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Article

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A Differential Equations Analysis of Renewable Energy Consumption Resilience for Climate Risk Mitigation

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Abstract

Climate change gives rise to escalating disruptions to energy systems, requiring resilient strategies for fostering sustainable consumption. Renewable energy provides a vital adaptive capability for mitigating climate threats. Using a three-phase data of energy consumption from 2000-2025, this study employs a set of differential equations to explore the dynamics of renewable-fossil energy consumption in the face of climate uncertainty. The results show that, there is high growth in energy consumption due to high value of energy intensity and high technology advancement in leveraging fossil fuels technology as indicated that, in the period from 2010 to 2020, the empirical outcomes unveil decrease to energy intensity ($\sigma = 1.39$). Additionally, at higher amount of carbon emissions of $\lambda = 0.19$, the rate of fossil fuel consumptions goes into diminishing there is a sharp increase of renewable energy as an optimal substitute. This study concludes that, the increase of energy intensity influenced the rise in fossil energy consumption. Nevertheless, the rise of technological advancement toward renewable sources enhanced the renewable energy consumption. The results of this work further emphasize that promoting the consumption resilience of renewable energy necessitates not only improving climate resilience, but also promoting less cost in energy integration. This context offers a quantitative basis for suggesting strategies that align renewable energy growth with long-term climate risk mitigation goals.

Keywords: Climate risks, fossil energy, renewable energy, bifurcation, logistic growth model

1. Introduction

Is renewable energy a key role toward reducing the increasing climate threats? As the world faces the challenge of increasing air pollutions, understanding the adoption of the renewable energy dynamics becomes critical for building adaptive capability and fostering a sustainable climate-resilient energy mix. Consumption of renewable energy have been found to be the best solution for climate-risks mitigations. Researchers such as Chen, Pinar, and Stengos (2021), demonstrated that the world's total renewable-based power integration would grow by 50% in the period from 2019 to 2024. In the light of mitigating the global environmental disruptions, renewable energy has been the emphasis of government attention as an effective strategy to promote environmental sustainability (F. Liu, Su, Qin, & Umar, 2023)**.** Explored the renewable energy integration strategies using the currently growth smart grids. ...examined the strategies like suggested energy system modelling based on discrete solution. Despite the solutions proposed, the problem of reducing fossil energy consumption using renewable energy is doggedly persistent as confirmed by (C. Liu & Wang, 2025). In the recent study who unveiled that more than 80% of fossil energy consumption and described as one of the challenges in the transition from air pollution energy to clean energy. This study uses logistic growth mathematical model to investigates the critical transitions of fossil-renewable interaction thereby demonstrating a tipping point beyond which the energy system will change the regime completely.

2. Background

Global energy topologies are undergoing a critical transformation influenced by the dual pressures of sustainable development needs and climate change mitigation. Fossil energies, which have dominated energy production for more than a century, remain the main source of carbon emissions and impact significantly to air pollution. Their continued use intensifies climate-related disruptions such as ecosystem degradation, sea-level rise, extreme weather events, and which in turn endanger energy infrastructure and economic resilience. In response, there has been an increasing global participation to low-carbon energy transition through the renewable energy deployment. Fossil fuels have been a crucial component of the global energy mix for many years, offering the mainstream of the world's transportation fuels and electricity (Zhang et al., 2023).

Fossil energy is a non-renewable energy generated from a natural resource that cannot be readily changed by natural means for an immediate consumption. Fossil energy, mainly derived

from oil, natural gas, and coal comes from the buried remains of ancient animals and plants that formed many years under immense pressure and heat. These energies produced from non-renewable resources have historically driven economies and currently amount supplied approximately 80% of the world's energy demands, but their burning releases large amounts of greenhouse gases thereby contributing to climate change. Fossil energies production peaks and depletions depend on their exploration, proved reserves, and consumption rates (Abas, Kalair, & Khan, 2015). However, the consumption of fossil fuels is also playing a pivotal role toward greenhouse gas emissions, which are contributing in the primary cause of climate change (S. Ma, Lei, Meng, Liang, & Guan, 2022). As the world faces the urgent need to reduce fossil energy consumption and transition to a renewable energy which is low-carbon economy, the future consumption of fossil fuels is increasingly uncertain (Alagoz & Alghawı, 2024). And current studies found renewable energy a crucial tool to combat energy security risks (Bashir, Pata, & Shahzad, 2025).

Renewable energy—comprising wind, solar, hydro, biomass, and geothermal—provides multiple benefits. It decreases dependency on finite fossil fuels consumption, lowers carbon paths, and fosters energy security by expanding supply sources. Studies found that renewable energy sources will rise to two-thirds of the global fossil energy supply by 2050 (Hassan et al., 2024). Natural gas is one of the cleaner burning fuels which is critical in the transition to a carbon world. Despite the need for the consumption of renewable energy for replacing fossil fuels, the cost of generating energy from renewable sources is high as exhibited by...but has been a source that can enhance new employment creation. Renewable technological advancement has become a crucial role in increasing the rate of clean energy consumption (Østergaard, Duic, Noorollahi, & Kalogirou, 2020). Recently, renewable energy technologies have been rising and promote the utilization which increase the rate of consumption for various purposes as shown in Figure 1. Several researches jointly explore the analysis of renewable energy system and their contributing role on fostering new jobs and climate resilience (Nnabuife, Hamzat, Whidborne, Kuang, & Jenkins, 2025; Østergaard et al., 2020; Wysocka, 2023). For instance, based on comparative perspective, renewable energy offers more full-time equivalent employments per $1 million invested than non-renewable. At the same time, it has been witnessed a decrease of ambient air pollution accounts to medical cost containment of 2.9-5.11 trillion dollars annually (Bhuiya et al., 2025). Additionally, renewable energy consumption has been found to promote green job creation (B. Ma & Wang, 2025).

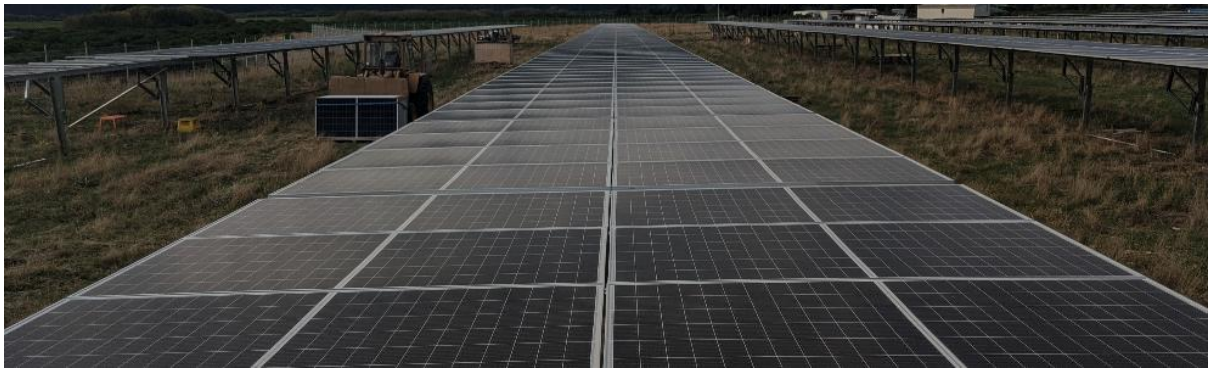


Figure 1: Renewable energy technologies

Source: trackingsdg7

3. Methodology

This study adopts a logistic growth modelling approach to analyse the dynamics of renewable energy consumption and its role in building resilience against climate risks. The methodology consists of three key components: Model formulation and analysis and numerical simulation.

3.1.The Fossil-Renewable Model and Analysis

We proposed and analysed a two-dimensional non-linear model for fossil-renewable energy consumption dynamics by dividing into two different compartments, namely, the fossil fuel consumption x and renewable energy consumption y. The variables x and y are time (t) dependant functions. The developed differential equation model is suggested as:

$$\begin{aligned} \frac{dx}{dt} &= \sigma x + \alpha x(1 - x/K) - \lambda xy \\ \frac{dy}{dt} &= \beta y(1 - y/L) + \gamma xy \end{aligned} \qquad (3.1)$$

where $\alpha x\left(1-\frac{x}{K}\right)$ refers to logistic growth of fossil consumption up to carrying capacity K,

similarly for $\beta x\left(1-\frac{x}{L}\right)$ for logistic growth of renewable consumption up to carrying

capacity L,

$-\lambda xy$: competition term governed with carbon emission parameter (λ) as a competition coefficient parameter with an effect from renewables reducing fossil consumption growth.

σx: Energy intensity (term that influence the increase the fossil consumption)

γxy**:** Technological advancement term governed with renewable electricity output parameter that support renewable consumption promotion

If $\lambda > 0$ and $\gamma > 0$, this model demonstrates fossil energy consumption x grows logistically but is limited by y, while the renewable energy consumption benefits from the fossil fuel consumption.

3.2.Existence of Equilibria

We obtain a differential equation model's equilibrium by setting the right-hand side of the model to zero (Duan, Madasi, & Khurshid, 2023; Duan, Madasi, Khurshid, & Ma, 2022). To determine the steady-state solutions, we have, $\frac{dx}{dt} = 0$ and $\frac{dy}{dt} = 0$:

$$\begin{cases} \sigma x + \alpha x(1 - x/K) - \lambda xy = 0 \\ \beta y(1 - y/L) + \gamma xy = 0 \end{cases} \quad (3.2)$$

Solving x and y from Eq (3.2) we obtain:

$$(\sigma + \alpha(1 - x/K) - \lambda y)x = 0 \quad (3.3.)$$

From which we get the following possible solutions:

$x = 0$ or $\sigma + \alpha(1 - Kx) - \lambda y = 0$. Similarly, in the rate of change of renewable energy consumption equation we get:

$y = 0$ and $\beta(1 - Ly) + \gamma x = 0$.

For case 1: $x = 0$

We substitute $x = 0$ into Eq (3.3) to get:

$y = 0$ or $\beta(1 - yL) = 0 \implies y = L\beta(1 - Ly) = 0 \Longrightarrow y = L$.

We thus have two equilibrium points $(0,0)$ and $(0, L)$

For case 2:

By plugging $y = 0$ into the Eq (3.1) we have:

$\sigma + \alpha(1 - Kx)$ which implies $Kx = 1 + \alpha\sigma \Longrightarrow x = K(1 + \alpha\sigma)$. Thus, one additional equilibrium is $(K(1 + \sigma\alpha),0)$.

Note: For this equilibrium to be mathematically meaningful, $\sigma\alpha + 1 > 0$. If $\sigma < -\alpha\sigma < -\alpha$, this steady-state may be negative, which is unrealistic for fossil-renewable models).

For case 3: $x \neq 0 \ and \ y \neq 0$

We now considering the case where neither x nor y is zero. By re writing Eq (3.1) and Eq (3.2) we find the solutions by getting the following:

$$\alpha - K\alpha x - \lambda y + \sigma = 0 \Longrightarrow K\alpha x + \lambda y = \alpha + \sigma,\ \beta - L\beta y + \gamma x = 0 \Longrightarrow -L\beta y + \gamma x = -\beta.$$

We further compute to get:

$$K\alpha x + \lambda y = \sigma + \alpha,$$
$$\gamma x - L\beta y = -\beta.$$

3.3.Stability Analysis of the Equilibrium Points

To solve the system, we put in matrix form as:

$$\begin{bmatrix} \frac{\alpha}{K} & \lambda \\ \gamma & -\frac{\alpha}{K} \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \alpha + \gamma \\ -\beta \end{bmatrix} \qquad (3.4)$$

From which we obtain the determinant of the coefficient matrix as:

$$\Delta = (K\alpha)(-L\beta) - \lambda\gamma = -\lambda\gamma - KL\alpha\beta.$$

By letting $\Delta \neq 0$, and solving x and y using Cramer's rule we get:

$$x = \frac{\beta\left(-\frac{\alpha+\sigma}{L} + \lambda\right)}{-\lambda\gamma - \frac{\alpha\beta}{KL}}, y = \frac{-\gamma(\alpha+\sigma) - \frac{\alpha\beta}{K}}{-\lambda\gamma - \frac{\alpha\beta}{KL}}$$

To analyse the stability of each steady point, we determine the Jacobian matrix of the model system and compute it at each equilibrium point. The eigenvalues of the Jacobian identify the stability of the system state. To compute Jacobian matrix from the Eq (3.1), we have:

$$\frac{dx}{dt} = f(x,y) = \sigma x + \alpha x(1 - x/K) - \lambda xy$$
$$\frac{dy}{dt} = g(x,y) = \beta y(1 - y/L) + \gamma xy$$

From which we get the following Jacobian matrix:

$$J(x,y)=\begin{bmatrix}\frac{\partial f}{\partial x} & \frac{\partial f}{\partial y}\\ \frac{\partial g}{\partial x} & \frac{\partial g}{\partial y}\end{bmatrix}=\begin{bmatrix}\sigma+\alpha(1-x/K)-\lambda y & -\lambda x\\ \gamma y & \beta(1-2y/L)+\gamma x\end{bmatrix}$$

We further get the eigenvalues at variant equilibrium points as:

At trivial point $(x,y)=(0,0)$, we get:

$J(0,0)=\begin{bmatrix}\alpha+\sigma & 0\\ 0 & \beta\end{bmatrix}$, therefore, $\lambda_1=\alpha+\sigma$ and $\lambda_2=\beta$ which indicate that: Unstable if either $\alpha+\sigma>0$ or $\beta>0$ (at least one type of energy consumption grows), and stable which found only if $\alpha+\sigma<0$ or $\beta<0$ (both fossil and renewable energy decline).

Similarly, for y-only equilibrium point $(x,y)=(0,L)$ we have:

$\lambda_1=\alpha+\sigma-\lambda L$ and $\lambda_2=-\beta<0$ which implies the stability to depend only on λ_1 such that the system becomes stable only if $\alpha+\sigma-\lambda L<0\Longrightarrow L>\frac{\alpha+\sigma}{\lambda}$, and unstable otherwise. For for x-only equilibrium point $(x,y)=(K(1+{}^{\sigma}/_{\alpha}),0)$ and assuming $\alpha+\sigma>0$ (for fossil energy to exist) we have: $\lambda_1=-(\alpha+\sigma)<0$ and thus, the stability depends only on λ_2 such that $\beta+\gamma x^*<0\ \Longrightarrow\gamma<-\frac{\beta}{x^*}$ and unstable otherwise. In the coexistence equilibrium (x^*,y^*), the system is stable only if $x>0$ and $y>0$ (both fossil and renewable energy persist if they interact in a balance way). The results further unveil that if the renewable energy (y) consumed too efficiently (when carbon emissions become too large), the fossil fuels (x) consumption may go to zero. Nevertheless, if the technology in electricity production from renewable sources (γ) becomes too strong, the renewable energy may dominate and descourage the consumption in fossil fuels.

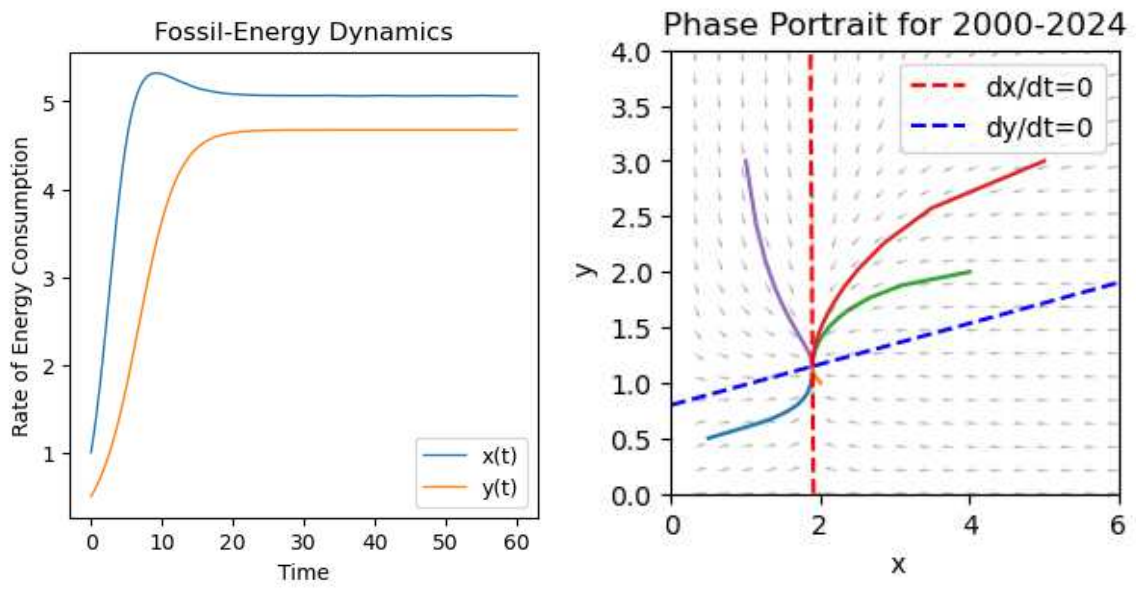
4. Numerical Simulation and Discussion

Here, we simulate the fossil-renewable logistic growth model for the following set of parameters:

The Eq (1) is simulated for different sets of parameters sufficient the conditions of stability equilibrium. Figure 2-5 demostrate the influence of various parameters on the equilibrium level fossil and renewable energy consumption. Figure 2 (a) reveals cruicial insights into energy system's transient and long term under variant ecosystem regimes. For the baseline parameters, we observe energy consumption dynamics where rapid expontial intial growth phase of fossil energy, benefiting from intrinsic growth $(\alpha+\sigma)$ and the trend prevails in three phases. First,

the dynamics indicates the reflection of uncontrolled expansion of fossil fuel consumption when the pressure of renewable energy consumption is low. Second, as renewable energy increases, the competiton term $(-\lambda xy)$ becomes dominant, causing fossil consumption to peak then decline sharply. The maximum fossil fuel consumption occurs at the intersection point where $\frac{dx}{dt}$ changes sign. Finally, as renewable energy consumption overwhelms the fossil fuel consumption capacity, $x(t) \to 0$ (i.e., fossil energy consumption will eventually collapse). If electricity production from renewable sources will keep increasing and reaches to $\gamma =$, then the consumption in the fossil fuel will prove insufficient to sustain coexistence (i.e., the decay follows a non-linear trajectory as the fossil-renewable system approaches the $(0, L)$ equilibrium. At $\gamma =$ (coexistence case), both energy consumptions show damped osccilations before stabilizing. With the settling time demostrating system stability properties. From the findings we further observe that, the rapid fossil fuel collapse suggests fragile systems may need external intervention before renewable energy peaks.

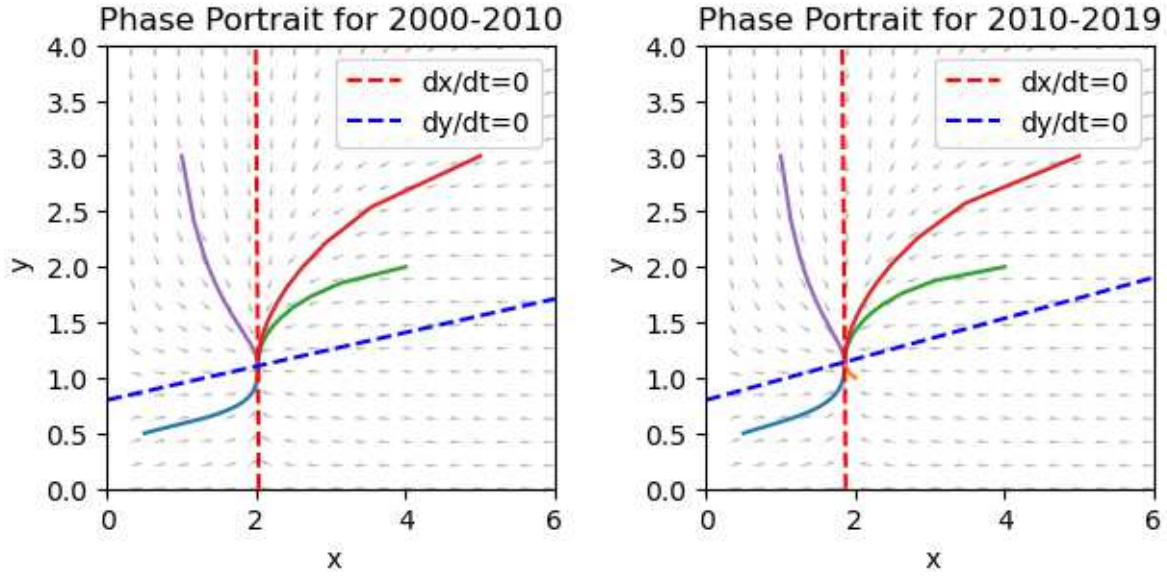
In Figure 2 (b) the simulation of phase potrait from the period of 2000 to 2024 show the trajectories of the fossil-renewable dynamical system in the xy-plane (where x is the fossil energy consumption, y is the renewable energy consumption). The arrows in the figure indicates the direction of flow and unveil the system trajectories converge to stable node. Figure 3 (a-c) show the phase potraits in three periods. These illustrate the dynamical behavior of our model in the period from 2000 to 2024 in different phases. In phase 1 (*see* Figure 3a), the results reveal that the system features a single equilbrium point at $(x, y) = (2.00, 1.00)$, which captures the intersection of the two nullclines. Similarly phase 2 (*see* Figure 3b) the equilbrium point is $(x, y) = (1.90, 1.15)$ while phase 3 (see Figure 3c) we see that the system exhibits a single equilbrium at $(x, y) = (1.90, 1.25)$. This indicates that, from phase 1 to phase 3, the system's equilibrium state was shifting toward of slightly fossil energy consumption and distinctly higher renewable energy consumption.



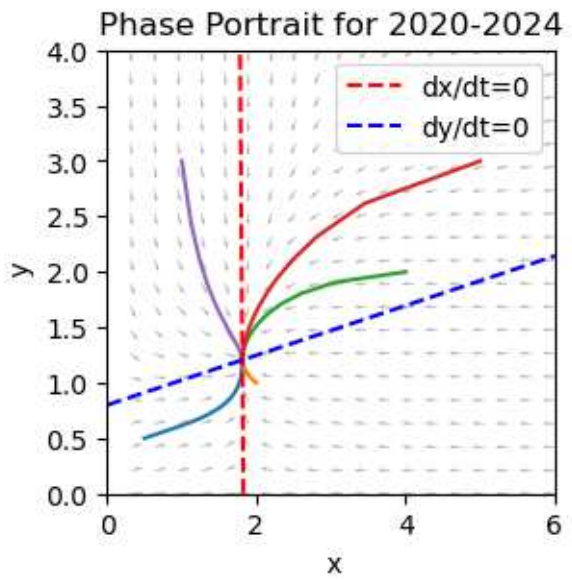
(a) (b)

Figure 2 (a) Variation of fossil and renewable energy showing the behavioural dyanamics (b) Phase potrait for both fossil and renewable energy from the period of 2000 to 2024

Source: Authors' Python simulation



(a) (b)



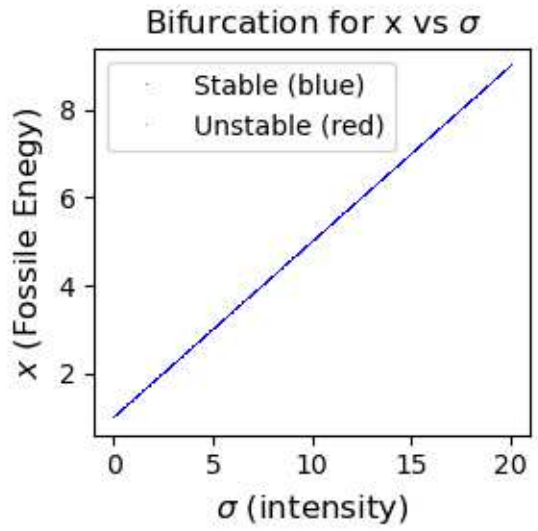
(c)

Figure 3 Variation of fossil and renewable energy showing the phase potraits for both fossil and renewable energy in three periods (a) 2000-2010 (b) 2010-2019 and (c) 2020-2024

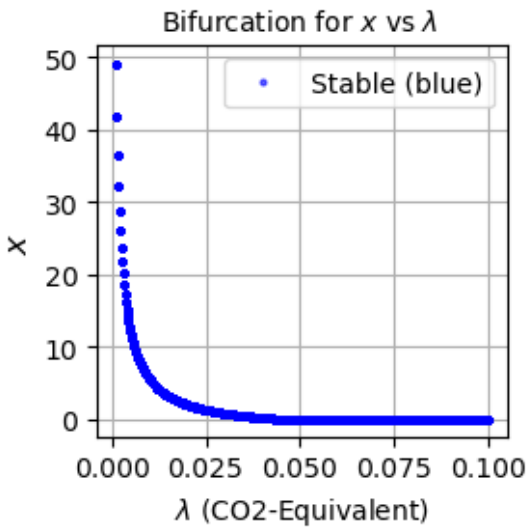
Source: Authors' Python simulation

Bifurcation demostrates rich ecosystem implications, exhibiting how mutualic interactios γ and λ shape long time energy outcomes. Figure 4(a-c) demostrate bifurcation analysis of the modified fossil-renewable system that exhibits how small changes in mutualistic strength (γ) and competetion parameter (λ) which can lead to dramatic shifts in ecosystem behaviour. The results show that, the energy intensity (σ) affects the fossil energy consumption linearly (i.e., as the energy intensity increases, the consumption of fossil energy icreases). This indicates that at all values of σ the system of fossil fuel consumption remain stable as displayed in Figure 4(a). Figure 4(b) shows how varrying carbon emissions (λ) drive system fossil-renewable energy system stability and indicates that higher rate of air pollution through carbon emissions leads to higher demand of renewable energy which destabilizes coexistence, eventually leading to a saddle-node steady-state where the coexistence equilibrium vanishes. This fossil-renewable system lacks cyclic dynamics (i.e., system lacks the patterns of fluctuation or repetition that occur over time in various parameters), instead converging to stable equilibrium points or extinction. When the production of elctricity from renewable resources (γ) is weak (e.g., $\gamma = 0.01$), the system collapses to a renewable energy consumption-only equilibrium $(0, L)$, as the fossil consumption's growth cannot compensate for renewable consumption pressure as shown in Figure 4(c). However, as γ increases beyond a critical threshold ($\gamma = 0.23$) for the given parameters), a renewable energy will stabilize at any value of y and marking

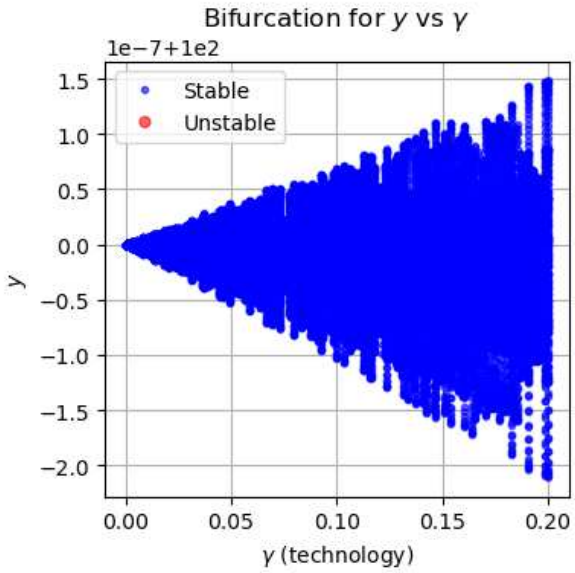
to transition to sustainable coexistence, indicating that fossil-renewable mutualism must be sufficiently optimize the consumption of renewable energy.



(a)



(b)



(c)

Figure 4 Variation of critical transitions for energy with various parameters (a) Fossil energy vs energy intensity (b) Fossil energy vs carbon emissions, and (c) Renewable energy vs electricity production from renewable sources from the period of 2000 to 2024

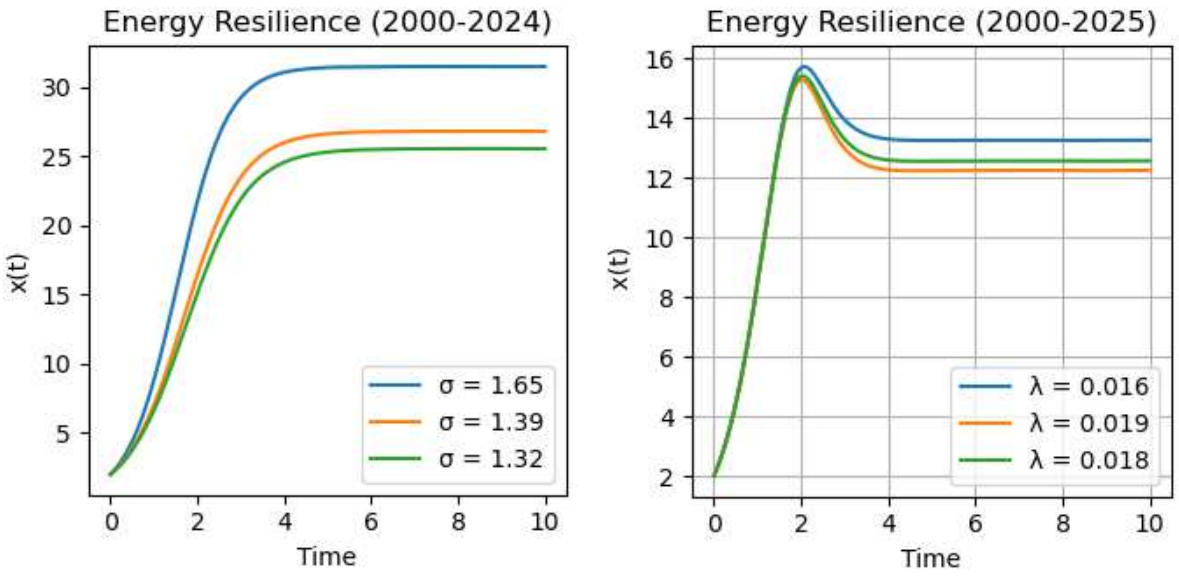
Source: Authors' Python simulation

We further simulated the fossil-renewable system at variant parameters to obtain energy resilience dynamics and unveiled in Figure 5(a-c). Figure 5(a) shows $\sigma \in [1.65, 1.39, 1.32]$, having other parameters constant $(\alpha = 0.10, \beta = 2.80, \lambda = 0.02, \gamma =$

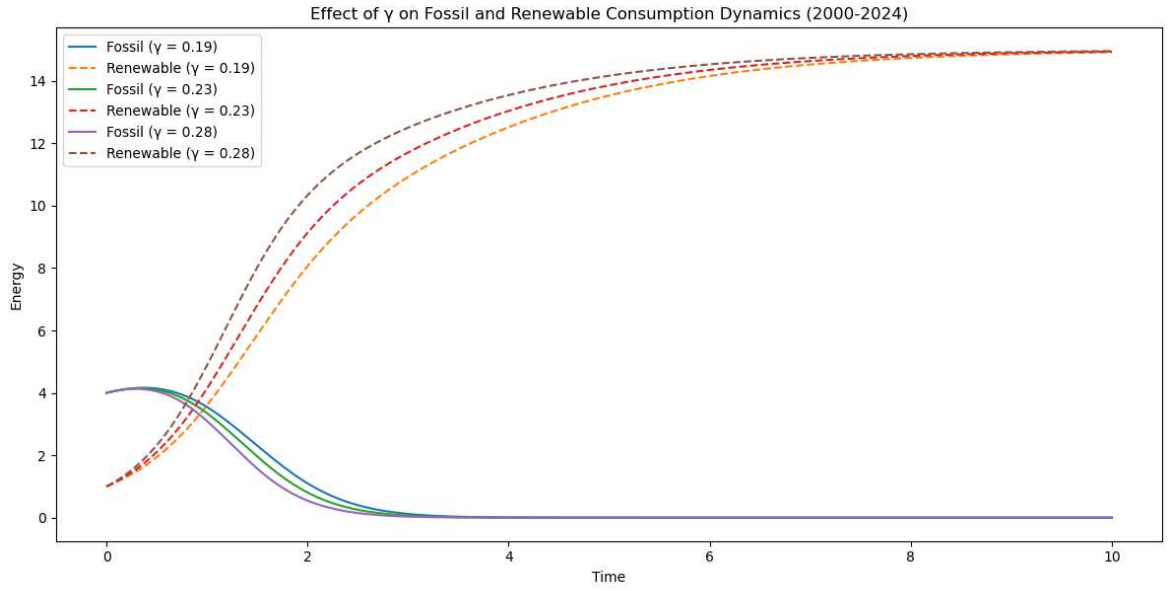
$0.23, K = 1.8, L = 0.8$). At early phase (2000-2010) with high σ ($\sigma = 1.65$), the results show high growth in energy consumption due to high value of energy intensity and high technology advancement in leveraging fossil fuels technology. In the period from 2010 to 2020, the empirical outcomes unveil decrease to energy intensity ($\sigma = 1.39$), from fossil resources which causes the decline of fossil fuels consmption. This phase also exhibited a sharp increase in clean (renewable) energy adoption, influenced by declining costs of wind and solar technologies, stronger environment policies (e.g., the Paris Agreement), and improved electricity production from renewable sources. The empirical outcomes in the period from 2020-2025 highlights a transition toward a saturation phase, where fossil energy growth keep slowing ($\sigma = 1.32$), as renewable energy begins to attain systemic constraints, such as grid resource intermittency, capacity limits, and market maturity.

Figure 5(b) unveils how climate change through carbon emissions drives the decline of fossil fuel consumption. The results show that in all three phases (2000-2010, 2010-2020, 2020-2024), fossil energy consumption increasing rapidly to the point where $\frac{dx}{dt} = 0$ at which start to decline. At higher amount of carbon emissions (λ), the rate of fossil fuel consumptions goes into diminishing as exhibited in the figure that, the one with highest carbon emissions ($\lambda = 0.19$) experienced during the period of sharp increase of renewable energy as an optimal substitute (2010-2020) unveiled the highest rate of decline (orange line) followed by the saturation phase (2020-2024) with green colour and the period with low impact of climate change (2000-2010) as demonstrated in blue colour.

Figure 5 (c) shows the effect of technological advancement (γ) through electricity production from renewable sources. The findings unveil that as γ goes higher, renewable energy consumption becomes more resilient while fossil energy consumption goes into diminishing as exhibited in the figure.



(a) (b)



(c)

Figure 5 Variation of fossil-renewable energy phase potraits in the period (a) low fossil energy consumption (b) high fossil energy consumption and (c) improved renewable energy consumption

5.0.Conclusion

The logistic growth mathematical model offers a robust framework for understanding the dynamics of renewable energy consumption in the face of climate disruptions. Our analysis unveils that resilience in renewable energy adoption depends on technological advancement through electricity production from renewable sources and therefore can reduce the consumption of fossil energy, thereby mitigating the climate risks caused by carbon emissions. Bifurcation analysis identified critical transitions beyond which the stability occurs, providing

policymakers, scientists and other stakeholders actionable insights for intervention. Empirical validation confirms that the increase of energy demand (energy intensity) triggers the consumption increase in fossil energy thereby causing the climate uncertainty. The results further confirmed that at maximum electricity production from renewable source (γ =0.28), renewable energy systems resilience improved at maximum level which led to discourage the use of fossil energy fuels to the minimum level. Ultimately, this study highlights the importance of dynamic mathematical modelling in energy transition planning. By predicting tipping points and suggesting adaptive strategies that can mitigate climate disruptions while accelerating the shift toward promoting sustainable energy systems. Future research of energy transitions should investigate stochastic climate impacts to further refine sustainable resilience strategies.

Data availability: Sourced from http://www.iea.org

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