International Journal of Sustainable Energy Planning and Management Vol. 42 2024 72–87

International Journal of
Sustainable Energy Planning and Management

System Dynamics Analysis of Vietnam's Energy-related Carbon Emissions: Towards a Net Zero Future

Hoang Ha Anh*, **Tran Minh Da Hanh**

Faculty of Economics, Nong Lam University, 700000 Ho Chi Minh City, Vietnam

ABSTRACT

Vietnam, a rapidly growing economy with high energy demand, aims for net-zero emissions by 2050. This study employs a system dynamics model to analyze the complex dynamics of energy-related carbon emissions at the national level. This study utilized historical data from 1990 to 2020 and projections up to 2050 from five shared socioeconomic pathway (SSP) scenarios from the International Institute for Applied Systems Analysis (IIASA). Sensitivity analysis identifies gross domestic product growth rate, energy intensity, and energy structure as crucial drivers of energy consumption and carbon emissions. Predictions show that energy consumption and emissions peak in the SSP5 scenario, followed by SSP1, SSP2, SSP4, and SSP3. The projected energy consumption and carbon emissions for Vietnam in 2050 are highest under SSP5, reaching 16,536 PJ and 1,001 Mt CO_2, respectively. While all scenarios meet the 2030 emission targets, they fail to meet the 2050 targets, with SSP5 requiring the most significant emission reductions. With robust policy interventions, Vietnam may achieve its net-zero emission goal, emphasizing the need to promote energy-efficient sectors and transition to renewable energy sources. Efforts for Vietnam's energy system to meet the 2050 carbon emission target require increasing the renewable energy share by 20%-28% and reducing the energy intensity of the residential sector by 21–65% and the industrial sector by 21%-50%, depending on the scenarios.

Keywords

Carbon emission;
Energy system;
Net zero emission;
Socioeconomic pathway;
System dynamic;
Vietnam

http://doi.org/10.54337/ijsepm.8327

1. Introduction

Global economic progress has seen significant growth; however, it is accompanied by a growing recognition of the profound challenges posed by climate change. Consequently, major emitting countries such as China, Brazil, and the USA should accelerate their transition to low-carbon alternatives to achieve zero emission or net-zero emissions or neutrality targets in 2050 [1]. However, in 2022, global energy-related CO_2 emissions surged to a record high, surpassing 36.8 Gt [2]. Therefore, the primary focus of current policies should be on controlling energy-related carbon emissions. To formulate effective emission reduction policies, it is crucial to address three key issues, which are (i) key factors influencing energy-related carbon emissions, (ii) the future trend of emissions, and (iii) the impacts brought by different measures [3].

Previous studies attempted to model and analyze the complex and dynamic problem of energy-related CO_2 emission at the national level. Most of these papers examined the drivers of energy consumption and emissions based on time-series data. For example, the effects of population, economics, and energy variables on carbon emission were explored using the LMDI technique in China, Turkey, Malaysia, and the European Union [4–7]. In other studies, the ARDL model and Granger causality test have been widely used to examine the link between emission, energy consumption, and economic growth in Indonesia, Myanmar, and Malaysia [8], and multi-periods

*Corresponding author – e-mail: hoanghaanh@hcmuaf.edu.vn

in Vietnam from 1971–2011 [9], 1971–2017 [10], 1980–2014 [11], 1995-2018 [12], and 1995–2019 [13]. Recently, wavelet analysis was applied to examine the relationships between foreign direct investment, trade openness, energy consumption, and CO_2 growth in Vietnam [14,15]. Although these studies provide in-depth analyses of past trends in energy demand and carbon emission, they do not perform well when predicting future trends.

Approaches to analyzing energy systems can be categorized into optimization models, simulation models [16], and equilibrium models [17]. Optimization models aim to identify the optimal energy solution. Endogenous investment optimization models, such as Homer, were used to assess the feasibility of a grid-connected biomass-based hybrid energy system in the Himalayan territory [18]. Similarly, Balmurel was adopted to evaluate scenarios for sustainable electricity and heat supply in Greater Copenhagen [19].

Simulation models seek to envision and compare different options or scenarios. Kumar and Madlener [20] employed the LEAP model to create scenarios and forecast India's energy-related carbon emissions. Wang and Lin [21] adopted STIRPAT to forecast China's carbon emissions in the commercial sector by 2030. Then, the possibility of China achieving a carbon peak in 2030 was examined using the environmental Kuzets curve (EKC) [22]. Besides, Wu, Liu [23] used a multi-variable grey mode to forecast CO_2 emission of BRICS countries. The AIM/Enduse model was adopted to analyze the technological and energy transition needed to achieve net zero emission in Thailand by 2050 [24]. Viesi, Mahbub [25] applied the EnergyPLAN model to examine future energy scenarios of an energy community in the European Alps in 2030 and 2050.

Nevertheless, the approaches mentioned above face certain limitations. The LEAP model was found to be subjective as it relies on expert judgments [26]. The EKC only focuses on GDP per capita and carbon emissions per capita [27]. The STIRPAT model was found to lack physical considerations and flexibility of the estimated coefficients [23]. The gray model cannot identify drivers and needs more transparency [28]. Also, Ahmad, Mat Tahar [29] underscored that other holistic and top-down optimization models, such as MARKAL, TIMES, CGE, and MESSAGE, fail to recognize the feedback, delay, and nonlinearity interactions of complicated systems of society, economy, environment, and technology. While some models, such as PRIMES or EnergyPLAN, have been used for policy support, many models have not had significant policy contributions due to their recent development or limited usage [17].

The literature review reveals a gap in the availability of a standardized method or research framework capable of comprehensively analyzing the driving factors, future trends, and policy scenarios related to energy-related carbon emissions at the national level. Furthermore, even in studies predicting future scenarios, the consideration of dynamic feedback mechanisms between social, economic, energy, and emission factors is limited. Chang, Thellufsen [17] found that widely considered tools with policy applications should include the ability to provide long-term outcomes and represent multiple energy sectors.

In this context, System Dynamics Modeling (SDM) is an appropriate approach to address the above gaps [30,31]. J.W. Forrester developed this model at the Massachusetts Institute of Technology (MIT) in 1950. It provides the benefits of examining various scenarios from proposed policies, helping decision-makers predict and adjust policy implications before making final decisions [32]. SDM has been widely adopted in studies that examined complex problems of energy-related carbon emissions, such as the analyses of renewable energy [33], urban energy [34], emissions in the cement industry [35], or evaluating the achievement of emission targets [36,37]. SDM can integrate societal and behavioral elements, examining the sociopolitical feasibility of energy transition pathways influenced by governmental decision-making processes, human behavior, and societal changes [38]. Nonetheless, there are still a few studies that have adopted SDM on energy-related carbon emission at the national level.

Vietnam announced its target to achieve net zero emissions by 2050 during the COP26 World Leaders' Summit in 2021. In July 2022, Vietnam included its net-zero target in the National Climate Change Strategy, which aims to guide Vietnam's climate action through 2050 [39]. However, there is still no clear and recognized pathway for Vietnam to meet the goals of the National Climate Change Strategy. From 1990 to 2020, Vietnam's energy consumption increased by 355%, and CO2e emissions climbed by 542% [40]. This trend underscores the urgency of research on Vietnam's energy-related CO_2 emissions. Previous studies regarding this field in Vietnam mainly focus on examining the historical trend to understand the causal relationship between economic growth, population, energy demand, and CO_2 emission, neglecting the dynamic interactions among these elements [10,13,15,41–46].

This study applies SDM to examine the interactions between carbon emissions, economic factors, population, and energy consumption at the national level. It aims to uncover the key factors influencing carbon emissions in various future scenarios. A comprehensive SDM model was conceptualized in VENSIM (Vensim is a simulation software that is used for developing, analyzing, and packaging dynamic feedback models) [47] and implemented in RStudio (RStudio is an integrated development environment for R, a programming language for statistical computing and graphics) [48]. The study simulated the trend of Vietnam's carbon emissions from 1990 to 2020, identifying its key influencing factors through sensitivity analysis. Subsequently, the model, incorporating Shared Socioeconomic Pathways (SSP) scenarios and the national energy development strategy, was utilized to predict future trends in national energy consumption and energy-related carbon emissions from 2020 to 2050. The five SSP scenarios are summarized as follows: a sustainability-focused development path emphasizing growth and equality (SSP1); a "middle-of-the-road" path where trends broadly follow historical patterns (SSP2); a fragmented path characterized by "resurgent nationalism" and regional rivalry (SSP3); a path marked by ever-increasing inequality (SSP4); and a path of rapid and unconstrained growth in economic output and energy use (SSP5). Concerning Vietnam's energy development targets, as outlined in the national climate change strategy, renewable energy sources are expected to account for at least 33% of the country's energy consumption by 2030 and at least 55% by 2050. Moreover, the country's emission targets in 2030 and 2050 are 524 and 185 Mt CO_2e, respectively [39].

This study contributes a unified SDM-based framework for a systematic and holistic assessment of energy-related carbon emissions at the national level, including its influencing factors and long-term future trends. In terms of practical application, this work provides Vietnam with a model to predict its future energy demand and carbon emissions. It offers valuable insights for policymakers to design and adjust policies accordingly. Moreover, the parameters in this model can be adjusted to align with new socioeconomic development pathways or energy development strategies to meet the decision-makers evolving needs. This paper is the first study in Vietnam to re-assess the concerns of scholars about whether Vietnam can achieve the 2050 commitment [49–51] based on a quantity, holistic, and dynamic approach.

The remaining sections of the paper are structured as follows: Section 2 explains the approach and the SDM model's framework; Section 3 discusses the main findings, including model validation, sensitivity analysis, and scenario analysis; and finally, section 4 presents the conclusion and policy implications.

2. Methodology

This section explains the research framework and the construction of the SDM model.

2.1. Research framework

SDM is a methodology that allows for the simultaneous evaluation of multiple modules and stock and flow variables within a system through a set of simultaneous difference equations [52]. The construction of a system dynamic model involves the following five interdependent steps: (1) articulate the problem, (2) propose the dynamic hypothesis, (3) build the simulation model, (4) test the simulation model, and (5) design and evaluate policy [53]. The final object of this paper is the country's energy-related carbon emissions, which result from the interactions of multi-variables from the economic, population, and energy sectors. The mathematical foundation of such decomposition was refined from the Kaya identity [36,54]. In the first step, we developed a system dynamic (SD) model from the refined Kaya identity to represent CO_2 emissions in Vietnam, encompassing sub-sectors related to population, economy, and energy. The second step involved identifying the model's parameters using time-series data from 1990 to 2020, with other variables being fitted and regressed to anticipate future carbon emissions. In the third step, the model underwent calibration and validation, adjusting causal chains and parameters to minimize variance when comparing simulation results with historical values. In the fourth step, the validated model was utilized for simulation, prediction, and analysis to address the following research questions: (1) What is the future trend of Vietnam's CO_2 emissions under the current development rate and without constraints? (2) What are the primary factors influencing Vietnam's CO_2 emissions? (3) What are the future trends in Vietnam's CO_2 emissions when considering the country's climate change strategy, energy development goals, and different socio-economic development pathways? To address the first question, a baseline scenario was extrapolated from historical trends without integrating any constraints. Sensitivity analyses were then conducted to answer the second question, examining the impacts on CO_2 emissions and identifying variables with the strongest influences. For the third question, we simulated five scenarios from 2020 to 2050 based on the SSPs and Vietnam's energy development targets outlined in the national climate change strategy. Drawing conclusions from the predicted scenarios, this paper provides insights into future CO_2 emissions and offers policy implications for Vietnam.

2.2. Basic mathematical model

Vietnam's energy-related CO_2 emission was found to be correlated with population growth and economic and energy consumption [9,11,13,44]. In 1989, Toichi Kaya proposed the Kaya identity to assess a county's carbon emissions:

$$C = POP.\frac{GDP}{POP}.\frac{E}{GDP}.\frac{C}{E} = POP.GP.EI.\eta \qquad (1)$$

Wherein C is CO_2 emission, POP is total population, GP is GDP per capita, EI is energy intensity, and η is carbon emission coefficient. Then, we adopted the approach of Yang, Li [36] to categorize the emission into productive and resident emissions for a more detailed assessment:

$$C = C_P + C_r \qquad (2)$$

Wherein C_P is CO_2 emission from industrial energy consumption, and C_r is CO_2 emission from residential energy consumption. Next, each type of emission were expressed in Equation (3) and (4) as follows:

$$C_P = \sum_i GDP.\frac{E}{GDP}.\frac{E_i}{E}.\eta_i = \sum_i GDP.EI.ES_i.\eta_i \qquad (3)$$

$$C_r = \sum_i POP.\frac{E}{POP}.\frac{E_i}{E}.\eta_i = \sum_i POP.EP.ES_i.\eta_i \qquad (4)$$

Wherein i is the energy sources (including fossil fuels energy (coal, oil, and gas) and renewable energy), ES is the energy structure, EP is the residential living energy consumption per capita. The adjusted Kaya identity allows an in-depth examination of different types of energy demands, which in turn leads to different types of CO_2 emissions. Previous studies in Vietnam mostly focused on the relationship between GDP, CO_2 emissions, and energy use [12,45,55] while population was also found to be a significant factor [44]. Moreover, categorizing fossil fuels and renewable energy would provide useful information on the path toward net-zero emission target in Vietnam [41]. The refired Kaya identity serves as the basic mathematical model for the next phase of modeling.

2.3. SDM model

Based on the refined Kaya identity, the SD model of energy-related CO_2 emissions in Vietnam was structured with four subsystems: population, economic, energy, and CO_2 emissions. The population subsystem explains total population (POP), population growth rate (POPGR), urban population (UPOP), rural population (RPOP), and urban population share (UPOPS), representing residential energy consumption and carbon emissions. The economic subsystem contained gross domestic product based on purchasing power parity (GDPPPP), GDDPPP growth rate (GDPGR), and GDPPPP per capita (GPCAP). The energy subsystem included total energy consumption (TEC), residential energy consumption (REC), industrial energy consumption (IEC), fossil energy consumption (FEC), and renewable energy consumption (RNEC). The carbon emissions subsystem described CO_2 emissions (TC), assumed to be attributed to fossil energy (coal CO_2 emissions, oil CO_2 emissions, and gas CO_2 emissions). The four subsystems were linked by auxiliary variables: GPCAP connected the population and economic subsystems, EPR linked the population and energy subsystems, EI connected the economic and energy subsystems, and emission factors of each emission source linked the energy and CO_2 subsystems. These auxiliaries bridged all variables in the model, allowing the system to operate dynamically as a whole.

The feedback model and stock-flow model were first conceptualized and visualized in VENSIM [47] (Figure 1), and all of the equations within the model and analyses were conducted in RStudio using the package "deSolve" [56]. The definitions of variables and their mathematical relationships are presented in Table 1.

2.4. Data input

The historical data was collected from 1990–2020 with one year interval. Data from the population, economic subsystem and CO_2 emissions were collected from the country database of The World Bank [40]. Energy consumption data was collected from the energy balance sheets of Vietnam [57]. Emission factors was extracted from the Decision No. 2626/QD-BTNMT of MONRE [58]. Regarding population and GDP projection data, the study relied on the SSP database of the International Institute for Applied Systems Analysis (IIASA) and the Organization for Economic Co-operation and Development (OECD) [59–61]. Vietnam's policy goals of energy development and carbon emissions refer to the National Climate Change Strategy [39].

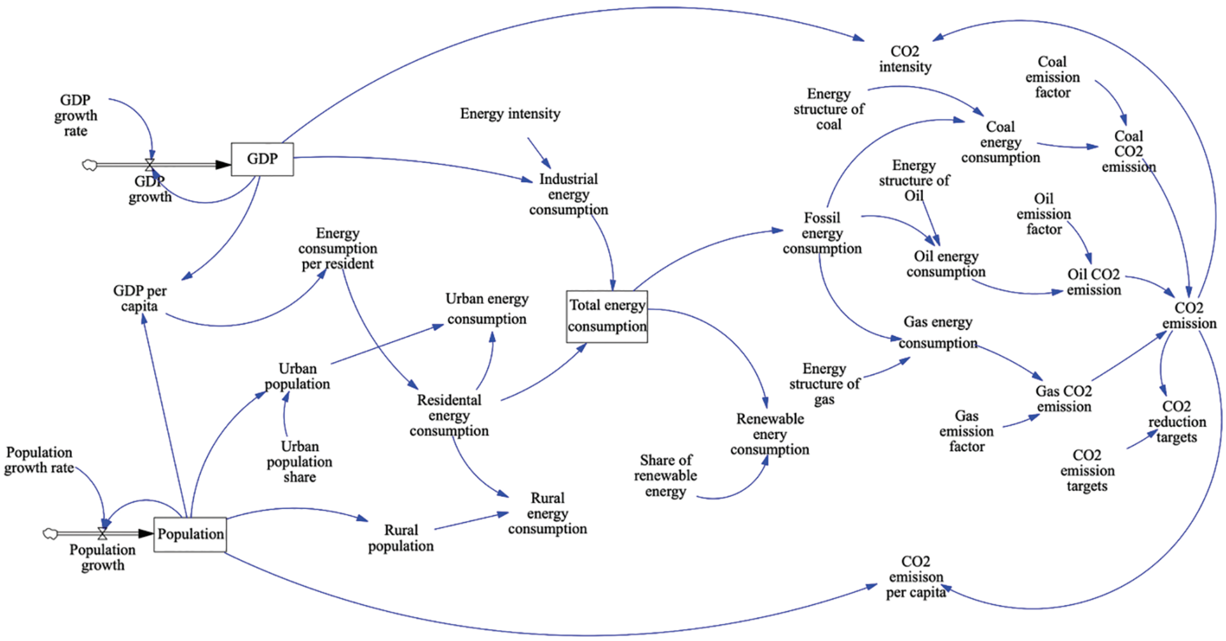

Figure 1: The proposed SD model for energy-related CO_2 emissions.

Table 1: Variables and mathematical relationships in the SD model.

Variables	Description	Type	Equations	Units
CEF	Coal emission factor	Constant	0.168	Kt CO_2/TJ
OEF	Oil emission factor	Constant	0.1161	Kt CO_2/TJ
GEF	Gas emission factor	Constant	0.09465	Kt CO_2/TJ
POP_0	Total population in 1990	Constant	66,912,613	People
$GDPPPP_0$	GDPPPP in 1990	Constant	140,475,979,634	US 2017$
POPGR	Population growth rate	Variable	$POPGR(time)$	%
POPG	Population growth	Flow	$POPG = POP.POPGR$	People
GDPGR	GDPPPP growth rate	Variable	$GDPGR(time)$	%
GDPG	GDPPPP growth	Flow	$GDPG = GDPPPP.GDPGR(time)$	US 2017$
POP	Total population	Stock	$POP = POP_0 + \int_1^T POP.POPGR(time).dt$	People
GDPPPP	GDP based on PPP	Stock	$GDPPPP = GDPPPP_0 + \int_1^T GDPPPP.GDPGR(time).dt$	US 2017$
UPOPS	Urban population share	Variable	$UPOPS(time)$	%
UPOP	Urban population	Variable	$UPOP = POP.UPOPS(time)$	People
RPOP	Rural population	Variable	$RPOP = POP - UPOP$	People
GPCAP	GDPPPP per capita	Variable	$GPCAP = GDPPPP / POP$	US 2017$/Person
EPR	Energy consumption per resident	Variable	$EPR = 5.918.10^{-3} + 1.514.10^{-7}.GPCAP$	TJ/Person

(Table 1 continued)

(Table 1 continued)

Variables	Description	Type	Equations	Units
REC	Residential energy consumption	Variable	$REC = EPR.POP$	TJ
UREC	Urban residential energy consumption	Variable	$\text{UREC} = \text{REC}.UPOPS(time)$	TJ
RREC	Rural residential Energy consumption	Variable	$RREC = REC - UREC$	TJ
EI	Energy intensity	Variable	$EI = 1.967.10^{-6} + 2.347.10^{-19} GDPPPP$	TJ/GDPPPP
IEC	Industrial energy consumption	Variable	IEC = $EI.GDPPPP$	TJ
TEC	Total energy consumption	Variable	$TEC = IEC + REC$	TJ
RES	Renewable energy share	Variable	$RES(time)$	%
RNEC	Renewable energy consumption	Variable	$RNEC = TEC.RES(time)$	TJ
FEC	Fossil energy consumption	Variable	$FEC = TEC - RNEC$	TJ
ESC	Energy structure of coal	Variable	$ESC(time)$	%
ESO	Energy structure of oil	Variable	$ESO(time)$	%
ESG	Energy structure of gas	Variable	$ESG(time)$	%
ECC	Energy consumption of coal	Variable	$ECC = FEC.ESC(time)$	TJ
ECO	Energy consumption of oil	Variable	$ECO = FEC.ESO(time)$	TJ
ECG	Energy consumption of gas	Variable	$ECO = FEC.ESG(time)$	TJ
CO2C	CO_2 emissions from coal	Variable	$CO2C = ECC.CEF$	Kt CO_2
CO2O	CO_2 emissions from oil	Variable	$CO2O = ECO.OEF$	Kt CO_2
CO2G	CO_2 emissions from gas	Variable	$CO2G = ECG.GEF$	Kt CO_2
TC	Total CO_2 emissions	Variable	$TC = CO2C + CO2O + CO2G$	Kt CO_2
CI	CO_2 emission intensity	Variable	CI = TC/GDPPPP	Kt CO_2 / US 2017$
CR	CO_2 emission per capita	Variable	$CR = TC / POP$	Kt CO_2 / Person
CTAR	CO_2 emission targets	Variable	$CTAR(time)$	Kt CO_2
CRED	CO_2 reduction targets	Variable	$CRED = TC \quad CTAR(time)$	Kt CO_2

2.5. Model calibration and validation

A system dynamic model gradually gains confidence as it undergoes multiple tests, considering that there is no single test to validate it fully. The model's validation relies on structural and behavioral validity [62]. In this study, the calibration and validation of the model were conducted using historical data from 1990 to 2017 as the known values to simulate and predict data from 2018–2020. Starting with the initial year 1990, a series of trial-and-error simulations were performed until the relative errors between the simulation results and the actual values reached an acceptable level (no more than 10%) with no further significant increase. The historical test of the model involved comparing the simulation values with the real values of major variables, which were total population, GDPPPP, total energy consumption, and CO_2 emissions. The error between these two values fell within the acceptable range (Table 2), indicating the model's high credibility and suitability for the subsequent analysis.

2.6. Sensitivity analysis

After validating the model, we conducted a sensitivity analysis to examine its responses to changed input parameters. We adopted the method of Yang, Li [36] changing key variables at the same rate (plus or minus 10%) while keeping the remaining variables constant. By using the same rate of change, future impacts on CO_2 emissions can be compared to identify which variables have stronger influences and vice versa. We chose five variables to test the sensitivity analysis: (S1) population growth rate +10%; (S2) GDPPPP growth rate +10%, (S3) energy intensity –10%, (S4) Energy consumption per resident -10%, (S5) renewable energy share +10%.

2.7. Scenarios

To predict the future trend of energy-related carbon emissions in Vietnam, this study established five scenarios based on the combination of SSPs and Vietnam's energy development targets (Table 3). The scenarios incorporated predicted values of population and GDPPPP, along with development targets for future energy structure, to simulate future trends in energy-related carbon emissions. The significance of this scenario analysis phase lies in providing scientific evidence for policy implications. The SSP scenarios outline different future trajectories based on varying socioeconomic factors. SSP1 envisions a shift towards more inclusive development and reduced resource intensity, promoting environmental and social sustainability. SSP2 follows historical patterns without significant changes, representing a moderate and steady development path. SSP3 depicts a fragmented world with increasing nationalism and slower economic progress, marked by reduced international cooperation. SSP4 highlights growing disparities within and between countries with uneven

Table 2: Validity check of the SD model.

		2018	2019	2020
Population (million people)	Actual value	94.9	95.8	96.6
	Simulation value	94.9	95.8	96.6
	Relative error (%)	0.0	0.0	0.0
GDPPPP (Billion US 2017$)	Actual value	914.6	981.9	1,010.0
	Simulation value	914.6	982.3	1,055.0
	Relative error (%)	0.0	0.0	4.4
Total energy consumption (PJ)	Actual value	2,611	3,012	3,105
	Simulation value	2,725	2,908	3,107
	Relative error (%)	4.3	–3.5	0.1
CO_2 emission (Mt CO_2)	Actual value	286.1	341.7	355.3
	Simulation value	291.0	310.6	331.8
	Relative error (%)	1.7	–9.1	–6.6

Table 3: Summary of scenarios.

Variables		SSP1	SSP2	SSP3	SSP4	SSP5
Population (million people)	2030	99.299	101.958	105.134	99.169	98.547
	2050	98.224	104.376	112.599	96.940	96.630
GDPPPP (Billion US 2017$)	2030	1,573.359	1,439.435	1,360.611	1,433.140	1,694.591
	2050	3,819.060	2,930.034	2,291.996	2,821.426	4,705.671
Renewable energy share (%)	2030			33		
	2050			55		
CO_2 emissions (Mt)	2030			524		
	2050			185		

Source: The World Bank [40], United Nations [57], IIASA, OECD [59–61], and Vietnam's Climate Change Strategy [39] economic growth and development. Finally, SSP5 foresees rapid economic growth fueled by intensive fossil fuel use and technological advancements, leading to high resource consumption and greenhouse gas emissions. More detailed explanations of SSP scenarios can be found in Riahi, van Vuuren [59] and O'Neill, Kriegler [63]. As outlined in the national climate change strategy, Vietnam's renewable energy sources are expected to account for at least 33% of the country's energy consumption by 2030 and at least 55% by 2050. Moreover, the country's emission targets in 2030 and 2050 are 524 and 185 Mt CO_2e, respectively [39].

3. Results

This section presents the main findings, including model validation, sensitivity analysis, and scenario analysis.

3.1. Sensitivity analysis and key influencing variables

Vietnam's energy consumption and CO_2 emissions witnessed distinct trends in the baseline scenarios from 1990 to 2020. In the initial decade (1990–2000), the industrial sector experienced slow development, leading to low fossil energy consumption and a prevalence of renewable energy sources. However, from 2000 to 2020, Vietnam underwent rapid economic growth, resulting in an exponential increase in fossil energy consumption and a subsequent surge in CO_2 emissions. Notably, oil energy dominated the consumption landscape since 1990, with coal following closely until 2018, when the country had to resort to importing coal due to challenges in domestic mining. Notably, the development of new mines and domestic coal production is insufficient to meet the demand for thermal power plants using domestic coal. The energy landscape in Vietnam exhibited remarkable growth, with energy demand surging at an average rate of 4.3% annually between 2010 and 2019. Despite this, the economy's energy intensity dropped by 14% during the same period, attributed to the faster GDP growth outpacing energy demand. However, Vietnam's energy intensity remains notably higher than neighboring countries. The challenges in domestic coal production led to a substantial increase in coal demand for power generation, rising from 24 million tons in 2015 to 40 million tons in 2018, marking a 67% increase.

For the sensitivity analysis, we controlled the parameters of five variables to measure their potential impacts on energy consumption and CO_2 emissions. The results are presented in Figure 2. In the baseline estimate, CO_2 emissions were projected to continuously grow,

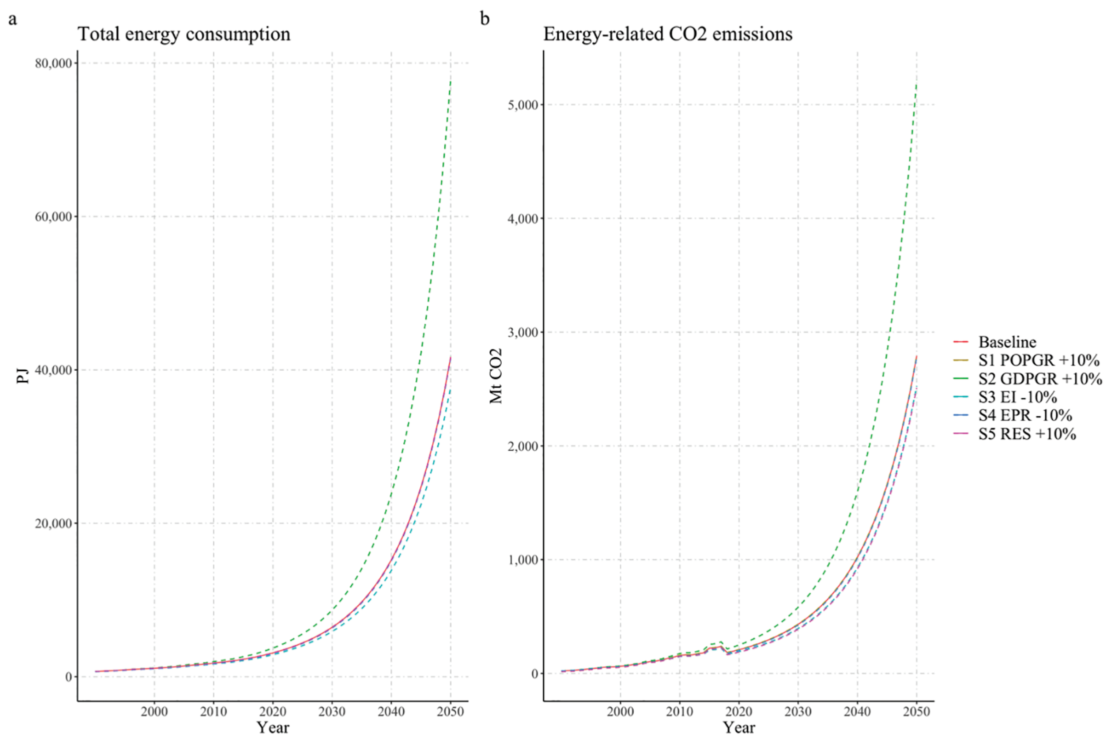

Figure 2: Sensitivity analysis results.

reaching 2,791 Mt CO_2 in 2050. The energy intensity in 2050 stands at 0.311 t/10^3 US 2017\$, representing a 1.9-fold increase from the 1990 level of 0.161 t/10^3 US 2017\$.During the sensitivity analysis, it was observed that population growth had minimal impacts. A 10% increase in the population growth rate (S1) resulted in only a 0.12% increase in both energy consumption and CO_2 emissions by 2050, showing a negligible difference from the baseline estimate. Economic growth demonstrated the most substantial positive effects, with a 10% increase in the GDPPPP growth rate (S2) leading to an 86.88% rise in energy consumption and CO_2 emissions by 2050. Carbon emissions and energy demand were also found to be sensitive to energy intensity, as a 10% reduction in energy consumption per GDP (S3) contributed to a 9.5% reduction in energy consumption and CO_2 emissions by 2050. Oppositely to energy intensity, the energy consumption per resident was only found to have trivial impacts as a 10% lower in energy consumption per resident (S4) only created a 0.51% reduction in energy consumption and CO_2 emissions by 2050. Finally, changes in energy structure, particularly the increased use of renewable energy, were found to have no impact on total energy consumption but contributed to reducing carbon emissions. Substituting a 10% share of fossil energy with renewable energy (S5) resulted in a 10.07% reduction in carbon emissions by 2050.

In summary, economic growth emerged as the primary driver of energy consumption and carbon emissions, with adjusted energy structure and energy intensity following closely. Population growth and energy consumption per resident showed limited influences during the sensitivity analysis. Furthermore, the analysis underscores the significance of transitioning the energy structure toward renewable sources to achieve carbon emission reduction and the zero-emission target by 2050. It also highlights that adjusting a single variable in the system is insufficient to meet Vietnam's current carbon emission reduction targets, emphasizing the need for comprehensive and dynamic transitional policies.

3.2. Scenario analysis of energy consumption and CO_2 emissions

Overall, all predicted scenarios displayed increasing trends in total energy consumption and CO_2 emissions for Vietnam from 2020 to 2050 (Figure 3). It is important to note that this paper does not consider emission reduction initiatives or the adoption of advanced energy-efficient technologies. The only change related to cleaner production is the transformation in the energy

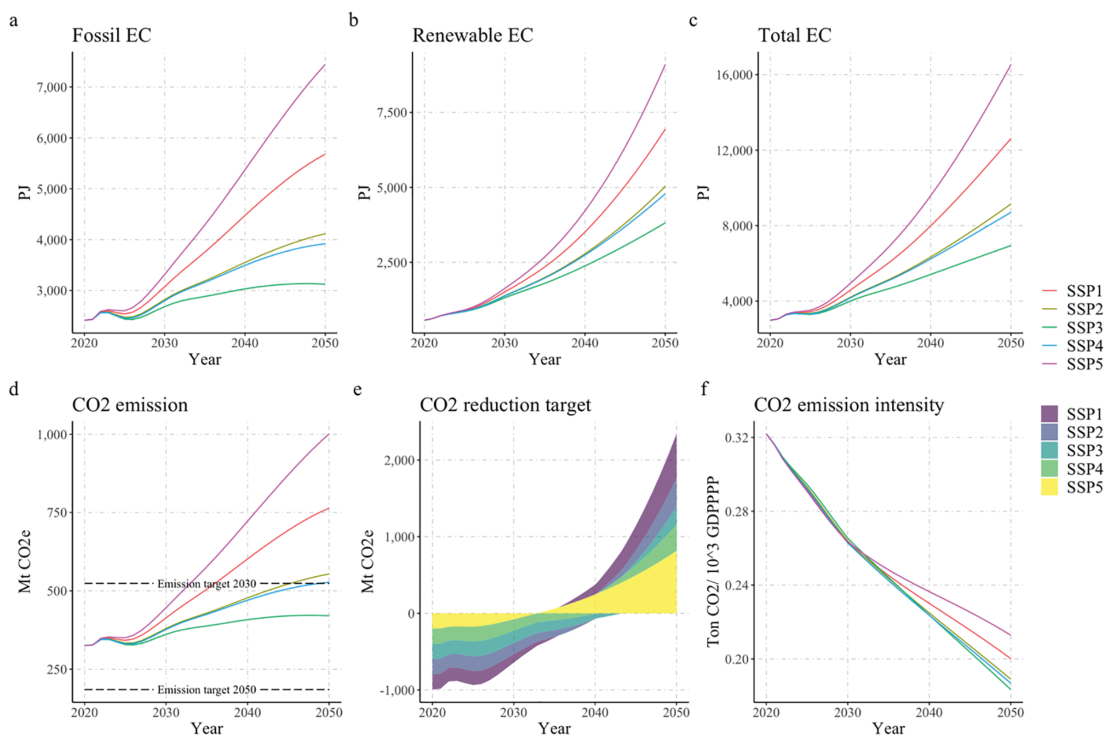

Figure 3: Results of scenario analysis.

structure, where renewable energy is projected to account for 33% and 55% of the total energy demand in 2030 and 2050, respectively.

The SSP1 scenario depicted a gradual development path. Vietnam's population grew at an average rate of 0.64% and peaked at 100.2 million people in 2037 before decreasing to 98.2 million in 2050. In contrast, Vietnam's GDPPPP continuously increased to $3,819 billion US (2017) in 2050. The total energy consumption for Vietnam was projected to reach 4,589 and 12,620 PJ in 2030 and 2050, respectively.

For the SSP2 scenario, both population and economic growth were moderate. The population peak was projected to occur in 2044 at 104.96 million people, while the GDPPPP in 2050 was estimated to be $2,930 billion US (2017), 24% lower than the SSP1 scenario. The lower population and economic growth in SSP2 resulted in reduced energy consumption and carbon emissions. Specifically, the total energy demand in SSP2 for 2050 was projected to be 9,147 PJ, which is 27.4% lower than the SSP1 scenario. SSP4 exhibited energy consumption closely following the pattern of SSP2, with a level 4.9% lower than the energy demand in SSP2 for 2050.

In the SSP3 scenario, despite having the highest population growth, economic development was the lowest. In this scenario, the predicted population for Vietnam in 2050 was 112.6 million people, 7.2% higher than the second-highest population in SSP2. Conversely, the GDPPPP in 2050 was estimated to be $2,291 billion US (2017), the lowest among the examined SSPs. Despite exponential population growth, low economic development was the main driver of low energy consumption in SSP3, as revealed in the sensitivity analysis, which indicated that GDP has more impact than population variables.

Similarly, the SSP5 scenario was found to have the highest energy demand (16,536 PJ in 2050) with a continuous growth rate of 6% per year. This was attributed to the highest GDPPPP prediction, not accounting for the lowest population growth among the five SSPs.

The trends in CO_2 emissions followed a consistent order with energy consumption, with slight differences in growth rates among the scenarios. SSP5 exhibited the highest CO_2 emissions, projecting 446 Mt CO_2 in 2030 and 1001 Mt CO_2 in 2050. SSP1 ranked second with 413 and 764 Mt CO_2 in 2030 and 2050, respectively. The carbon emissions of SSP2 and SSP4 in 2050 showed only a 4.9% difference. The emission trends in SSP2 and SSP4 were almost identical, with less than a 1% difference from 2020 to 2030. After 2020, SSP2 tended to have higher GDP growth than SSP4, leading to gradual deviations in carbon emissions towards 2050. Additionally, CO_2 emissions in the SSP4 scenario exhibited a gradually slower growth rate after 2028 but had yet to reach its peak by the mid-century. SSP3 emitted the least CO_2 during the 2020–2050 period, peaking at 422 Mt CO_2 by 2048 and decreasing afterward.

In comparing the predicted carbon emissions with Vietnam's targets in the National Climate Change Strategy, all scenarios achieved the 2030 target but failed to meet the 2050 target. This highlights the possibility of Vietnam falling short of its net-zero commitment unless strong initiatives are implemented.

4. Discussion

The sensitivity analysis revealed that economic growth is the primary factor influencing Vietnam's energy demand and carbon emissions. This finding aligns with prior studies that identified GDP as the driver of significant energy consumption in Vietnam [55,64]. On the other hand, the reduction of energy intensity and energy demand can significantly reduce energy consumption and CO_2 emissions in Vietnam by 2050. This underscores the importance of implementing energy-efficient technologies in Vietnam to achieve economic development and net-zero emission goals simultaneously. A notable trend in Vietnam's energy intensity is the rapid electrification of the economy. Between 2010 and 2019, electricity intensity (electricity demand per unit of GDP) increased by 43% [65]. Meeting the challenge of expanding electricity generation capacity to match the swift growth in energy demand, especially electricity demand, remains crucial. In response, Vietnam has been actively promoting energy efficiency since 2006 through various programs, with the main initiative being the Vietnam Energy Efficiency and Conservation Program. This program achieved energy savings of 3.4% from 2006 to 2010 and a 5.7% reduction from 2011–2015 [65]. In Europe, environmental regulations and financial incentives created through government grants and subsidies were also found to reduce energy use and CO_2 footprint [66].

The increases in population growth and reductions in energy consumption per resident have trivial impacts on carbon emissions. This is likely attributed to the fact that boosting population growth while keeping other variables constant tends to decrease GDPPPP per capita.

However, the GDPPPP growth rate outpaces the population growth rate, mitigating the impact of population change. This finding aligns with the results reported by Yang, Li [36].

The transition of Vietnam's energy structure towards renewable energy does not reduce the country's energy demand but helps reduce a considerable portion of carbon emissions. This finding is consistent with Tran [41] who also observed that renewable energy consumption and green finance can help mitigate pollution in Vietnam. The substantial reduction underscores the importance of restructuring the country's energy sector. This trend is not unique to Vietnam but is a global phenomenon as global investment in clean energy has risen by 40% since 2020. In Indonesia, the share of renewables in power generation is expected to double by 2030, reaching more than 35%. In Brazil, biofuels are projected to meet 40% of road transport fuel demand by the decade's end, up from 25% today. In sub-Saharan Africa, meeting diverse national energy and climate targets means that 85% of new power generation plants by 2030 will be based on renewables [67].

The estimation of the SDM model indicates that Vietnam is at risk of not meeting its carbon emission target in 2050, which jeopardizes its net-zero commitment. Dang and Baruah [68] also predicted the risks of Vietnam missing the commitment due to heavy reliance on external support in its climate change policy, making it insufficient and infeasible.

Considering the predicted emissions and the country's strategy, we roughly calculated the amount of CO_2 emissions that need to be reduced for Vietnam to meet its emission targets. The reduction amount increased exponentially after 2030 in all SSP scenarios due to substantial emissions from fossil energy consumption. Ali, Bakhsh [42] similarly found that carbon emissions in Vietnam have grown significantly over the years, primarily due to the consumption of fossil fuels. Therefore, a transition in the national energy structure is crucial. To achieve the net-zero target by 2050, Vietnam must further invest in renewable energy to reduce its substantial emissions, incurring a cost estimated at 300–400 billion US$ [69]. Implementing efforts to navigate the national energy system as soon as possible is imperative. This proactive approach is necessary to control and minimize the impacts of socioeconomic growth on continuously increasing energy demand and the consequent carbon emissions. Delayed management would lead to substantial accumulated excessive emissions that must be reduced to achieve the net-zero emission target in 2050, especially in the SSP5 scenario.

To examine the transitions needed for Vietnam's energy system to achieve the carbon emission target of 185 Mt CO_2 in 2050, we performed a series of trial-and-error simulations. Adjustments were made to the parameters of three variables: energy intensity (EI), energy consumption per resident (EPR), and renewable energy share (RES). EI and EPR were gradually lowered while RES was increased to reflect the transition towards green and sustainable energy sources, aiming to reduce the intensity of energy consumption from both residential and industrial sectors.

In the SSP1 scenario, characterized by sustainability-focused growth and equality, Vietnam would need to increase its renewable energy share by 25% and reduce energy intensity and energy consumption per resident by 46%. This scenario emphasizes the necessity of substantial investments in renewable energy sources, including solar, wind, hydropower, and biomass, and enforcing stricter environmental regulations to achieve notable reductions in energy intensity and carbon emissions. A key strategy in this scenario involves reducing residential energy intensity through households' widespread adoption of rooftop solar systems, which the government is promoting [70]. By encouraging and subsidizing rooftop solar installations, Vietnam can significantly reduce residential energy consumption from the grid, leading to lower overall energy intensity. Policies should promote energy efficiency across all sectors, encouraging the adoption of energy-saving technologies and practices while ensuring that households contribute to the energy transition through decentralized renewable energy generation.

For the SSP2 scenario, which represents a "middle-of-the-road" world, achieving the carbon emission target requires a 25% increase in the renewable energy share and a 25% reduction in energy intensity and energy consumption per resident. This moderate growth pathway highlights the importance of adopting a balanced energy mix that prioritizes renewables. Leveraging economic growth to invest in advanced energy technologies and infrastructure improvements is crucial. Policymakers should focus on steady, incremental progress in enhancing renewable energy capacity, improving energy storage solutions, and promoting energy-saving practices among consumers and industries.

In the SSP3 scenario, characterized by resurgent nationalism with the highest population growth and the lowest economic development, a 20% increase in renewable energy share and a 21% reduction in energy intensity and energy consumption per resident are necessary to meet the carbon emission target. This scenario underscores the importance of maximizing the efficiency of available domestic resources and promoting local renewable energy projects. Regional cooperation and community-based energy initiatives, focusing on small-scale solar, wind, and biomass projects, are essential to reduce dependency on fossil fuels. Strengthening regional collaboration and supporting joint energy projects can facilitate infrastructure development, which is crucial for a scenario with limited access to international technology and financial resources.

In SSP4, high inequality results in uneven energy access and development, with advanced urban areas adopting cleaner technologies while rural regions lag behind. In this scenario, in 2050, Vietnam's urban population was projected to be 2.1 times higher than its rural population. This scenario necessitates a 25% increase in renewable energy share and a 23% reduction in energy intensity and energy consumption per resident to meet the 2050 emissions target. Implementing social programs to support vulnerable populations and promote inclusive economic growth is essential. Policies to enhance energy efficiency in urban centers must be complemented with measures to introduce and promote energy-saving technologies in rural households and industries. This could involve government-funded programs to provide energy-efficient appliances and building materials, ensuring that the benefits of reduced energy consumption are widespread.

The SSP5 scenario, which anticipates the highest energy demand due to rapid economic growth and intensive fossil fuel use, poses significant challenges. Achieving the emission target in this scenario requires a 28% increase in renewable energy share, a 50% reduction in energy intensity, and a 65% reduction in energy consumption per resident. This scenario underscores the critical need for investing in cleaner fossil fuel technologies to manage high fossil fuel dependency while fostering the transition towards renewable energy. Encouraging technological innovation to improve energy efficiency and reduce the industrial carbon footprint is vital. Additionally, economic policies must be implemented to mitigate the environmental impact of growth, addressing issues such as air pollution from intensive emissions.

After these transitions, the projected carbon emissions in 2050 for SSP1, SSP2, SSP3, SSP4, and SSP5 scenarios are 183.4 Mt, 184.7 Mt, 184.5 Mt, 184.9 Mt, and 184.7 Mt CO_2, respectively. These findings underscore the varying degrees of policy adjustments required across different scenarios, highlighting the need for tailored strategies to achieve Vietnam's net-zero emission target by 2050.

5. Conclusion

This paper has established a unified analytical framework based on SDM to systematically assess energy-related CO_2 emissions in Vietnam. The analysis includes identifying key determinants, predicting future trends in SSP scenarios, and comparing predicted emissions with the country's CO_2 emission targets until 2050. The SD model revealed intricate and dynamic interactions among population growth, economic development, energy structure, and carbon emissions. The main findings are as follows: (1) The growth rate of GDPPPP is identified as the primary driver of Vietnam's energy-related carbon emissions. Reduced energy intensity and adjustments to the energy structure, particularly towards renewable energy, also significantly reduce carbon emissions. The influences of population growth and energy consumption per resident on carbon emissions are relatively limited. The identified key influencing factors offer valuable information for policymakers to target priority sectors for carbon emission reduction. (2) Predicted estimations in SSP scenarios show that energy consumption and CO_2 emissions are highest in SSP5, followed by SSP1, SSP2, SSP4, and SSP3. In the 2050 forecast, energy consumptions range from the highest at 16,536 PJ to the lowest at 6,942 PJ, and CO_2 emissions range from the highest at 1001 Mt CO_2 to the lowest at 420 Mt CO_2. (3) A comparison with the national carbon emission targets in 2030 and 2050 reveals that the predicted values in all SSP scenarios can meet the 2030 CO_2 emission target but fail to meet the 2050 CO_2 emission target. This failure is attributed to high fossil energy demand for economic development. The amount of CO_2 emissions that need to be reduced for Vietnam to meet its emission targets is highest in SSP5, driven by enormous CO_2 emissions from rapid economic development. These results highlight the risks of the infeasibility of Vietnam meeting its net-zero emission commitment in 2050.

Addressing the challenges linked to energy-related CO_2 emissions in Vietnam necessitates a comprehensive strategy. Drawing from our findings, policy implications were recommended for each examined scenario. These recommendations focus on economic restructuring with sectoral approaches, restructuring the energy sector towards renewable energy, enhancing energy efficiency, and strengthening policy coordination and integration.

Aside from the findings, this paper still faces some limitations. Due to the complexity of national-scale carbon emissions, there are assumptions and constraints in the structured and estimated SD model. Firstly, this study did not account for the adoption of green technologies or reduction initiatives over time in efforts to reduce energy intensity and carbon emissions. Secondly, due to a lack of data, we assumed a fixed structure of coal, gas, and oil within fossil energy, which may change in the future with the adoption of more advanced energy technologies. Thirdly, there are potential variables that can affect the population and economic subsectors, but their causal relationships and feedback were simplified. These limitations also present further opportunities for future studies.

References

[1] van Soest, H.L., M.G.J. den Elzen, and D.P. van Vuuren, *Net-zero emission targets for major emitting countries consistent with the Paris Agreement,* Nature Communications, vol. 12, no. 1, 2021, p.2140. http://doi.org/10.1038/s41467-021-22294-x.

[2] IEA, *CO_2 Emissions in 2022*. 2023, International Energy Agency,: France. p. 19.

[3] Liu, Z., et al., *Predictions and driving factors of production-based CO_2 emissions in Beijing, China,* Sustainable Cities and Society, vol. 53, no., 2020, p.101909. http://doi.org/10.1016/j.scs.2019.101909.

[4] Fernández González, P., M. Landajo, and M.J. Presno, *Tracking European Union CO_2 emissions through LMDI (logarithmic-mean Divisia index) decomposition. The activity revaluation approach,* Energy, vol. 73, no., 2014, pp. 741–750. http://doi.org/10.1016/j.energy.2014.06.078.

[5] Chong, C.H., et al., *The driving factors of energy-related CO_2 emission growth in Malaysia: The LMDI decomposition method based on energy allocation analysis,* Renewable and Sustainable Energy Reviews, vol. 115, no., 2019, p.109356. http://doi.org/10.1016/j.rser.2019.109356.

[6] İpek Tunç, G., S. Türüt-Aşık, and E. Akbostancı, *A decomposition analysis of CO_2 emissions from energy use: Turkish case,* Energy Policy, vol. 37, no. 11, 2009, pp. 4689–4699. http://doi.org/10.1016/j.enpol.2009.06.019.

[7] Zhang, F., et al., *China's energy-related carbon emissions projections for the shared socioeconomic pathways,* Resources, Conservation and Recycling, vol. 168, no., 2021, p.105456. http://doi.org/10.1016/j.resconrec.2021.105456.

[8] Vo, A.T., D.H. Vo, and Q.T.-T. Le, *CO_2 Emissions, Energy Consumption, and Economic Growth: New Evidence in the ASEAN Countries,* Journal of Risk and Financial Management, vol. 12, no. 3, 2019, p.145. http://doi.org/10.3390/jrfm12030145.

[9] Tang, C.F., B.W. Tan, and I. Ozturk, *Energy consumption and economic growth in Vietnam,* Renewable and Sustainable Energy Reviews, vol. 54, no., 2016, pp. 1506–1514. http://doi.org/10.1016/j.rser.2015.10.083.

[10] Ha, N.M. and B.H. Ngoc, *Revisiting the relationship between energy consumption and economic growth nexus in Vietnam: new evidence by asymmetric ARDL cointegration,* Applied Economics Letters, vol. 28, no. 12, 2021, pp. 978–984. http://doi.org/10.1080/13504851.2020.1789543.

[11] Nguyen, H.M., et al., *Energy consumption and economic growth: Evidence from Vietnam,* Journal of Reviews on Global Economics, vol. 8, no., 2019, pp. 350–361. http://doi.org/10.6000/1929-7092.2019.08.30.

[12] Ho, T.L. and T.T. Ho, *Economic growth, energy consumption and environmental quality: Evidence from Vietnam,* International Energy Journal, vol. 21, no. 2, 2021, pp. 213–2.24.

[13] Bui Minh, T. and H. Bui Van, *Evaluating the relationship between renewable energy consumption and economic growth in Vietnam, 1995–2019,* Energy Reports, vol. 9, no., 2023, pp. 609–617. http://doi.org/10.1016/j.egyr.2022.11.074.

[14] Thi Hong Nham, N. and L. Thanh Ha, *A wavelet analysis of connectedness between economic globalization, nonrenewable, and renewable energy consumption, and CO_2 emissions in Vietnam,* Sustainable Energy Technologies and Assessments, vol. 57, no., 2023, p.103227. http://doi.org/10.1016/j.seta.2023.103227.

[15] Le, T.H., *Connectedness between nonrenewable and renewable energy consumption, economic growth and CO_2 emission in Vietnam: New evidence from a wavelet analysis,* Renewable Energy, vol. 195, no., 2022, pp. 442–454. http://doi.org/10.1016/j.renene.2022.05.083.

[16] Lund, H., et al., *Simulation versus Optimisation: Theoretical Positions in Energy System Modelling,* Energies, vol. 10, no. 7, 2017, pp. 840. http://doi.org/10.3390/en10070840.

[17] Chang, M., et al., *Trends in tools and approaches for modelling the energy transition,* Applied Energy, vol. 290, no., 2021, pp. 116731. http://doi.org/10.1016/j.apenergy.2021.116731.

[18] Malik, P., M. Awasthi, and S. Sinha, *Study of grid integrated biomass-based hybrid renewable energy systems for Himalayan terrain,* International Journal of Sustainable Energy Planning and Management, vol. 28, no., 2020, pp. 71–88. http://doi.org/10.5278/ijsepm.3674.

[19] Ben Amer, S., et al., *Modelling the future low-carbon energy systems - case study of Greater Copenhagen, Denmark,* International Journal of Sustainable Energy Planning and Management, vol. 24, no. 0, 2019, pp. 21–32. http://doi.org/10.5278/ijsepm.3356.

[20] Kumar, S. and R. Madlener, *CO_2 emission reduction potential assessment using renewable energy in India,* Energy, vol. 97, no., 2016, pp. 273–282. http://doi.org/10.1016/j.energy.2015.12.131.

[21] Wang, A. and B. Lin, *Assessing CO_2 emissions in China's commercial sector: Determinants and reduction strategies,* Journal of Cleaner Production, vol. 164, no., 2017, pp. 1542–1552. http://doi.org/10.1016/j.jclepro.2017.07.058.

[22] Wang, H., et al., *China's CO_2 peak before 2030 implied from characteristics and growth of cities,* Nature Sustainability, vol. 2, no. 8, 2019, pp. 748–754. http://doi.org/10.1038/s41893-019-0339-6.

[23] Wu, L., et al., *Modelling and forecasting CO_2 emissions in the BRICS (Brazil, Russia, India, China, and South Africa) countries using a novel multi-variable grey model,* Energy, vol. 79, no., 2015, pp. 489–495. http://doi.org/10.1016/j.energy.2014.11.052.

[24] Limmeechokchai, B., et al., *Energy system transformation for attainability of net zero emissions in Thailand,* International Journal of Sustainable Energy Planning and Management, vol. 35, no., 2022, pp. 27–44. http://doi.org/10.54337/ijsepm.7116.

[25] Viesi, D., et al., *Multi-objective optimization of an energy community: an integrated and dynamic approach for full decarbonisation in the European Alps,* International Journal of Sustainable Energy Planning and Management, vol. 38, no., 2023, pp. 8–29. http://doi.org/10.54337/ijsepm.7607.

[26] Li, W. and S. Gao, *Prospective on energy related carbon emissions peak integrating optimized intelligent algorithm with dry process technique application for China's cement industry,* Energy, vol. 165, no., 2018, pp. 33–54. http://doi.org/10.1016/j.energy.2018.09.152.

[27] Fang, K., et al., *Will China peak its energy-related carbon emissions by 2030? Lessons from 30 Chinese provinces,* Applied Energy, vol. 255, no., 2019, p.113852. http://doi.org/10.1016/j.apenergy.2019.113852.

[28] Zeng, B., et al., *Forecasting the output of shale gas in China using an unbiased grey model and weakening buffer operator,* Energy, vol. 151, no., 2018, pp. 238–249. http://doi.org/10.1016/j.energy.2018.03.045.

[29] Ahmad, S., et al., *Application of system dynamics approach in electricity sector modelling: A review,* Renewable and Sustainable Energy Reviews, vol. 56, no., 2016, pp. 29–37. http://doi.org/10.1016/j.rser.2015.11.034.

[30] Zuo, Y., Y.-l. Shi, and Y.-z. Zhang, *Research on the Sustainable Development of an Economic-Energy-Environment (3E) System Based on System Dynamics (SD): A Case Study of the Beijing-Tianjin-Hebei Region in China,* Sustainability, vol. 9, no. 10, 2017, pp. 1727. http://doi.org/10.3390/su9101727.

[31] Wang, F., et al., *Scenarios and sustainability of the economy–nitrogen-resource–environment system using a system dynamic model on the Qinghai-Tibet Plateau,* Journal of Environmental Management, vol. 318, no., 2022, p.115623. http://doi.org/10.1016/j.jenvman.2022.115623.

[32] Bastan, M., F. Abdollahi, and K. Shokoufi, *Analysis of Iran's dust emission with system dynamics methodology,* Technical Journal of Engineering and applied sciences, vol. 3, no. 24, 2013, pp. 3515–3524.

[33] Robalino-López, A., A. Mena-Nieto, and J.E. García-Ramos, *System dynamics modeling for renewable energy and CO_2 emissions: A case study of Ecuador,* Energy for Sustainable Development, vol. 20, no., 2014, pp. 11–20. http://doi.org/10.1016/j.esd.2014.02.001.

[34] Gu, S., et al., *Coupled LMDI and system dynamics model for estimating urban CO_2 emission mitigation potential in Shanghai, China,* Journal of Cleaner Production, vol. 240, no., 2019, pp. 118034. http://doi.org/10.1016/j.jclepro.2019.118034.

[35] Ansari, N. and A. Seifi, *A system dynamics model for analyzing energy consumption and CO_2 emission in Iranian cement industry under various production and export scenarios,* Energy Policy, vol. 58, no., 2013, pp. 75–89. http://doi.org/10.1016/j.enpol.2013.02.042.

[36] Yang, H., et al., *Using system dynamics to analyse key factors influencing China's energy-related CO_2 emissions and emission reduction scenarios,* Journal of Cleaner Production, vol. 320, no., 2021, p.128811. http://doi.org/10.1016/j.jclepro.2021.128811.

[37] Liu, X., et al., *How might China achieve its 2020 emissions target? A scenario analysis of energy consumption and CO_2 emissions using the system dynamics model,* Journal of Cleaner Production, vol. 103, no., 2015, pp. 401–410. http://doi.org/10.1016/j.jclepro.2014.12.080.

[38] Chang, M., et al., *Perspectives on purpose-driven coupling of energy system models,* Energy, vol. 265, no., 2023, pp. 126335. http://doi.org/https://doi.org/10.1016/j.energy.2022.126335.

[39] Government of the Socialist Republic of Vietnam, *Decision No. 896/QD-TTg On Approving The National Strategy For Climate Change Until 2050*. 2022: Hanoi, Vietnam. p. 22.

[40] The World Bank, *World Bank Open Data*. 2024.

[41] Tran, Q.H., *The impact of green finance, economic growth and energy usage on CO emission in Vietnam – a multivariate time series analysis,* China Finance Review International, vol. 12,

no. 2, 2022, pp. 280–296. http://doi.org/10.1108/CFRI-03-2021-0049.

[42] Ali, K., et al., *Industrial growth and CO_2 emissions in Vietnam: the key role of financial development and fossil fuel consumption,* Environmental Science and Pollution Research, vol. 28, no. 6, 2021, pp. 7515–7527. http://doi.org/10.1007/s11356-020-10996-6.

[43] Bui, X.H., *An Investigation of the Causal Relationship between Energy Consumption and Economic Growth: A Case Study of Vietnam,* International Journal of Energy Economics and Policy, vol. 10, no. 5, 2020, pp. 415–421. http://doi.org/10.32479/ijeep.9583.

[44] Thuy Ho, N., et al., *The Causal Relationship Between Gdp, Energy Consumption, Population, And Oil Price: Evidence From Vietnam,* Humanities & Social Sciences Reviews, vol. 7, no. 2, 2019, pp. 100–105. http://doi.org/10.18510/hssr.2019.7211.

[45] Tang, C.F. and B.W. Tan, *The impact of energy consumption, income and foreign direct investment on carbon dioxide emissions in Vietnam,* Energy, vol. 79, no., 2015, pp. 447–454. http://doi.org/10.1016/j.energy.2014.11.033.

[46] Nguyen, V.C.T. and H.Q. Le, *Renewable energy consumption, nonrenewable energy consumption, CO emissions and economic growth in Vietnam,* Management of Environmental Quality: An International Journal, vol. 33, no. 2, 2022, pp. 419–434. http://doi.org/10.1108/MEQ-08-2021-0199.

[47] Ventana Systems, *VENSIM PLE*. 2023, Ventana Systems UK Ltd. — Sable,: UK.

[48] Posit team, *RStudio: Integrated Development Environment for R. Posit Software*. 2023: PBC, Boston, MA.

[49] Ngoc, D.D., K.D. Trung, and P.V. Minh. *Assessing the Possibility of Hydrogen Application in Vietnam's Energy System Towards Net Zero Emissions by 2050*. in *2023 Asia Meeting on Environment and Electrical Engineering (EEE-AM)*. 2023.

[50] Raihan, A., *Influences of foreign direct investment and carbon emission on economic growth in Vietnam,* Journal of Environmental Science and Economics, vol. 3, no. 1, 2024, pp. 1–17. http://doi.org/10.56556/jescae.v3i1.670.

[51] Bui Minh, T., T. Nguyen Ngoc, and H. Bui Van, *Relationship between carbon emissions, economic growth, renewable energy consumption, foreign direct investment, and urban population in Vietnam,* Heliyon, vol. 9, no. 6, 2023, p.e17544. http://doi.org/10.1016/j.heliyon.2023.e17544.

[52] Bala, B.K., F.M. Arshad, and K.M. Noh, *System Dynamics: Modelling and Simulation*. 2016: Springer Singapore. 278.

[53] Duggan, J., *System Dynamics Modeling with R*. 2016, Switzerland: Springer International Publishing. 176.

[54] Yang, J., et al., *Driving forces of China's CO_2 emissions from energy consumption based on Kaya-LMDI methods,* Science of The Total Environment, vol. 711, no., 2020, pp. 134569. http://doi.org/10.1016/j.scitotenv.2019.134569.

[55] Morelli, G. and M. Mele, *Energy Consumption, CO_2 and Economic Growth Nexus in Vietnam,* International Journal of Energy Economics and Policy, vol. 10, no. 2, 2020, pp. 443–449. http://doi.org/10.32479/ijeep.8248.

[56] Soetaert, K., T. Petzoldt, and R.W. Setzer, *Solving differential equations in R: package deSolve,* Journal of Statistical Software, vol. 33, no. 9, 2010, pp. 1–25. http://doi.org/10.18637/jss.v033.i09.

[57] UN, *UNSD Energy statistics*. 2024, The United Nations Statistics Division,: New York, USA.

[58] MONRE, *Decision No. 2626/QD-BTNMT on Publishing List Of Emission Factors Serving Greenhouse Gas (Ghg) Inventory Development*, M.O.N.R.A.E.O. Vietnam, Editor. 2022: Hanoi, Vietnam.

[59] Riahi, K., et al., *The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview,* Global Environmental Change, vol. 42, no., 2017, pp. 153–168. http://doi.org/10.1016/j.gloenvcha.2016.05.009.

[60] Crespo Cuaresma, J., *Income projections for climate change research: A framework based on human capital dynamics,* Global Environmental Change, vol. 42, no., 2017, pp. 226–236. http://doi.org/10.1016/j.gloenvcha.2015.02.012.

[61] Kc, S. and W. Lutz, *The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100,* Global Environmental Change, vol. 42, no., 2017, pp. 181–192. http://doi.org/10.1016/j.gloenvcha.2014.06.004.

[62] Barlas, Y., *Formal aspects of model validity and validation in system dynamics,* System Dynamics Review: The Journal of the System Dynamics Society, vol. 12, no. 3, 1996, pp. 183–210. http://doi.org/10.1002/(SICI)1099-1727(199623)12:3%3C183::AID-SDR103%3E3.0.CO;2-4.

[63] O'Neill, B.C., et al., *The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century,* Global Environmental Change, vol. 42, no., 2017, pp. 169–180. http://doi.org/10.1016/j.gloenvcha.2015.01.004.

[64] Thai Hung, N., *Causal relationship between globalization, economic growth and CO_2 emissions in Vietnam using Wavelet analysis,* Energy & Environment, vol. 34, no. 7, 2023, pp. 2386–2412. http://doi.org/10.1177/0958305x221108498.

[65] EREA and DEA, *Viet Nam Energy Outlook Report 2021*. 2022, Electricity and Renewable Energy Authority & Danish Energy Agency,: Hanoi, Vietnam.

[66] Silva, P., et al., *Eco-Innovation and Emissions Trading: a sector analysis for European countries,* International Journal of Sustainable Energy Planning and Management, vol. 32, no., 2021, pp. 5–18. http://doi.org/10.5278/ijsepm.6567.

[67] IEA, *World Energy Outlook 2023*. 2023, IEA: Paris.

[68] Dang, P.T. and B. Baruah. *An evaluation of Vietnam's pathway to net-zero by 2050: Reconciling the Developmental State and Civil Society*. in *11th Congress of the Asian Association of Environmental and Resource Economics (2022)–A Pathway Towards Carbon Neutrality in Asia*. 2022.

[69] TAKE, K., et al., *Net Zero Emission Scenarios in Vietnam,* Global Environmental Research, vol. 26, no., 2022, pp. 49−56. http://doi.org/10.57466/ger.26.1-2_49.

[70] Government of the Socialist Republic of Vietnam, *Decision No. 500/QD-TTg/2023 on the approval of the National Power Development Master Plan for the period 2021 - 2030, with a vision to 2050 (Power Plan VIII)*. 2023: Hanoi, Vietnam. p. 22.