using the Lotka-Volterra and Bass models (*Fig. 5a and b*). Predicted consumption of the Lotka-Volterra model were extremely close to the actual consumption 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<sub>2</sub> emissions of fossil fuels and nuclear energy, respectively, during the test period. *Figure 6b* shows that the forecast CO<sub>2</sub> emission savings predicted by the Lotka-Volterra model is closer to the actual CO<sub>2</sub> 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<sub>2</sub> emission on nuclear energy CO<sub>2</sub> emission savings, the Bass model underestimated the nuclear CO<sub>2</sub> emission savings in test period.

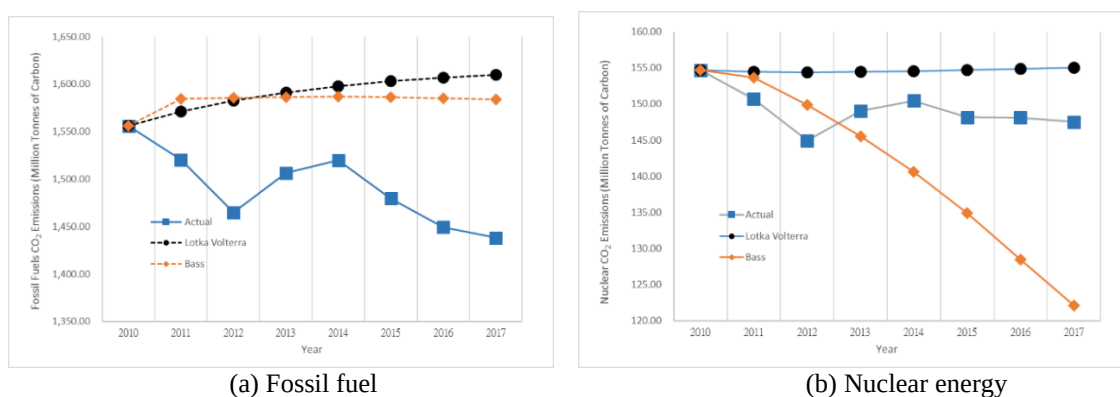
*Table 3* summarizes the forecast accuracy of fossil fuel and nuclear energy consumption and CO<sub>2</sub> emissions indicators during the test period. Graphs stagnation of the Lotka-Volterra predicted value caused by the fact that the error rate of the prediction value of Lotka-Volterra model is lower 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



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.



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



**Figure 6.** The trajectory of fossil fuel CO<sub>2</sub> emission (a) and nuclear CO<sub>2</sub> 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 <sub>2</sub> emission indicators                |                |        |
| CO <sub>2</sub> emissions of fossil fuel           | 7.62%          | 6.98%  |
| CO <sub>2</sub> 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



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<sub>2</sub> emissions from fossil fuels and the savings of CO<sub>2</sub> 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<sub>2</sub> emissions. In contrast, the MAPEs of the predicted CO<sub>2</sub> 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<sub>2</sub> emissions generated from fossil fuels between Lotka-Volterra and Bass models were no more than 1%, but the MAPE of the predicted CO<sub>2</sub> emissions savings of nuclear energy forecasted by the Lotka-Volterra model was lower than that of the CO<sub>2</sub> emissions savings forecasted by the Bass model by more than 3%.

The predictions of the CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> emissions and predicting future energy consumption in the US.

## Discussion

Regarding the long-term CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub>e/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<sub>2</sub>e/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<sub>2</sub>e/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<sub>2</sub>e/kWh in the construction, operation and methane leakage phases, respectively for liquefied natural gas combined cycle power generation. Since fossil fuels are

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<sub>2</sub>e/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<sub>2</sub> footprint per kWh at every stage. There are at least 0.58 gCO<sub>2</sub>e/kWh, at most 118 gCO<sub>2</sub>e/kWh, in average 25.09 gCO<sub>2</sub>e/kWh in the frontend phase, including mining, milling, conversion, enrichment, fuel fabrication and transportation. Then, there are at least 0.27 gCO<sub>2</sub>e/kWh, at most 35 gCO<sub>2</sub>e/kWh, in average 8.2 gCO<sub>2</sub>e/kWh in the construction phase, including all materials and energy input for building the facility. Additionally, there are at least 0.1 gCO<sub>2</sub>e/kWh, at most 40 gCO<sub>2</sub>e/kWh, in average 11.58 gCO<sub>2</sub>e/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<sub>2</sub>e/kWh, at most 40.75 gCO<sub>2</sub>e/kWh, in average 9.2 gCO<sub>2</sub>e/kWh in the backend phase, including fuel processing, conditioning, reprocessing, interim and permanent storage. Lastly, there are at least 0.01 gCO<sub>2</sub>e/kWh, at most 54.5 gCO<sub>2</sub>e/kWh, in average 12.01 gCO<sub>2</sub>e/kWh in the decommissioning phase, including deconstruction of facility and land reclamation. From Sovacool (2008), we could observe that the CO<sub>2</sub> emission intensity in the frontend and decommissioning phases is larger than those in the other phases. Nuclear energy totally causes long-term CO<sub>2</sub> emissions at least 1.36, gCO<sub>2</sub>e/kWh in average 66.08 gCO<sub>2</sub>e/kWh, and at most 288.25 gCO<sub>2</sub>e/kWh. CO<sub>2</sub> emissions of the nuclear energy seem no less than fossil fuels CO<sub>2</sub> emissions 91.8 gCO<sub>2</sub>e/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<sub>2</sub>.

## Conclusion

This study assessed energy consumption and CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> emissions. Nuclear energy is not the suitable resource to reduce fossil fuel usage and CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> emissions. This result verifies that from the construction of a nuclear plant until its decommissioning,

nuclear power plants increase fossil fuels consumption, which explains the difficulty of the CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> emission indicators of fossil fuels and nuclear energy. To sum up, reducing CO<sub>2</sub> 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<sub>2</sub> emission. However, this paper does 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<sub>2</sub> emissions.

**Acknowledgements.** The author would like to thank Ministry of Science and Technology of the Republic of China, for partially supporting this research under Contract No. MOST 110-2410-H-A49 -050.

## REFERENCES

- [1] Abatzoglou, J., Williams, A. (2016): Impact of anthropogenic climate change on wildfire across western US forests. – *Proceedings of the National Academy of Sciences* 113(42): 11770-75.
- [2] Al-Harbi, M., Bin Shams, M., Alhajri, I. (2020): Connectionist modelling for anthropogenic greenhouse gases (GHG) emissions in urban environments. – *Applied Ecology and Environment Research* 18(2): 2087-2107.
- [3] Alley, W. M., Alley, R. (2012): *Too Hot to Touch: The Problem of High-Level Nuclear Waste*. – Cambridge University Press, Cambridge, UK.
- [4] Bass, F. M. (1969): A new product growth for model consumer durables. – *Management Science* 15: 215-27.
- [5] Cui, D., Deng, Z., Liu, Z. (2019): China's non-fossil fuel CO<sub>2</sub> emissions from industrial processes. – *Applied Energy* 254: 113537.
- [6] Energy Information Administration (2012): *Annual Energy Review 2011*. – U.S. Energy Information Administration, Washington DC.

- [7] Fan, Z. P., Che, Y. J., Chen, Z. Y. (2017): Product sales forecasting using online reviews and historical sales data: a method combining the Bass model and sentiment analysis. – *Journal of Business Research* 74(1): 90-100.
- [8] García-Martosa, C., Rodríguez, J., Jesús Sánchez, M. (2013): Modelling and forecasting fossil fuels, CO<sub>2</sub> and electricity prices and their volatilities. – *Applied Energy* 101: 363-75.
- [9] Gustavsson, L., Eriksson, L., Sathre, R. (2011): Costs and CO<sub>2</sub> benefits of recovering, refining and transporting logging residues for fossil fuel replacement. – *Applied Energy* 88(1): 192-97.
- [10] Hondo, H. (2005): Life cycle GHG emission of power generation systems: Japanese case. – *Energy* 30: 2042-2056.
- [11] Hritonenko, N., Yatsenko, Y. (1999): Mathematical Modelling in Economics. – In: Monson, R. K. (ed.) *Ecology and the Environment*. Springer, New York.
- [12] Kamimura, A., Guerra, S. M. G., Sauer, I. L. (2006): On the substitution of energy sources: prospective of the natural gas market share in the Brazilian urban transportation and dwelling sectors. – *Energy Policy* 34(8): 3583-90.
- [13] Lee, C. Y., Lee, M. K. (2017): Demand forecasting in the early stage of the technology's life cycle using a Bayesian update. – *Sustainability* 9(8): 1-15.
- [14] Lenzen, M. (2008): Life cycle energy and greenhouse gas emissions of nuclear energy. A review. – *Energy Conversion and Management* 49(8): 2178-99.
- [15] Leslie, P. H. (1958): A stochastic model for studying the properties of certain biological systems by numerical methods. – *Biometrika* 45: 16-31.
- [16] Lin, C. S. (2013): Forecasting and analyzing the competitive diffusion of mobile cellular broadband and fixed broadband in Taiwan with limited historical data. – *Economics Modelling* 35: 207-13.
- [17] Lukas, E., Thomas, S. S., Kupfer, S., Kieckhäfer, K. (2017): When and how much to invest? Investment and capacity choice under product life cycle uncertainty. – *European Journal of Operational Research* 260(3): 1105-14.
- [18] Martin, C. A., Witt, S. F. (1989): Accuracy of econometric forecasts of tourism. – *Annals of Tourism Research* 16(3): 407-28.
- [19] Monahan, W., Rosemartin, A., Gerst, K., Fisichelli, N., Ault, T., Schwartz, M., Gross, J., Weltzin, J. (2016): Climate change is advancing spring onset across the U.S. national park system. – *Ecosphere* 7(10): 1-17.
- [20] Nuclear Energy Agency (2012): *The Role of Nuclear Energy in a Low-carbon Energy Future*. – NEA, Paris.
- [21] Pac, F. M., Savin, S., Velu, C. (2018): When to adopt a service innovation: Nash equilibria in a competitive diffusion framework. – *European Journal of Operational Research* 271(3): 968-84.
- [22] Rietbroek, R., Brunnabend, S., Kusche, J., Schröter, J., Dahle, C. (2016): Revisiting the contemporary sea-level budget on global and regional scales. – *Proceedings of the National Academy of Sciences* 113(6): 1504-09.
- [23] Sodero, A. C., Rabinovich, E. (2017): Demand and revenue management of deteriorating inventory on the internet- An empirical study of flash sales markets. – *Journal of Business Logistics* 38(3): 170-83.
- [24] Sovacool, B. K. (2008): Valuing the greenhouse gas emissions from nuclear power: a critical survey. – *Energy Policy* 36(8): 2950-63.
- [25] Torfs, R., Huybrechts, D., Wouters, G. (1998): *Greenhouse Gas Emissions, Acidifying Emissions and Energy Carriers from Resource to End User*. – Flemish Institute for Technological Research, Mol.
- [26] Tsai, B. H. (2013a): Modeling diffusion of multi-generational LCD TVs while considering generation-specific price effects and consumer behaviors. – *Technovation* 33: 345-54.

- [27] Tsai, B. H. (2013b): Predicting the Diffusion of LCD TVs by incorporating price in the extended Gompertz model. – *Technological Forecasting and Social Change* 80: 106-31.
- [28] Tsai, B. H. (2017): Predicting the competitive relationships of industrial production between Taiwan and China using Lotka-Volterra model. – *Applied Economics* 49(25): 2428-42.
- [29] Tsai, B. H., Chen, C. C. (2020): Forecasting interactive relationships and long-term equilibrium of CO<sub>2</sub> emissions in industrial interdependent regions. – *Carbon Management* 11(1): 57-67.
- [30] Tsai, B. H., Chang, C. J., Chang, C. H. (2016): Elucidating the consumption and CO<sub>2</sub> emissions of fossil fuels and low-carbon energy in the United States using Lotka-Volterra models. – *Energy* 100(1): 416-24.
- [31] Zhang, T., Chen, L. Q., Wang, R., Wang, B. Y., Liu, Y. Q., Liu, W. Q., Wang, J., Wen, M. X. (2019): The influencing factors of industrial carbon emissions in the context of undertaking industrial transfer in Anhui Province, China. – *Applied Ecology and Environment Research* 17(2): 4205-4227.