Validating and Forecasting Carbon Emissions in the Framework of the Environmental Kuznets Curve: The Case of Vietnam

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Abstract: This paper examines the environmental Kuznets curve (EKC) in Vietnam between 1977 and 2019. Using the autoregressive distributed lag (ARDL) approach, we find an inverted N-shaped relation between economic growth and carbon dioxide emissions in both the long- and short-run. The econometric results also reveal that energy consumption and urbanization statistically positively impact pollution. The long-run Granger causality test shows a unidirectional causality from energy consumption and economic growth to pollution while there is no causal relationship between energy consumption and economic growth. These suggest some crucial policies for curtailing emissions without harming economic development. In the second step, we also employed the back-propagation neural networks (BPN) to compare the work of econometrics in carbon dioxide emissions forecasting. A 5-4-1 multi-layer perceptron with BPN and learning rate was set at 0.1, which outperforms the ARDL’s outputs. Our findings suggest the potential application of machine learning to notably improve the econometric method’s forecasting results in the literature.

Keywords: backpropagation neural network; energy consumption; environmental Kuznets curve; pollution; urbanization; Vietnam

1. Introduction

Vietnam is a developing country with notable economic growth during the last four decades. Since 1986, there have been some critical political and social reform milestones. The government has adopted open-door policies toward international trade and investment, and industrial activity in large cities has become increasingly active. As a result, Vietnam has risen from a low-income country to lower-middle-income status, with an average Gross Domestic Product (GDP) of US $ 2700 with more than 45 million people lifted out of poverty since 1986 [1]. Vietnam has also developed strategies to pursue economic growth associated with sustainable development. In particular, Vietnam has ratified international treaties, namely, the Kyoto Protocol (2002) and the Paris Agreement (2016), to adapt to climate change and reduce carbon emissions. Vietnam has amended the national law on environmental protection since 2014. The legislation focuses on three pillars, i.e., cap and trade, industrial emissions reporting provisions, and a database of all carbon and mitigation steps. For instance, cap and trade concentrate on creating a domestic carbon credit market where companies are limited in their emissions, so if they do not reach the cap, they could trade the surplus with other companies to optimize the cost of emissions. On the other hand, companies also regularly report their emissions to the authorized agency to monitor the quota.

Regarding renewable energies, the primary objective is to accelerate the production towards the maximal replacement of fossil energy sources. In particular, renewable electricity sources account for 15–20% of overall primary energy production in 2030 [2], biomass power, wind power, and solar power reach 6.3%, 2.7%, and 6% of total electricity output,
respectively [3]. Furthermore, the government establishes a framework for fostering and attracting non-state investment in the nation’s power transmission system [2]. These steps are expected to create a free energy market and efficiently monitor environmental policies. Although those attempts have been recognized to serve sustainable development, Vietnam faces the over fossil fuel consumption to hardly obtain the low carbon economy by 2030. Coal consumption accounts for between 65% and 75% of overall CO$_2$ emissions from the entire electricity sector, and oil consumption increases an average of 2.73% from 1977 to 2013 [4]. The excessive demand for natural resources and fossil-fuel energy due to the significant economic transformation has increased air pollution, especially in big cities where traffic congestion and industrial issues have become more serious [5,6]. For example, according to Our World in Data [7] and Euromonitor Passport Database [8], the average increase in carbon dioxide (CO$_2$) emissions reached 5.14%, along with the 6.53% increase in energy consumption and a 4.62% increase in real income for the period 1977 to 2019. Additionally, for the period 2007 to 2017, the total economic development by 6.1% resulted in a 9.3% growth of the industrial sector’s energy consumption (Electricity and Renewable Energy Authority in Vietnam and Danish Energy Agency-EREA and DEA [9]). The evidence suggests that economic expansion is related to a rise in Vietnam’s energy consumption and environmental deterioration. The CO$_2$ emissions and economic growth were normalized and presented in Figure 1.

![Figure 1. Evolution of carbon dioxide emissions and economic growth (normalized values), 1977–2019.](image)

As shown in Figure 1, the trend is not a linear relationship. While real income saw a steadily upward trend after 1981, the CO$_2$ emissions line has fluctuated with several decreased points, for instance, 1983–1985, 2011–2013, and 2017–2018. In other words, these historical data suggest the possibility that an environmental Kuznets curve (EKC) hypothesis existed during the period 1977 to 2019. Although the EKC hypothesis has been widely examined in both developing and developed countries, few studies have been conducted in the context of Vietnam. Accordingly, we are interested in gaining insight into the EKC pattern for a specific developing economy since environmental issues have been seriously concerned in Vietnam recently. Furthermore, recent studies have applied advanced techniques in environmental issues [10–13]. One primary reason is that forecasts of CO$_2$ emissions are difficult due to nonlinear regression. Therefore, the econometric method may not accurately capture the complicated behavior of analyzed variables [10,14]. As a result, finding a reliable model that can predict CO$_2$ emissions patterns could be used to formulate policies that will mitigate environmental problems [10]. Although previous studies have adopted artificial neural
networks (ANN) on this topic, few studies test benchmarks between econometrics and machine-learning approaches. In this study, once the form of EKC trajectory is determined for the long run, we apply the back-propagation algorithm (BPN) to ANN to calculate the forecast results and compare them to the econometric results. We aim to fill this gap by adding to the literature an empirical study that presents the predictive effectiveness of BPN.

From the analysis above, the study’s first aim is to validate the EKC in Vietnam from 1977 to 2019. We employed the autoregressive distributed lag (ARDL) method to examine the cointegration between analyzed variables. We also investigate the long- and short-run estimations to ascertain the parameters of the EKC curve in the sample. We further analyze the Granger causality to determine the directional effects between variables to raise reliable policy implications. The second aim of the paper is to enhance the predictive results by the machine learning method. We suppose that a machine learning approach is suitable for the complex predictive task than the econometrics approach. To conduct the comparison, we employed BPN to show the CO\textsubscript{2} emissions forecasting results and then compare the results to the ARDL’s by examining benchmarked indicators. We expect that the BPN has outperformed results due to capturing the complex behaviors between variables. Based on our findings, we add to the literature an improvement of CO\textsubscript{2} emissions forecasting by BPN.

The rest of the paper is organized as follows: Section 2 provides a review of the EKC literature. Sections 3 and 4 present the proposed model and data sources. Section 5 demonstrates the framework of ARDL, BPN, and comparative forecasting indicators between the ARDL and the BPN approaches. The empirical results and discussions are presented in Sections 6–8 discusses the conclusion and future research.

2. Related Literature

The fundamental idea of EKC is understandable and intuitive. The EKC reveals the inverted quadratic linkage between economic growth and environmental degradation, in which high economic growth initially leads to environmental deterioration due to scale effects. Then the economy reaches a certain level of average economic development when the environmental quality starts to improve because of the technical effects [15,16]. Since Grossman and Krueger [17] and Panayotou [18] had pioneering endeavors to investigate the EKC hypothesis, a considerable number of empirical studies have focused on this issue. The studies that tested the hypothesis of the EKC used multiple variables of environmental deterioration, i.e., CO\textsubscript{2} [19–21], nitrous oxide (N\textsubscript{2}O) emission [22,23], ecological footprints [24–26], electronic waste [27], water quality [28–30], and chromium emissions [31]. Regarding explanatory variables, previous studies used a range of indicators, such as economic growth [20,31,32], energy consumption [33–37], trade openness [31,38,39], urban population [40–42], financial development [43–45], technological development [22,46], and education expenditure [47,48]. Regarding econometric approaches, several studies employed the semiparametric method as alternatives to the parametric method [49–51] because the results obtained from the semiparametric approach avoid the parametric functional form assumptions [50]. The summary of empirical studies published from 2015 to 2020 is presented in Appendix A. The review shows that 48% of studies find appropriate evidence while 52% of ones find mixed or no evidence of the EKC hypothesis in the analyzed sample. Therefore, the evidence has not converged [15].

The empirical evidence of the EKC hypothesis is found in developed economies in, for instance, the USA [49], the UK [52], the EU [25], Canada [53], Australia [48], and Singapore [31,45]. Whereas it is not widely supported in developing countries such as Cambodia [54], Malaysia [55], Myanmar [41], Sri Lanka [56], and African countries [39,57,58]. The differences in environmental awareness may explain the significant reason for this phenomenon. While awareness is driven mainly by environmental protection perceptions in developed countries, protections are lax in developing countries due to their primary focus on achieving economic growth [15,59]. In other words, developed countries have
reached their turning point; they have passed the phase of using technological efficiency to enhance economic growth while keeping in place environmental protections, whereas developing countries are in the early stage of scale effects in economic development [15,16,18]. However, several empirical studies show the opposite trend. The presence of the EKC hypothesis is confirmed in developing countries such as Pakistan [32,43], Indonesia [60], South Africa [61], India [62,63], and China [40,64]. Meanwhile, several empirical studies provide no existence of the EKC hypothesis in developed countries, for example, the USA [50,65], Australia [66], the EU [67,68], and the OECD [16,69]. The main reasons behind the mixed results may be due to scaling factors employed in models [70], datasets, timespan, economic specifications in a country, and methods used to investigate the EKC hypothesis [12,30,71]. For these previous practical experiences, in this paper, we focus on studies that examine the EKC in developing countries which have similar conditions to Vietnam to find out the relationship between environmental deterioration and related explanatory factors.

Shahbaz et al. [72] employed the ARDL technique to examine the EKC trajectory of Pakistan from 1971 to 2009 and confirms the presence of EKC both in the long- and short-run. In addition, energy consumption also significantly increases CO\textsubscript{2} emissions. The study emphasizes the country’s effort to mitigate CO\textsubscript{2} emissions based on a national environmental law released in 2005 and suggests a green tax to support the law in protecting the environment. For China and India, Pal and Mitra [73] confirm the N-shaped pattern of the EKC hypothesis rather than the inverted U-curve. The N-shaped curve indicates that environmental degeneration will increase in both economies, increasing population growth, urban congestion, and industrial emissions. The results suggest that Indian policymakers could direct their efforts toward renewable energy sources such as hydropower, nuclear power, windmills, and solar power to replace coal in producing electric power. Meanwhile, the policymakers in China should consider the speed of urbanization to reduce the high electricity demand and encourage technological enhancement in the energy supply.

In Southeast Asia, Saboori and Sulaiman [74] find the EKC hypothesis for both long- and short-run in Malaysia. Moreover, the results also show the unidirectional causality from economic growth to CO\textsubscript{2} emissions in the long run. As a result, the government could implement policies that reduce emissions without harming economic growth to obtain sustainable development in the long run. Similarly, Sugiawan and Managi [60] also confirm the EKC hypothesis in Indonesia, with the turning point occurring outside the period from 1971–2010. Energy consumption has a significantly positive effect on CO\textsubscript{2} emissions, whereas electricity production from renewable energy is a statistically negative sign for both the long- and short-run. These indicate the necessity for switching to CO\textsubscript{2} emission-free energy shortly. However, Ozturk and Al-Mulali [54] find no EKC hypothesis in Cambodia. Similarly, Al-Mulali et al. [75] find a monotonically positive relationship between income and environmental degradation in Vietnam. The EKC hypothesis does not exist because these economies are still in their early stages, so environmental degradation has not reached the turning point yet.

Meanwhile, Shahbaz et al. [76] found N-shaped EKC in the long run and suggest some policies to prevent the economy from reaching the second turning point. For developing countries, mixed results could raise arguments over the presence of the EKC hypothesis. The divergent results are found even in the same country, i.e., using the example of China, Jalil and Mahmud [77] find the inverted U-shaped EKC while Pal and Mitra [73] find the N-shaped EKC; in the case of Malaysia, Lau et al. [78] confirmed the EKC hypothesis whereas Gill, Viswanathan and Hassan [55] showed the monotonically increase of EKC. Therefore, our work investigates the existence of the EKC hypothesis in Vietnam, a country that has undergone notable changes in economic growth.

Regarding ANN application in the literature, Acheampong and Boateng [10] employed BPN to predict carbon emissions intensity with nine explanatory inputs and five nodes in the hidden layer. A 9-5-1 multilayer perceptron (MLP) system shows that the predictive errors are trivial. More specifically, the mean absolute deviations and the mean
squared errors are close to zero. In addition, some factors such as urbanization, energy consumption, and population have the most significant impact on CO$_2$ emissions, especially in the USA, India, and China. Aydin, Jang and Topal [11] also used BPN to establish a system of four attributes, i.e., population, GDP, exports, and imports, to forecast energy consumption in the top-10 highest energy-consuming countries. The 4-10-1 MLP shows that correlation coefficients in the training set and testing set are over 0.96 and 0.89, respectively. Meanwhile, the performance values such as mean absolute percentage error and root mean square error are insignificant. These indicate that the BPN adopted in this study could suggest adequate predicting results within the analyzed economies. Bildirici and Ersin [12] proposed the Markov-switching vector autoregressive MLP approach to investigate the nonlinear relationship between emissions, petrol prices, and economic growth in the USA and the UK. The proposed approach has values of Mean Squared Errors (MSE), Mean Absolute Error (MAE), and Root Mean Squared Error (RMSE) that are less than the approach without MLP in both expansion and recession regimes. These indicate that the complicated nonlinear connection between analyzed variables may be adequately explained using neural networks.

From the analysis of the related literature, few studies focus on this topic in Vietnam even though the EKC hypothesis could affect economic development for the last four decades. Second, we emphasize the importance of energy consumption and urbanization variables, which significantly affect CO$_2$ emissions in developing countries like Vietnam. Third, finding a reliable model of CO$_2$ emissions prediction is needed to formulate effective environmental protection policies. Therefore, in the first stage, we employed the ARDL to examine the presence of the EKC hypothesis in Vietnam by investigating the relationship between CO$_2$ emissions and the explanatory variables. In the second stage, once the long run EKC form is determined, we applied the BPN method to predict CO$_2$ emissions. We then compare the predicted outcome between BPN and ARDL by using the comparative indicators. Our work further analyzes the forecasting improvement of BPN and will show potential approaches for future studies.

3. Proposed Model

The shape of the EKC hypothesis has always varied. Some studies initially assumed the monotonic relationship between economic growth and CO$_2$ emissions [75,79,80], some favored the quadratic function [55,64,65,71] to test the presence of the EKC hypothesis. This study initially examines the cubic form of the EKC hypothesis in Vietnam because this assumed function is the general form, including linear and quadratic functions. Based on some recent models such as Pal and Mitra [73], Onafowora and Owoye [81], and Neve and Hamaide [82], we propose a general cubic form that shows the relationship between CO$_2$ emissions, economic growth, energy consumption, and urbanization. We transformed all variables into the natural logarithm before testing for less non-normality and heteroscedasticity (for a similar approach, see [44,73,83,84]). The proposed model is specified as:

$$CO_{2t} = \beta_0 + \beta_1 GDP_t + \beta_2 GDP_t^2 + \beta_3 GDP_t^3 + \beta_4 EC_t + \beta_5 UrB_t + u_t$$

where CO$_2$ represents environmental degradation, GDP denotes economic growth. EC stands for energy consumption, UrB depicts urbanization, and $u_t$ is independent and identically distributed. The specific functional form is determined by the Beta coefficients [15,81,85] as follows:

- $\beta_1 \neq 0, \beta_2 = \beta_3 = 0$: linear relationship between CO$_2$ and growth
- $\beta_1 < 0, \beta_2 > 0, \beta_3 = 0$: U-shaped CO$_2$-growth nexus
- $\beta_1 > 0, \beta_2 < 0, \beta_3 = 0$: inverted U-shaped CO$_2$-growth nexus
- $\beta_1 > 0, \beta_2 < 0, \beta_3 > 0$: N-shaped CO$_2$-growth nexus
- $\beta_1 < 0, \beta_2 > 0, \beta_3 < 0$: inverted N-shaped CO$_2$-growth nexus
The only turning point is calculated by \( t^* = \exp(-\frac{\beta_2}{3\beta_3}) \) if the first derivative function of Equation (1) has one solution, or two turning points are computed by \( t^*_{1,2} = \exp((-\frac{\beta_2}{3\beta_2\beta_1}1/2)/3\beta_3) \) if the first derivative function of Equation (1) has two solutions (Appendix B).

4. Data Sources

We test the validating of the EKC hypothesis in Vietnam between 1977 and 2019. With data for analysis, CO₂ emissions and energy consumption are collected from Our World In Data [7], real GDP data are compiled from Euromonitor Passport Database [8], and data on urbanization are collected from World Development Indicators [86]. CO₂ emissions are measured by kilogrammes per capita. Energy consumption is measured by kilowatt-hours per capita and compiled from seven sources: oil, coal, gas, hydropower, solar, wind, nuclear, and other renewables. GDP refers to economic growth measured per capita in 1977 of constant Vietnam currency. Urbanization is measured by the population ratio in urban agglomerations of more than one million of the total population. The descriptive statistics for all the analyzed variables were presented in Table 1.

Table 1. Descriptive Statistics of the data of Vietnam, 1977–2019.

| Variables                  | Mean  | Std. Dev. | Median | Maximum | Minimum |
|----------------------------|-------|-----------|--------|---------|---------|
| Gross Domestic Product     | 253.80| 187.64    | 174.34 | 642.29  | 68.42   |
| Carbon Dioxide Emissions   | 855.45| 626.92    | 587.70 | 2091.61 | 259.54  |
| Energy Consumption         | 3523.48| 3025.53   | 2264.72| 10861.72| 828.33  |
| Urbanization               | 10.48 | 3.00      | 9.06   | 10861.72| 7.61    |

5. Methodological Framework

5.1. Auto Regressive Distributed Lag Approach

In this study, we employ the ARDL, developed by Pesaran et al. [87], to determine CO₂ behavior and other explanatory variables in the Vietnamese context. The ARDL method is widely applied compared to other cointegration approaches, such as those suggested by Engle and Granger [88], Johansen and Juselius [89]. The ARDL method is a good fit for our research purposes and the data we collected because the ARDL can be applied for integration at different orders whether the latent variables are a mixture of I(0) and I(1). For our research purposes and the data we collected because the ARDL can be applied for integration at different orders whether the latent variables are a mixture of I(0) and I(1).

\[
\Delta CO_2 = a_0 + \sum_{i=1}^{p} \beta_{0i} \Delta CO_2_{t-i} + \sum_{i=0}^{q1} \beta_{1i} \Delta GDP_{t-i} + \sum_{i=0}^{q2} \beta_{2i} \Delta GDP_{t-i} + \sum_{i=0}^{q3} \beta_{3i} \Delta GDP_{t-i} + \sum_{i=0}^{q4} \beta_{4i} \Delta EC_{t-i} + \sum_{i=0}^{q5} \beta_{5i} \DeltaUb_{t-i} + \rho_0 CO_2_{t-1} + \rho_1 GDP_{t-1} + \rho_2 GDP_{t-1} + \rho_3 GDP_{t-1} + \rho_4 EC_{t-1} + \rho_5 Ub_{t-1} + \epsilon_t \tag{2}
\]

where CO₂, GDP, EC, and UrB are represented for CO₂ emissions, economic growth, energy consumption, and urbanization. \( \Delta \), \( a_0 \), and \( \epsilon_t \) are the differenced operator, the intercept, and the white noise, respectively. The parameters \( \beta_{0i}, \beta_{1i}, \beta_{2i}, \beta_{3i}, \beta_{4i}, \) and \( \beta_{5i} \) represent the short-run dynamics while the parameters \( \rho_0, \rho_1, \rho_2, \rho_3, \rho_4, \) and \( \rho_5 \) indicate the long-run relationship between these variables.
5.1. ARDL Bounds Testing for Cointegration Approach

In the ARDL bounds testing method, to examine long-run associations, the null hypothesis of no cointegration was examined, H0: $\rho_0 = \rho_1 = \rho_2 = \rho_3 = \rho_4 = \rho_5 = 0$ against the alternative of H1: $\rho_0 \neq \rho_1 \neq \rho_2 \neq \rho_3 \neq \rho_4 \neq \rho_5 \neq 0$. The F-statistic was compared with the upper critical bound (UCB) for the mixed of I(1) or/and I(0). This study used the UCB derived from Narayan [90] due to the small sample size. If the F-statistic is higher than the UCB, we reject the null hypothesis of no cointegration. The Akaike information criterion (AIC) was used to determine the optimal lag length before testing for cointegration [55,65,71]. We choose AIC(p) because of its ability to correctly determining the true lag length (refer to Liew [93] for seeing the experimental testing on those criteria). After confirming long-run cointegration, we then analyzed the function to identify the existing state of EKC in Vietnam. We also presented the short-run estimation to confirm the persistence of the proposed model. The robustness of the long run ARDL model could be investigated for both diagnostic and stability tests. More precisely, we employed the Jarque-Bera test for residual normality Jarque and Bera [94], the Breusch-Godfrey Lagrange multiplier test for serial correlation [95,96], the White test for heteroscedasticity [97], the Ramsey reset test for the correct form of the chosen model [98], the cumulative sum of recursive residuals (CUSUM), and the cumulative sum of squares of recursive residuals (CUSUMSQ) [99] (for similar approach see [32,45,48,60,100]). We also obtain the predicted Jarque-Bera test for residual normality Jarque and Bera [94], the Breusch-Godfrey Lagrange multiplier test for serial correlation [95,96], the White test for heteroscedasticity [97], the Ramsey reset test for the correct form of the chosen model [98], the cumulative sum of recursive residuals (CUSUM), and the cumulative sum of squares of recursive residuals (CUSUMSQ) [99] (for similar approach see [32,45,48,60,100]). We also obtain the predicted CO$_2$ emissions values by replacing the actual values of explanatory variables in the long-run form. We then compare the predicted CO$_2$ values to actual CO$_2$ values by applying three comparative indicators for ARDL’s and artificial neural networks’ results.

5.1.2. The VECM Granger Causality Analysis

The causal relationship between the variables determines the framework of policy analysis. We, therefore, applied the vector error correction model (VECM) to investigate the causality between CO$_2$ emissions, energy consumption, economic growth, and urbanization in the context of Vietnam. The results derived from the VECM could suggest policies to reduce environmental degradation by increasing/decreasing determinant factors for both the short run and long run. Once the long-run relationship is confirmed, the lagged error correction term (LECT$_{t-1}$) derived from the long-run relationship was added into the VECM to examine the long- and short-run Granger causality between these variables as follows:

$$[\Delta CO_2, \Delta GDP, \Delta GDP^2, \Delta GDP^3, \Delta EC, \Delta Urb] = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \\ a_6 \end{bmatrix} + \sum_{i=1}^{p-1} \begin{bmatrix} \gamma_{1i} \\ \gamma_{2i} \\ \gamma_{3i} \\ \gamma_{4i} \\ \gamma_{5i} \\ \gamma_{6i} \end{bmatrix} + \begin{bmatrix} \Delta CO_2_{t-1} \\ \Delta GDP_{t-1} \\ \Delta GDP^2_{t-1} \\ \Delta GDP^3_{t-1} \\ \Delta EC_{t-1} \\ \Delta Urb_{t-1} \end{bmatrix} \times \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \\ \varphi_4 \\ \varphi_5 \\ \varphi_6 \end{bmatrix} + \begin{bmatrix} \epsilon_{1t} \\ \epsilon_{2t} \\ \epsilon_{3t} \\ \epsilon_{4t} \\ \epsilon_{5t} \\ \epsilon_{6t} \end{bmatrix} \tag{3}$$

The coefficient of LECT$_{t-1}$, which lies between $-1$ and 0, for each equation ($\varphi_i$) should be significantly negative to indicate the speed of adjustment to long-run equilibrium. Furthermore, the significant $\varphi_i$ also implies the long-run Granger causality from independent variables to dependent variable in each equation. For the short-run relationship, the significance of the first difference for each variable confirms the short-run Granger causality between variables. For instance, if $\gamma_{15i} \neq 0 \forall i$ is significant, energy consumption Granger-causes CO$_2$ emissions, and vice versa for $\gamma_{51i} \neq 0 \forall i$ [101].

5.2. Backpropagation Neural Networks Algorithm

The ARDL method could confirm the pattern of the EKC in Vietnam, and the ARDL could predict the CO$_2$ emissions based on the relationship between analyzed variables. However, our aim is not to stop at the econometrics approach for predicting. We further investigate the ability of the machine learning technique in forecasting. We suppose that advanced techniques such as machine learning could enhance the forecasting results be-
cause those methods could capture the complicated fluctuation patterns between variables, especially nonlinear relationships. Recently, several previous studies have applied ANN to examine environmental problems [10–12,14]. ANN has several advantages in the regressing task. There is no need to determine mathematical relations between the inputs and corresponding outputs [14,102]. ANN is also free from statistical assumptions and captures complex nonlinear behavior in analyzed attributes [103–105]. Additionally, ANN does not require steady data and could learn from data [106]. These advantages motivate us to employ ANN as a valuable method compared to the econometrics approach. In this study, we implement the backpropagation neural networks algorithm (BPN), which is the essence of neural network training, developed by Rumelhart et al. [107], Werbos [108], Parker [109].

Generally, a predicted output is computed in a feed-forward procedure based on the chosen activation function, which transfers information from inputs to hidden nodes and then from hidden nodes to the predicted output. The output is then compared to the actual value to compute the error, which is calculated using a back-propagated procedure to update all weight-connected inputs. Afterward, the next iteration proceeds until the stop condition is met. In this study, the BPN we set up includes the framework of an MLP, which has one hidden layer between the input layer and the output layer. The five-neuron input denotes the five independent variables, and the one-neuron output represents the dependent variable, as shown in Figure 2.

Figure 2. Illustration for the BPN procedure with three hidden nodes.

The number of nodes in the hidden layer could affect the output error. The optimal number of nodes in the hidden layer should avoid overfitting and satisfy minimal error [110]. Additionally, the optimum number of hidden-layer neurons generally has to be found via trial and error [11,111], and the number of hidden layers changes depending on the complexity of data [112]. Several previous studies show the different optimal hidden nodes [10,110,113]. In other words, there is no theoretical assumption to expect the number of hidden nodes needed to obtain the specific performance of the model [114]. Therefore, we tested several hidden nodes according to previous studies [110,115–118].

To reduce computational consumption during training due to unstable later layers [119,120] and expedite the sigmoid function’s application for both hidden layer and output layer [10], we normalized data to feed into the neural networks. We also note that the sigmoid function was chosen due to better performance than the tanh function. In addition, data normalizing could eliminate the dominance of any large-scale variable [121] and improve the precision of consecutive numeric calculations [110]. We then de-normalized data to the original for analysis. The algorithm was coded by Python language. The BPN flowchart is shown in Figure 3.
5.3. Criteria for Comparison

To evaluate the accuracy for either the ARDL or BPN approach, we used comparative indicators such as Mean Relative Error (MRE), MSE, and MAE as the following formulas:

\[
MSE = \frac{1}{n} \sum_{i=1}^{n} (A_i - F_i)^2
\]  

(4)

\[
MRE = \frac{1}{n} \sum_{i=1}^{n} \frac{|A_i - F_i|}{F_i}
\]  

(5)

\[
MAE = \frac{1}{n} \sum_{i=1}^{n} |A_i - F_i|
\]  

(6)

where \( n \) is the number of input data; \( A_i \) and \( F_i \) are actual and forecasted values of CO\(_2\). All three indicators measure the performance of point forecasts; hence the smaller the values are, the better the forecasting is [110]. Additionally, the MAE indicator is used to reduce the effect of heavily weighted outliers [122].

Concerning the number of iterations, we set 200 epochs to converge on the minimum values of these indicators due to our small sample. Additionally, BPN randomly produces connecting weights until convergence, and the output value is also different for each whole procedure. This study tried five different numbers of hidden nodes introduced by [110,115–118] and three different learning rates, which are 0.01, 0.1, and 0.9. We ran each combination between hidden node and learning rate ten times to obtain stable results. Therefore, for each criterion of MSE, MRE, and MAE, we have a total of \(10 \times 3 \times 5 = 150\) cells for the training set (the period from 1977 to 2010, equal to 80% of the sample size) and also 150 cells for the testing set (the period between 2011 and 2019, equal to 20% of the sample size). We then select the minimum value of each MSE, MRE, and MAE indicator in the testing set for comparison with the ARDL method.
6. Empirical Results

6.1. Auto Regressive Distributed Lag approach

6.1.1. Unit Root Test

The first step aims to check the order of integration for each variable to confirm whether the data series is stationary. The ARDL bounds testing cointegration approach can be used to identify the possible long-run cointegration among the variables, which have mixed order I(0) and/or I(1). In this study, we employed the Zivot and Andrews [123] and the Perron [124] tests to examine the unit roots due to the probability of the presence of structural breakpoints in the analyzed variables [83,125]. More specifically, the Zivot and Andrews [123] test with a one-unknown structural break which allows for a one-time change in both intercept and trend function of the variables as the following equation:

\[ y_t = \beta_0 + \beta_1 t + \beta_2 DU_t + \beta_3 DT_t + \beta_4 y_{t-1} + \sum_{i=1}^{k} \rho_i \Delta x_{t-i} + u_t \]  

(7)

where DU\(_t\) is the intercept dummy, representing a mean shift; DU\(_t\) = 1 if \( t \geq \) Time break (\( T_b \)), and 0 otherwise. DT\(_t\) is the slope dummy, which denotes a trend shift; DT\(_t\) = \( t - T_b \) if \( t > T_b \), and 0 otherwise. The \( T_b \) is determined by the minimum t-Statistic of the autoregressive variable (\( t_\alpha \)), and the Schwartz Information Criterion determines the lag length (k).

The Perron [124] test is based on Zivot and Andrews [123] except for the time shock dummy variable D(\( T_B \)):

\[ y_t = \beta_0 + \beta_1 t + \beta_2 DU_t + \beta_3 DT_t + \beta_4 y_{t-1} + \beta_5 D(T_B)_t + \sum_{i=1}^{k} \rho_i \Delta x_{t-i} + u_t \]  

(8)

where the indicator D(\( T_B \)) = 1 if \( t = T_B + 1 \). The Perron test chooses the breakpoint where the t-statistic for testing \( \beta_4 = 1 \) is the minimum as explained for Zivot and Andrews [123] test.

The results from both tests with intercept and trend are presented in Table 2. Overall, the time break for the series is found about 1986–1992. The break also refers to the 1986–1990 transition from centrally planned to the open-door economy. Due to the stagflation issue, i.e., hyperinflation (average of 497%) and high unemployment (13%) from 1986–1989 [126], the industrial sector dramatically decreased. As a result, the fuel fossil consumption and the emissions were reduced to approximately 19.12% and 14.46%, respectively, from 1986 to 1989 [7]. These facts explain why the computed \( \text{CO}_2 \) emissions and economic growth results are consistent with the downward trend for 1986–1989, as shown in Figure 1.

Table 2. Unit root test with structural break: Intercept and time trend included.

| Variable | Zivot-Andrews Unit Root Test | Perron Unit Root |
|----------|-----------------------------|-----------------|
|          | Levels                      | First Differences | Levels | First Differences |
|          | t-Statistic | Time Break | t-Statistic | Time Break | t-Statistic | Time Break | t-Statistic | Time Break |
| CO\(_2\) | -3.66 (2) | 1989 | -7.82 (1) \(^b\) | 1990 | -3.82 (2) | 1995 | -8.97 (1) \(^a\) | 1989 |
| GDP     | -3.90 (4) | 2012 | -4.39 (2) \(^b\) | 1993 | -3.86 (4) | 2012 | -6.26 (2) \(^b\) | 1992 |
| GDP\(^2\) | -3.84 (4) | 1987 | -4.27 (2) \(^a\) | 1993 | -3.55 (4) | 2012 | -6.23 (2) \(^b\) | 1992 |
| GDP\(^3\) | -4.04 (4) | 1987 | -4.94 (3) \(^b\) | 1993 | -4.09 (4) | 1986 | -6.13 (3) \(^b\) | 1992 |
| EC      | -4.21 (2) \(^c\) | 1988 | -8.07 (1) \(^a\) | 1992 | -4.27 (2) | 1994 | -6.67 (1) \(^a\) | 2006 |
| UrB     | -4.72 (1) \(^c\) | 1986 | -9.62 (1) \(^a\) | 1990 | -4.88 (1) | 1985 | -10.2 (1) \(^a\) | 1989 |

Note: \(^a,b,c\) indicate statistical significance at 1%, 5%, and 10%. The number in parentheses are the lag orders chosen based on Schwarz Information Criterion (SC). The critical values are derived from Table 4 in Zivot and Andrews [123].

The results show that \( \text{CO}_2 \) emissions and GDP are I(1) while energy consumption and urbanization are I(0). We note that all the series are stationary after the first difference.
The result indicates the ARDL approach is appropriate for testing cointegration for mixed integrated variables. Readers may refer to Appendix D to extend the discussion about the breakpoint that existed within our data sample.

### 6.1.2. ARDL Bounds Testing for Cointegration Test

According to all of the criteria used and presented in Table 3, the maximum lag order is chosen at 2 to minimize the possible loss in degrees of freedom [61]. The optimal ARDL(p,q1,q2,q3,q4,q5) model for Equation (2) was then chosen by the Akaike information criteria (AIC) from (k + 1)^n regressions, where k is the maximum number of lags, and n is the number of variables [127].

Table 3. Selection of optimal lag order.

| Lag | LogL | LR   | FPE     | AIC      | SC     | HQ     |
|-----|------|------|---------|----------|--------|--------|
| 0   | 85.89| NA   | 1.21*10^{-8} | -4.04    | -3.83  | -3.97  |
| 1   | 412.65| 555.48 | 3.42*10^{-15} | -19.13   | -17.87 | -18.67 |
| 2   | 450.76| 55.27 | 1.88*10^{-15} | -19.79 a | -17.47 | -18.95 a |

*a indicates lag order selected by the criterion. LR: sequential modified LR test statistic (each test at 5% level), FPE: Final prediction error, AIC: Akaike information criterion, SC: Schwarz information criterion, HQ: Hannan-Quinn information criterion.

Table 4 reports the ARDL bounds testing approach. When CO\textsubscript{2}, GDP, and UrB are dependent variables, the F-statistics are 5.71, 8.23, and 3.75, respectively. These values are greater than the upper bounds testing developed by Narayan [90] at 5%, 1%, and 10% significance levels, respectively. In other words, the empirical evidence indicates the existence of cointegration between CO\textsubscript{2} emissions, economic growth, energy consumption, and urbanization in the case of Vietnam between 1977 and 2019.

Table 4. ARDL bounds test for cointegration.

| Dependent Variable, Independent Variables | Optimal ARDL Model | F-Statistic | Cointegration |
|------------------------------------------|--------------------|-------------|--------------|
| CO\textsubscript{2}, GDP, GDP\textsuperscript{2}, GDP\textsuperscript{3}, EC, UrB | 1, 0, 0, 0, 0, 1   | 4.84       | Yes          |
| EC, GDP, GDP\textsuperscript{2}, GDP\textsuperscript{3}, CO\textsubscript{2}, UrB | 1, 0, 0, 0, 1, 0   | 0.83       | No           |
| GDP, CO\textsubscript{2}, EC, GDP\textsuperscript{2}, GDP\textsuperscript{3}, UrB | 2, 2, 1, 2, 2, 2   | 10.9       | Yes          |
| UrB, CO\textsubscript{2}, GDP, GDP\textsuperscript{2}, GDP\textsuperscript{3}, EC | 2, 2, 0, 0, 0, 1   | 4.14       | Yes          |

| Significant level | Lower Bound (I0 bound) | Upper Bound (I1 bound) |
|-------------------|------------------------|------------------------|
| 10%               | 2.483                  | 3.708                  |
| 5%                | 2.962                  | 4.338                  |
| 1%                | 4.045                  | 5.898                  |

Table 4. ARDL bounds test for cointegration.

1. a The critical values are derived from case III: unrestricted intercept and no trend, k = 5, N = 40 in Narayan [90]. a, b, and c indicate significance at 1%, 5%, and 10%, respectively.

### 6.1.3. Long- and Short-Run Estimations

The result of the long-run relationship between variables is reported in Table 5. The optimal ARDL bounds testing (1, 0, 0, 0, 0, 1) specification indicates that explanatory variables have a long-run relationship with CO\textsubscript{2} emissions. Energy consumption positively affects CO\textsubscript{2} at a 1% level of significance. This finding is in line with [74,75,81]. Overall, the increase in energy consumption at 1% increases CO\textsubscript{2} by 0.5%. We also note that the energy consumption coefficient is larger in the long run than in the short run. In other words, Vietnam tends to consume more energy in the long run. Because fossil energy consumption accounts for 84.7% of total energy consumption in Vietnam, and fossil energy consumption is a well-known cause of CO\textsubscript{2} emissions (especially coal consumption) and contributes 65% to 75% of total CO\textsubscript{2} emissions [9]. Thus, our findings show that Vietnam may face an increase in CO\textsubscript{2} emissions in the future if fossil energy consumption continues at the current rate.
Table 5. Long run and short run estimations.

| Variables       | Coefficient | t-Statistic |
|-----------------|-------------|-------------|
| Long-run relationship (dependent variable CO<sub>2</sub>) |             |             |
| EC              | 0.477<sup>a</sup> | 2.789       |
| GDP             | −20.332<sup>a</sup> | −3.265      |
| GDP<sup>2</sup> | 4.086<sup>a</sup> | 3.628       |
| GDP<sup>3</sup> | −0.269<sup>a</sup> | −3.962      |
| UrB             | 1.338<sup>c</sup> | 1.999       |
| Intercept       | 32.94<sup>a</sup> | 2.812       |

| Short-run relationship (dependent variable ∆CO<sub>2</sub>) |     |     |
|-----------------------------------------------------------|-----|-----|
| ∆EC            | 0.359<sup>a</sup> | 2.983 |
| ∆GDP           | −15.287<sup>a</sup> | −2.755 |
| ∆GDP<sup>2</sup> | 3.072<sup>a</sup> | 2.995 |
| ∆GDP<sup>3</sup> | −0.202<sup>a</sup> | −3.246 |
| ∆UrB           | −1.757                                                   |
| LECT(t-1)      | −0.752<sup>a</sup> | −5.242 |

Residual Diagnostics       | F-Statistic (Prob.) |
---------------------------|---------------------|
Jarque-Berra               | 2.664 (0.264)       |
Correlation LM             | 0.674 (0.517)       |
Heteroscedasticity test    | 1.155 (0.379)       |
White                      |                     |
Stability Diagnostics      | F-Statistic (Prob.) |
Ramsey reset               | 1.432 (0.239)       |
CUSUM                      | Portrayed by two lines<sup>b</sup> |
CUSUMSQ                    | Portrayed by two lines<sup>b</sup> |

<sup>a, b</sup> and <sup>c</sup> indicate significance at 1%, 5%, and 10%, respectively.

Second, CO<sub>2</sub> emissions are positively associated with urbanization at a 10% level of significance. The elasticity of CO<sub>2</sub> emissions related to urbanization is 1.338, which implies that with each 1% growth in urbanization, CO<sub>2</sub> emissions increase by 1.338%. This finding is in line with Refs. [10,42,76,128]. The results are consistent with the reality of a developing country like Vietnam, where cities of more than a million people continue attracting migrants. The phenomenon may be because these cities have better hospitals, schools, and businesses than in other areas. This continuous flow of people into the cities inevitably leads to the rise in CO<sub>2</sub> emissions because of either industrial activities or transportation [5,129–132].

Third, both linear and nonlinear coefficients of income support the presence of an inverted N-curve between CO<sub>2</sub> emissions and economic growth. Specifically, the coefficient signs of GDP, GDP<sup>2</sup>, and GDP<sup>3</sup> are negative, positive, and negative at 1% level of significance. The negative effect of the cubic coefficient validates the trend of environmental degradation decreasing when income is higher. Additionally, according to logarithms (see the calculation in Appendix B), the two estimated turning points are per capita incomes of 4.413 and 5.706, equal to 82.49 and 300.55 in exponential values. Both are between the sample minimum value (68.42) and the maximum value (642.29), as shown in Table 1. The values indicate that the monotonic increase in pollution appears when the income lies between the turning points, and pollution decreases to monotonic levels when the income exceeds the threshold level of the second turning point (5.706). These findings confirm that the CO<sub>2</sub> and economic growth nexus in Vietnam is the inverted N-shaped function rather than the inverted U-shaped trajectory. However, the cubic form could probably support a bell-shaped performance for the CO<sub>2</sub>-GDP nexus if the income lies between the first and the second turning point [81]. In contrast to Al-Mulali, Saboori and Ozturk [75], this result shows the monotonic increase between CO<sub>2</sub> emissions and economic growth in the context of Vietnam. Our finding is in line with previous studies for Iran [85], Tunisia [133,134], and South Korea [81].

The short-run dynamic relationship based on the ARDL cointegration is also presented in Table 5. The results show that the cubic form of EKC remains steady in the short
run. In sum, the inverted N-shaped function exists for both long- and short-run in the context of Vietnam. It is notable that in the long run, the negative cubic term, which is the dominant factor of the EKC trend, is smaller than that of the short-run (−0.269 versus -0.202). Specifically, in the long run, 1% of income will decrease by every 0.269% of CO₂ emissions while the ratio is 1:0.202 in the short run. The results indicate that the environment has improved over time along with incremental income. Additionally, energy consumption statistically affects CO₂ emissions, whereas urbanization does not. This finding suggests that energy consumption is the cause of environmental degradation, while urbanization has an insignificant effect on the environment in the short run.

The diagnostic results of residual normality, serial correlation, and heteroscedasticity are shown in the lower part of Table 5. More precisely, the critical F-statistics are 2.664, 0.674, and 1.155, with all p-values greater than 10%. These results are failed to reject the null hypotheses. In other words, residuals are normality distributed, no serial correlation in the residuals, and the variances for the errors are equal. Regarding the stability test, the critical F-statistic of the Ramsey reset test is 1.432, with a p-value greater than 10%. This means the null hypothesis of no misspecification of functional form cannot be rejected.

Furthermore, Figure 4 shows the plot of CUSUM and CUSUMSQ converge between the boundary lines at the 5% level of significance. The results imply all the coefficients of the model are stable. In sum, the EKC curve in Vietnam is the inverted N-shaped form in both the long- and short-run.

![Figure 4. (a) The cumulative sum of recursive residuals; (b) the cumulative sum of squares of recursive residuals.](image)

6.1.4. Granger Causality Analysis

The long- and short-run Granger causalities based on VECM were shown in Table 6. In the long run, the coefficient of LECT_t−1 when CO₂ emissions as the dependent variable is −0.765 and statistically significant at the 1% level. The significant LECT_t−1 confirms the long-run relationship of CO₂ emissions with economic growth, energy consumption, and urbanization in Vietnam. Additionally, the result also indicates that 76.5% of changes in CO₂ emissions are adjusted by deviations in the short run toward long-run equilibrium each year. In other words, short-run deviations in CO₂ emissions converge with long-run equilibrium after approximately one year and four months.

In the long run, the results in Table 6 also suggest an existing bidirectional causal relationship between urbanization and CO₂ emissions. We find that economic growth and energy consumption have a unidirectional causality relationship with CO₂ emissions, and we also find that economic growth and energy consumption have a unidirectional causality relationship with urbanization. Our findings are supported by Shahbaz, Lean and Shabbir [72] and Onafowora and Owoye [81].
Table 6. Granger causality analysis.

|                  | Short-Run Granger Causality Wald Test (p-Value) | Long Run Granger Causality |
|------------------|-----------------------------------------------|----------------------------|
|                  | ∆CO₂                                         | ∆EC                        | ∆GDP          | ∆GDP²           | ∆GDP³           | ∆UrB          | LECT₄₄ (t-Stats) |
| ∆CO₂             | -                                            | 2.73 (0.011)ᵇ              | -1.78 (0.084)   | 1.69 (0.098)   | -1.60 (0.119)  | 0.68 (0.509)  | -0.765 (-3.822)ᵃ |
| ∆EC              | 4.08 (0.026)ᵇ                               | -                          | -0.38 (0.700)  | 0.35 (0.725)   | -0.29 (0.766)  | 0.43 (0.666)  | -              |
| ∆GDP             | 1.89 (0.161)                                | 0.52 (0.601)               | -              | 44.02 (0.000)ᵃ | 92.46 (0.000)ᵃ | 4.22 (0.029)ᵇ | -0.087 (-0.986)   |
| ∆GDP²            | 1.88 (0.174)                                | 1.196 (0.320)              | 4268 (0.000)ᵃ  | -              | 2907 (0.000)ᵃ  | 0.37 (0.691)  | 0.079 (-0.923)    |
| ∆GDP³            | 1.89 (0.173)                                | 1.26 (0.299)               | 883.1 (0.000)ᵃ | 2883 (0.000)ᵃ | -              | 0.40 (0.671)  | 0.072 (-0.851)    |
| ∆UrB             | 3.59 (0.027)ᵇ                               | 0.87 (0.431)               | -0.83 (0.414)  | 0.436 (0.729)  | -0.775 (0.445) | -              | -0.116 (-2.877)ᵃ |

Values are from the Wald test based on the Chi-square distribution;ᵇ,ᵇ andᶜ indicate significance at 1%, 5%, and 10%, respectively.

In the short run, the empirical evidence shows the bidirectional relationship between energy consumption and CO₂ emissions. Meanwhile, the unidirectional causality relationship is found from CO₂ emissions to urbanization, from urbanization to economic growth, and from economic growth to CO₂ emissions. Our findings are consistent with Dogan and Turkekul [65] and Saboori and Sulaiman [74]. All the Granger causality test results are summarized in Figure 5.

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6.2. Back-Propagation Neural Networks

Table 7 shows the minimum values of MSE, MRE, and MAE for all five hidden node approaches employed by BPN compared with the ARDL’s results. First, almost all values of MSE, MRE, and MAE in the testing set (approximately 86%) are lower than in the training set. The results indicate that the proposed model overcomes the overfitting problem, which occurs when the training data fits well, but the testing is poor [131]. The results also imply that the model is reliable to be an appropriate approach for forecasting CO₂ emissions. Second, BPN generally outshines ARDL in predicting CO₂ emissions. More precisely, with the MSE indicator, values ranged from 0.00356 to 0.00434, from 0.00676 to 0.00754 for the MRE indicator, and from 0.05081 to 0.056655 for the MAE indicator. These values are smaller than ARDL’s, which are 0.014639, 0.015693, 0.104254, respectively. The results show that the predictive errors of BPN’s are trivial than the ARDL’s. In other words, BPN’s approach is more precise than that of ARDL. Third, we find that the hidden nodes, as followed by Tamura and Tateishi [118], led to minimum MSE, MRE, and MAE compared with other approaches. Specifically, a 5-4-1 MLP has the better performance in which values of MSE, MRE, and MAE are 0.003565, 0.006761, and 0.050809, respectively. Fourth, concerning the learning rate, if the learning rate is set at 0.1, all the comparative criteria are the minimum compared to the others that are 0.01 and 0.9.

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Figure 5. Pairwise Granger causality flows.
Table 7. Criteria for comparison.

| Data         | Method | Hidden Nodes | MSE   | MRE   | MAE   | MSE   | MRE   | MAE   | MSE   | MRE   | MAE   |
|--------------|--------|--------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|              |        |              | 0.01  | 0.1   | 0.9   | 0.01  | 0.1   | 0.9   | 0.01  | 0.1   | 0.9   |
| Training set | [115]  | $N_h = 2n + 1 = 11$ | 0.00700 | 0.00401 | 0.00554 | 0.01133 | 0.00844 | 0.01004 | 0.06836 | 0.05065 | 0.06013 |
|              | [116]  | $N_h = (n + n^p)/2 = 3$ | 0.00681 | 0.00517 | 0.00386 | 0.01086 | 0.00929 | 0.00796 | 0.06551 | 0.05556 | 0.04785 |
|              | [117]  | $N_h = 2^n/(n + 1) = 5$ | 0.00727 | 0.00492 | 0.00365 | 0.01151 | 0.00900 | 0.00711 | 0.06979 | 0.05389 | 0.04333 |
|              | [118]  | $N_h = n − 1 = 4$ | 0.00667 | 0.00463 | 0.00450 | 0.01114 | 0.00871 | 0.00853 | 0.06673 | 0.05214 | 0.05085 |
|              | [110]  | $N_h = (4n^2 + 3)/(n^2 − 8) = 6$ | 0.00729 | 0.00465 | 0.00440 | 0.01183 | 0.00898 | 0.00836 | 0.07092 | 0.05396 | 0.05014 |
| Testing set  | [115]  | $N_h = 2n + 1 = 11$ | 0.00367 | 0.00370 | 0.00409 | 0.00676 | 0.00687 | 0.00739 | 0.05081 | 0.05164 | 0.05555 |
|              | [116]  | $N_h = (n + n^p)/2 = 3$ | 0.00362 | 0.00360 | 0.00394 | 0.00710 | 0.00680 | 0.00736 | 0.05328 | 0.05108 | 0.05528 |
|              | [117]  | $N_h = 2^n/(n + 1) = 5$ | 0.00370 | 0.00368 | 0.00356 | 0.00687 | 0.00697 | 0.00706 | 0.05159 | 0.05232 | 0.05295 |
|              | [118]  | $N_h = n − 1 = 4$ | 0.00387 | 0.00370 | 0.00434 | 0.00720 | 0.00694 | 0.00754 | 0.05408 | 0.05214 | 0.05665 |
|              | [110]  | $N_h = (4n^2 + 3)/(n^2 − 8) = 6$ | 0.00371 | 0.00381 | 0.00376 | 0.00707 | 0.00695 | 0.00730 | 0.05310 | 0.05219 | 0.05491 |
| ARDL        | n/a    | 0.01464      | 0.01569 | 0.10425 |

*N_h, n, and n^p indicate the number of hidden nodes, the number of inputs, and the number of output, respectively.*
The predictive results for both the ARDL and the BPN approaches were shown in Figure 6. Specifically, the ARDL’s outputs are derived from the long-run form of EKC trajectory, while the BPN’s outputs are obtained by setting a 5-4-1 MLP with the learning rate at 0.1. Figure 6 also illustrates that the BPN’s results are closer to the actual outputs than the ARDL’s, especially for 2011–2019, represented for the testing set. We also present all the best predictive results of each combination between hidden nodes and learning rates in Appendix C.

![Figure 6. CO₂ emissions predicting results for both BPN and ARDL methods.](image)

6.3. Sensitivity Analysis

The sensitivity analysis aims to analyze the extent of the crucial input variable of the model and quantify the effect of input instability [10,135,136]. We applied two approaches to examine the sensitivity analysis, i.e., partial Spearman’s rank correlation [137] and partial Kendall’s rank correlation [138], to test the sensitivity weight between CO₂ emissions and each explanatory variable. The former is suitable for describing the degree of monotonicity instead of linear relationship [135,139], while the latter is appropriate for relaxing of normal distribution assumption [140] (the intuitive correlation between each pair of analyzed variables and the distribution of each variable are illustrated in Figure A5).

The partial Spearman’s rank correlation results show that energy consumption (0.951), urbanization (0.917), and economic growth (0.906) (refer to Figure 7a). The partial Kendall’s rank correlation results also reveal that energy consumption (0.852), urbanization (0.798), and economic growth (0.787) (refer to Figure 7b). To summarize, both methods indicate that energy consumption has the highest sensitivity weight with CO₂ emissions, followed by urbanization and economic growth. The results are consistent with Granger causality when these explanatory variables statistically affect the CO₂ emissions in the long run. On the other hand, the findings of the sensitivity analysis implied that each input variable had a substantial and different effect on the level of the CO₂ emissions in the context of Vietnam. Therefore, in our proposed model, omitting these input variables could bias the actual CO₂ emissions.
7. Discussion

First, the inverted N-shaped curve between CO\(_2\) and real income for both long- and short-run shows the recovery of environmental quality in the context of Vietnam. The results are strictly related to increasing renewable consumption in recent years. In particular, we record an upward trend in the use of renewable energy sources in Vietnam. Specifically, the average increase of renewable energy use from 1977 to 2019 is 5.66% compared to the average decrease of 0.24% of fossil consumption [7] (see Figure A4). The results are also consistent with the vision of national energy development strategies, in which replacing fossil consumption with renewable use as much as possible and towards the ratio of 25–30% renewable use in 2045. By 2030, Vietnam aims to enhance renewable energies, i.e., hydroelectricity, wind, biomass, and solar, account for 15.5%, 2.1%, 2.1%, and 3.3% in total electricity generation [141]. To obtain this target, Vietnam prioritizes wind and solar energy production for electricity generation and plans to create a renewable energy center in Ninh Thuan province with geographical advantages for wind and solar energies. At the end of 2020, the center contributed 2473 MW electricity, equal to 25.9% of total renewable energies in the nation [142]. The trend indicates the Vietnam government aims to reduce CO\(_2\) emissions and opens to eco-friendly environmental projects in the long run. The inverted N-shaped relationship between CO\(_2\) emissions and economic growth also indicates that Vietnam may currently benefit from a reduction in CO\(_2\) emissions. However, CO\(_2\) emissions could increase in a new cycle of the EKC when fossil fuel sources still account for approximately 84.53% of energy consumption [7] (see Figure A4). This fact poses a challenge to mitigate fossil fuel energy to help preserve the environment. Therefore, to keep the current flow for reducing CO\(_2\) emissions, policymakers should keep the attractive price for buying electricity made from renewable sources. As a result, the policy could encourage private companies who invest capital to build the infrastructure served green electricity production.

Second, the Granger causality test shows a unidirectional causality relationship between energy consumption and CO\(_2\) emissions in the long run. Moreover, the sensitivity analysis also reveals that energy consumption is the most significant factor that affects CO\(_2\) emissions among analyzed variables. The result reinforces that the primary energy source in Vietnam is fossil fuels, which directly cause environmental degradation. Vietnam is an oil- and coal-producing country, and the national energy strategy serving economic development based on fossil fuels is understandable. Consequently, the environment is seriously degraded by industrial and residential activities. Another issue is that fossil fuels are non-renewable energy sources so that overexploitation will lead to depleting these sources, then the economic development scenarios based on fossil fuels will be failed. Thus, policymakers in Vietnam have set the goal of “roadmap to reduce the share of coal-fired power” and “reducing greenhouse gas emission from energy activities 15% by 2030” [2]. To obtain those
objectives, lawmakers create and develop the carbon credit market to optimize emissions from economic activities (National Assembly of Vietnam—NAV [143]). Furthermore, research and development utilizing new technologies should be prioritized to replace fossil fuels producing in the future. Therefore, minimizing fossil fuel use will decrease CO₂ emissions as expected.

On the other hand, energy consumption and economic growth do not have causal effects in the short and long run. One possible explanation for this finding is that the economy has relied on agricultural operations, which are only carried out with a small number of energy-consuming equipment [76]. Thus, Vietnam could encourage policies to lower fossil fuels, which account for most energy consumption ratio, without harming economic growth. In other words, Vietnam has a potential period to transform the economy based on fossil fuels into an economy that relied on renewable energies. As a result, Vietnam could achieve both goals of improving economic growth and reducing CO₂ emissions.

Third, GDP has a unidirectional causality relationship to CO₂ emissions in the long- and short-run. This finding is in line with Saboori and Sulaiman [74] for Malaysia. Our finding also indicates that CO₂ emissions will not affect income in Vietnam in the long run. In other words, causing less pollution will not impair economic growth and could be a way for Vietnam to pursue sustainable development in the long run. These numbers may suggest that renewable energy can likely replace fossil fuel energy to achieve a more environmentally friendly form of energy without harming economic growth. This target is within reach since the government has developed policies for sustainable energy expansion based on four main pillars: energy efficiency, renewable energy, energy market, and climate change [9]. Our findings reconfirm that Vietnam has an opportunity to adopt renewable energy sources to reduce CO₂ emissions without slowing down economic development.

Fourth, the urban population is an essential factor affecting CO₂ emissions. Our findings imply that densely populated cities lead to increases in CO₂ emissions in the long run. When CO₂ emissions in certain regions rise, it can signal that economic opportunity and infrastructure in the bigger cities in these regions are more attractive than in other areas. The signal promotes migration to the larger cities in Vietnam. Only the impact of CO₂ on urbanization is statistically significant in the short term. This empirical evidence may suggest that the government may focus on CO₂ emissions reduction policies by disintegrating industrial activities [131], reducing private vehicles [6], and collecting carbon taxes on automobiles and motorbikes [76] in large cities in the short term. As a result, these urbanization restrictions will improve environmental quality in the long run.

Fifth, the results show BPN is a reliable method for reducing prediction errors compared with ARDL’s results. Moreover, the sensitivity reveals that all inputs have high sensitivity weights with CO₂ emissions. Hence, these variables, i.e., energy consumption, economic growth, and urbanization, could be considered the most affecting factors to air pollution in Vietnam. Our findings suggest that the government could control the environmental degeneration by adjusting explanatory inputs based on the BPN framework. The forecasting improvement also makes the policy more practical, minimizing the overestimation or underestimation of the link between income and carbon emissions.

8. Conclusions and Future Research

In this study, we employed the ARDL method developed by Pesaran, Shin and Smith [87] to validate the EKC hypothesis from 1977 to 2019 in Vietnam. The cointegration result reveals the long-run relationship between CO₂ emissions, real income, energy consumption, and urbanization. The long- and short-run results show an inverted N-curve with two-income turning points equal to 82 and 300 (constant 1977 Vietnam currency prices). The diagnostic tests confirm that our finding is stable. Furthermore, the independent variable’s coefficients in the short run are statistically smaller than those in the long run. The results indicate that if the economy reduces fossil fuel consumption, the environment shows signs of recovery. The possible reason, in our opinion, is the recent increase in the rate of renewable energy use in Vietnam. Several projects investing in renewable
energies have been deployed in Ninh Thuan province, planned as a renewable energy center in Vietnam [142]. Overall, Vietnam may benefit from an inverse N-shaped relationship between CO₂ emissions-economic growth nexus. However, we also note that, with the characteristics of the industrial based on fossil energy consumption, Vietnam may face a new cycle of the EKC curve, i.e., an upward emissions trend in the future without the successful transition to a renewable energy-based economy. Therefore, Vietnam needs to consistently pursue environmental objectives by 2030 as approved by legislation [2,141,143].

The long- and short-run estimations show that urbanization factors significantly positively influence CO₂ emissions. The results are consistent with the densely populated cities phenomenon, which cause air pollution in Vietnam. To decrease the harmful effects of urbanization, Vietnam should consider redistribution of industrial factories to satellite towns. It could lessen citizens to free air pollution. Also, lawmakers could consider the carbon taxes on vehicles and encourage people to use public transportation to save the environment.

When CO₂ emissions play the role of the dependent variable, the LECT_{t−1} is statistically negative and less than −1, as expected. The coefficient confirms the cointegration between variables and shows the long-run Granger causality that ties income, energy consumption, and urbanization to CO₂ emissions. The result of long-run Granger causality shows that energy consumption has a unidirectional effect on CO₂ emissions. The result means that policies aiming to lessen energy consumption could reduce CO₂ emissions. Additionally, the Granger analysis also reveals that economic growth and energy consumption have no causal relationship. Our findings suggest that Vietnam has a possible chance to transform the fossil fuel-based economy to the one based on renewable energies without diminishing income.

We also adopted BPN to compare the results of econometrics predictions. The comparative criteria show that the BPN method outperforms the ARDL approach in forecasting. Our experiment provides a practical approach to shed light on how to improve these forecasting results. More precisely, the econometrics approach provides the background of the relationship between analyzed variables while the BPN performs well on forecasting results. This combination could enhance the reliable model and the predicting accuracy. The results suggest that BPN and other machine-learning approaches could be applied as practical tools for predicting CO₂ emissions in future studies, such as support vector regression (SVR). In particular, the SVR approach attempts to match the best line inside the threshold value, which is the distance from the hyperplane to the boundary line, instead of minimizing errors like the BPN procedure does within our study. Since the nonparametric method estimation has been considered [144], SVR combines the advantages of nonparametric and parametric methods, in which it could reflect complicated behaviors between variables, also avoid overfitting [145]. This approach is expected to provide more accurate predictions for the CO₂ emission, thereby amending the environmental protection policies to avoid the under/over estimation of the practical situation.

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**Conflicts of Interest:** The authors declare no conflict of interest.

**Appendix A**

**Table A1.** Summary of previous empirical studies on the EKC hypothesis.

| No. | Author | Period  | Country/Region | Methodologies | Dependent(s)/Explanatory Variables | Support the EKC Hypothesis? |
|-----|--------|---------|----------------|---------------|-----------------------------------|-----------------------------|
| 1   | [146]  | 1960–2009 | Turkey         | Dynamic OLS and Error Correction Model | CO₂ emissions/energy consumption, income, tourism development | Yes |
| 2   | [125]  | 1980–2009 | Tunisia        | ARDL          | CO₂ emissions/income, energy consumption, population, exports, imports | No |
| 3   | [147]  | 1911–2010 | South Africa   | Co-summability Generalized Least Square method of random effect | CO₂ emissions/income, environmental regulation, technical progress, population, trade | No |
| 4   | [148]  | 2000–2012 | China          |               |                                   | Yes |
| 5   | [28]   | 1985–2009 | South Korea    | Fixed-effects  | Water quality/income, trade, population | Mixed (Yes for Geum, Nakdong, and Yeongsan rivers. No for Han river) |
| 6   | [60]   | 1971–2010 | Indonesia      | ARDL          | CO₂ emissions/income, electricity production, energy consumption, total factor productivity | Yes |
| 7   | [40]   | 1996–2012 | China          | Generalized Method of Moments, ARDL | CO₂ emissions/income, energy consumption, trade, urbanization | Yes |
| 8   | [43]   | 1972–2013 | Pakistan       | ARDL          | CO₂ emissions/income, trade, financial development | Mixed (Yes for ecological footprint. No for CO₂ emissions) |
| 9   | [44]   | 1980–2011 | Qatar          | ARDL          | CO₂ emissions, ecological footprint/income, energy consumption, financial development, trade | Yes |
| 10  | [41]   | 1970–2014 | Myanmar        | ARDL          | CO₂ emissions/income, trade, financial openness, urbanization | No |
| 11  | [83]   | 1971–2011 | Saudi Arabia   | ARDL          | CO₂ emissions/income, road energy consumption | No |
| 12  | [66]   | 1960–2014 | Australia      | Fully Modified OLS, and Non-nested tests | CO₂ emissions/income | No |
| 13  | [63]   | 1971–2015 | India          | ARDL          | CO₂ emissions/income, trade, renewable energy generation, electric power consumption | Yes |
| 14  | [53]   | 1990–2014 | Canada         | Fixed-effects  | Greenhouse Gas emissions/income, trade, dummy interaction between GDP and province/territory | Yes |
| No. | Author | Period     | Country/Region       | Methodologies           | Dependent(s)/Explanatory Variables                                                                 | Support the EKC Hypothesis? |
|-----|--------|------------|----------------------|-------------------------|------------------------------------------------------------------------------------------------------|----------------------------|
| 15  | [48]   | 1950–2014  | Australia            | ARDL                    | CO₂ emissions/income, index of education                                                           | Yes                        |
| 16  | [21]   | 1995–2014  | France               | VECM                    | CO₂ emissions/income, tourism                                                                      | Yes                        |
| 17  | [33]   | 1980–2011  | Peru                 | ARDL                    | CO₂ emissions/income, renewable electricity, dry natural gas, and petroleum consumption            | No                         |
| 18  | [45]   | 1971–2011  | Singapore            | ARDL                    | CO₂ emissions/income, energy consumption, population density, financial development, trade           | Yes                        |
| 19  | [20]   | 2000–2018  | USA                  | Dynamic OLS             | CO₂ emissions/income, industrial production, renewable consumption                                | Yes                        |
| 20  | [32]   | 1980–2015  | Pakistan             | ARDL                    | CO₂ emissions/income, biomass energy, foreign direct investment, trade Chromium emissions/income,    | Yes                        |
| 21  | [31]   | 1900–2017  | Singapore            | Vector Error Correction model | Total waste/real income                                                                              | No                         |
| 22  | [50]   | 1988–2017  | USA                  | Partial linear          | Sulfur dioxide, nitrogen oxide/income                                                              | Yes                        |
| 23  | [49]   | 1929–1994  | USA                  | Semiparametric          | Mixed (Yes for upper middle- and high-income countries. No for low- and lower middle-income        |                            |
|     |        |            |                      | partially linear model  | countries.                                                                                         |                            |
| 24  | [149]  | 1990–2011  | 14 Asian countries   | Generalized Method of Moments | CO₂ emissions/income, population density, industry share, political stability, government        | Yes                        |
|     |        |            |                      |                         | effectiveness, quality of regulation, and corruption                                                |                            |
| 25  | [150]  | 1960–2010  | Arctic countries     | ARDL                    | CO₂ emissions/income, energy consumption                                                            | No                         |
|     |        |            | 149 countries, 30    |                         | Water withdrawals/income                                                                            | Yes                        |
|     |        |            | OECD countries, & 48 |                         |                                                                                                    |                            |
|     |        |            | US States            |                         |                                                                                                    |                            |
| 26  | [30]   | 2003–2008  | 17 OECD countries    | Semiparametric smooth coefficient model | Mixed (Yes for upper middle- and high-income countries. No for low- and lower middle-income        |                            |
|     |        |            |                      |                         | countries.                                                                                         |                            |
|     |        |            |                      | Fixed effects and      |                                                                                                    |                            |
|     |        |            |                      | Generalized Method of  |                                                                                                    |                            |
|     |        |            |                      | Moments                |                                                                                                    |                            |
| 27  | [51]   | 1981–1998  | 15 new European      | Panel co-integration     | Ecological footprint/income, energy consumption, urbanization, trade openness, and financial       | Mixed                      |
|     |        |            | Union countries      | and Panel Causality     | development                                                                                        |                            |
|     |        |            | 84 cities in both    | tests                   |                                                                                                    |                            |
|     |        |            | developed and        |                         |                                                                                                    |                            |
|     |        |            | developing countries  |                         |                                                                                                    |                            |
| 28  | [151]  | 1980–2008  | 93 countries         | Panel co-integration    | CO₂ emissions/income, energy consumption, trade openness, urban population                         | Yes                        |
|     |        |            |                      | and Panel Causality     |                                                                                                    |                            |
|     |        |            |                      | tests                   |                                                                                                    |                            |
| 29  | [42]   | 1992–2010  | 15 new European      | Panel co-integration    | CO₂ emissions/income, energy consumption, trade openness, urban population                         | Yes                        |
|     |        |            | Union countries      | and Panel Causality     |                                                                                                    |                            |
|     |        |            | 84 cities in both    | and Panel Causality     |                                                                                                    |                            |
|     |        |            | developed and        | and Panel Causality     |                                                                                                    |                            |
|     |        |            | developing countries  | and Panel Causality     |                                                                                                    |                            |
| 30  | [152]  | 1998–2000  | 400 countries        | Panel co-integration    | CO₂ emissions/income, energy consumption, trade openness, urban population                         | Yes                        |
|     |        |            |                      | and Panel Causality     |                                                                                                    |                            |
|     |        |            |                      | tests                   |                                                                                                    |                            |
| No. | Author | Period       | Country/Region                               | Methodologies                          | Dependent(s)/Explanatory Variables                                                                 | Support the EKC Hypothesis? |
|-----|--------|--------------|---------------------------------------------|----------------------------------------|-----------------------------------------------------------------------------------------------------|--------------------------|
| 31  | [153]  | 2005–2013    | 34 developed and developing countries       | Principal Component Analysis           | CO₂ emissions/income, tourism, energy consumption, health expenditure, CO₂ emissions/income, renewable energy consumption, public consumption for energy development | Yes                      |
| 32  | [69]   | 1990–2012    | 17 OECD countries                           | Fixed-effects                           | CO₂ emissions/income, energy intensity, energy structure, urbanization                              | No                       |
| 33  | [154]  | 1980–2011    | 5 African countries, 22 Latin American and Caribbean countries | Fully Modified OLS                     | Energy consumption/income, agriculture employment                                                  | No                       |
| 34  | [155]  | 1990–2011    | 17 OECD countries                           | Generalized Least Square               | CO₂ emissions/income, renewable energy consumption                                                  | Yes                      |
| 35  | [156]  | 1977–2010    | 17 OECD countries                           | Fully Modified OLS and Dynamic OLS     | CO₂ emissions/income, energy consumption, financial development, trade                                | Yes                      |
| 36  | [157]  | 1990–2012    | 56 countries                                | Generalized Method of Moments          | Total, household, productive transport energy consumption/gross value added, energy prices N₂O, Greenhouse gas emissions/income, finance, transport, renewable energy consumption | Mixed (Yes for Indonesia and Brazil. No for India) |
| 37  | [35]   | 1970–2012    | 4 countries: India, Indonesia, China, Brazil | ARDL                                   | CO₂ emissions/income, energy consumption, trade                                                      | No                       |
| 38  | [67]   | 1995–2009    | 27 EU countries                             | Feasible Generalized Least Squares     | Total, household, productive transport energy consumption/gross value added, energy prices N₂O, Greenhouse gas emissions/income, finance, transport, renewable energy consumption | No                       |
| 39  | [23]   | 1990–2015    | BRICS countries                             | Fixed-effects                           | Dynamic OLS, system GMM, Dynamic Fixed effects                                                      | Yes                      |
| 40  | [58]   | 1980–2012    | 25 African countries                        | Augmented Mean Group, Common Correlated Effects Mean Group Estimator | CO₂ emissions/income, energy consumption, electricity consumption, population growth               | No                       |
| 41  | [158]  | 1960–2010    | 50 US States                                | OLS estimation                         | CO₂ emissions/income, energy consumption, population growth                                        | Mixed (Yes for AMG method. No for CCEMG method) |
| 42  | [159]  | 1980–2010    | 26 OECD and 52 emerging countries           | Panel Data Estimation                  | CO₂ emissions/income, energy consumption                                                            | No                       |
| 43  | [24]   | 1975–2007    | 15 MENA countries                           | Fully Modified OLS, and Dynamic OLS     | Ecological footprint/income, energy consumption, urbanization, political index, fertility, life expectancy at birth | Mixed (Yes for oil-exporting countries. No for non-oil-exporting ones) |
| 44  | [160]  | 1970–2013    | ASEAN-4                                     | Fully Modified OLS and Dynamic OLS, panel VECM | CO₂ emissions/income, renewable, non-renewable energy consumption, agricultural value added Water footprint/income, agriculture, income level binary, coastal country binary | No                       |
| 45  | [29]   | 1996–2005    | 94 countries                                | OLS estimation                         | Water footprint/income, agriculture, income level binary, coastal country binary                     | No                       |
| No. | Author | Period     | Country/Region            | Methodologies                                      | Dependent(s)/Explanatory Variables                                                                                                                                                                                   | Support the EKC Hypothesis? |
|-----|--------|------------|---------------------------|----------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------|
| 46  | [25]   | 1980–2013  | EU countries              | Fully Modified OLS, and Dynamic OLS                 | Ecological footprint/income, renewable and non-renewable energy consumption, trade openness CO₂ emissions/income, renewable energy consumption, technical development, trade, institutional quality | Yes                         |
| 47  | [46]   | 1994–2012  | 74 countries              | Quantile regression                                | No                                                                                                                                                    |                             |
| 48  | [161]  | 1970–2016  | 14 Asia-Pacific countries | Fully Modified OLS, and Augmented mean group       | CO₂ emissions/income, natural gas consumption                                                                                                          | Yes                         |
| 49  | [162]  | 1980–2017  | Gulf Cooperation Council  | Fully Modified OLS, pooled mean group, and Dynamic common correlated effects | Mixed (No for Oman. Yes for other 5 countries)                                                                                                         |                             |
| 50  | [163]  | 2005–2013  | 64 developing countries   | Generalized Method of Moments                      | Ecological footprint, CO₂ emissions/income, energy consumption, corruption, trade, foreign direct investment Greenhouse gas emissions/income, renewable energy consumption | No                          |
| 51  | [164]  | 1990–2016  | 28 EU countries           | Fixed-effects                                       | Mixed (Yes for 17/28 countries)                                                                                                                              |                             |
| 52  | [165]  | 1990–2014  | 86 countries              | Generalized Method of Moments                      | Mixed (Yes for the whole sample and Africa. No for other groups)                                                                                         |                             |
| 53  | [166]  | 2000–2017  | 24 emerging countries     | Generalized Method of Moments                      | Mixed (Yes for 95/121 countries)                                                                                                                            |                             |
| 54  | [167]  | 1960–2014  | 121 countries             | Fixed-effects                                       | Mixed (Yes for 95/121 countries)                                                                                                                            |                             |
| 55  | [34]   | 1995–2014  | 14 countries              | Fixed-effects                                       | Mixed (Yes for 17/28 countries)                                                                                                                              |                             |
| 56  | [168]  | 1995–2015  | 27 EU countries           | Fully Modified OLS, and Dynamic OLS                 | Mixed (Yes for the whole sample and Africa. No for other groups)                                                                                         |                             |
| 57  | [169]  | 1995–2015  | 18 OECD countries         | Fully Modified OLS, and Generalized Method of Moments | Mixed (Yes for 95/121 countries)                                                                                                                            |                             |
### Table A1. Cont.

| No. | Author | Period | Country/Region | Methodologies | Dependent(s)/Explanatory Variables | Support the EKC Hypothesis? |
|-----|--------|--------|----------------|---------------|-----------------------------------|-----------------------------|
| 58  | [26]   | 1970–2014 | G7 countries | Bootstrap panel causality test | Ecological footprint (carbon, cropland, grounds, forest products, and grazing land)/income CO₂ emissions/income, energy efficiency, intermediate inputs, primary, secondary, and tertiary, trade | Mixed (Yes for USA and Japan. No for other 5 countries) |
| 59  | [68]   | 1995–2011 | 27 EU countries and 12 major countries | Fixed-effects | N₂O emissions/income, technological development, population | No |
| 60  | [22]   | 1990–2015 | 16 APEC countries | Generalized Method of Moments | CO₂ emissions/economic complexity index, energy intensity | No |
| 61  | [170]  | 1995–2017 | 25 EU countries | Fully Modified OLS, and Dynamic OLS | Electronic waste/income, ICT exports, population | No |
| 62  | [27]   | 2000–2016 | 30 EU countries | Generalized Method of Moments, Two-stage least square, and OLS | CO₂ emissions/income, energy consumption, trade, oil prices | No |
| 63  | [19]   | 1992–2015 | 12 OPEC countries | Panel corrected standard errors | CO₂ emissions/income, tourism, education expenditures, health expenditure, GNI index, foreign direct investment | No |
| 64  | [47]   | 1995–2015 | G7 countries | Random-effects | CO₂ emissions/income, trade, financial development, trade, human capital, bio capacity. CO₂ emissions/income, fossil fuel consumption, exergetic renewable, exergy intensity, trade, human development | Yes |
| 65  | [38]   | 1990–2016 | 34 Annex I countries | Fully Modified OLS, and Dynamic OLS | Ecological footprint/income, energy structure, energy intensity, population | Mixed (Yes for USA and Mexico. No for Canada) |
| 66  | [39]   | 1970–2017 | West African States | Panel Quantile regression | Ecological footprint/income, energy consumption, trade, patents applied | Yes |
| 67  | [171]  | 1990–2016 | 3 NAFTA countries | Vector Autoregression | Ecological footprint/income, energy consumption, trade. | No |
| 68  | [172]  | 1980–2014 | BRICST countries | Fully Modified OLS, Dynamic OLS, and Augmented Mean Group | Ecological footprint/income, energy consumption, trade. | Yes |
| 69  | [173]  | 1995–2013 | 98 developed and developing countries | Generalized Method of Moments, Pooled Mean Group Moments Quantile Regression | Ecological footprint/income, export diversification | Yes |
| 70  | [174]  | 1980–2016 | USA, Mexico, and Canada | Panel Quantile regression | Ecological footprint/income, trade, patents applied | Yes |
| 71  | [175]  | 1990–2014 | Sub-Saharan African countries | Panel cointegration | Ecological footprint/income, export diversification | Yes |

### Appendix B

The general cubic form is as follows:

\[ Y = \beta_1 X + \beta_2 X^2 + \beta_3 X^3 \]  \hspace{1cm} (A1)
In order to find out the turning points, we find the solution(s) for the first derivative of Equation (A1):

\[
\frac{\delta Y}{\delta X} = 3\beta_3 X^2 + 2\beta_2 X + \beta_1
\]  

(A2)

Equation (A2) is the quadratic function, so the solution(s) depends on the value of delta (\(\Delta\)):

\[
\Delta \left( \frac{\delta Y}{\delta X} \right) = (2\beta_2)^2 - 4 \times (3\beta_3\beta_1)
\]  

(A3)

If \(\Delta = 0\): Equation (A2) has only one solution that is the turning point of equation (A1):

\[
X = -\frac{4\beta_2}{12\beta_3\beta_1} = -\frac{\beta_2^2}{3\beta_3\beta_1}
\]  

(A4)

In this case, the variation of Equation (A1) as follows:

| \(X\) | \(-\infty\) | \(-\frac{\beta_2}{3\beta_3\beta_1}\) | \(+\infty\) |
|---|---|---|---|
| \(\frac{\delta Y}{\delta X}\) | \(+\) | \(0\) | \(+\) |
| \(Y\) | \(-\infty\) | \(Y_1\) | \(+\infty\) |

Table A2. \(\beta_3 > 0\).

If \(\Delta > 0\): Equation (A2) has two solutions that are the turning points of Equation (A1):

\[
X_{1,2} = \frac{-2\beta_2 \pm \sqrt{4(\beta_2^2 - 3\beta_3\beta_1)}}{6\beta_3} = \frac{-\beta_2 \pm \sqrt{\beta_2^2 - 3\beta_3\beta_1}}{3\beta_3}
\]  

(A5)

Table A3. \(\beta_3 < 0\).

Figure A1. The cubic shape when equation (A1) has one turning point: (a) \(\beta_3 < 0\); (b) \(\beta_3 > 0\).

If \(\Delta < 0\): Equation (A2) has two solutions that are the turning points of Equation (A1):

\[
X_{1,2} = \frac{-\beta_2 \pm \sqrt{\beta_2^2 - 3\beta_3\beta_1}}{3\beta_3}
\]  

(A6)

Table A4. \(\beta_3 < 0\).
Table A5. $\beta_3 > 0$.

| X       | $-\infty$ | $-\frac{\beta_2 \sqrt{\beta_2 - 3\beta_3 \beta_1}}{3\beta_3}$ | $\frac{-\beta_2 + \sqrt{\beta_2 - 3\beta_3 \beta_1}}{3\beta_3}$ | $+\infty$ |
|---------|-----------|---------------------------------------------------------------|---------------------------------------------------------------|-----------|
| $\frac{\delta Y}{\delta X}$ | + | 0 | + | 0 | + |
| f(X)    | $\infty$ | $Y_1$ | $+\infty$ |

Figure A2. The cubic shape when Equation (A1) has two turning points: (a) $\beta_3 < 0$; (b) $\beta_3 > 0$.

In our study, from the long-run cubic form between GDP and CO$_2$, we have:

$$Y = -20.332387X + 4.085637X^2 - 0.269191X^3 + k \quad (A6)$$

where $Y$, $X$, and $k$ represent CO$_2$, GDP, and other variables, respectively.

$\beta_3 = -0.269191 < 0$, and $\Delta(\frac{\delta Y}{\delta X}) = 8.171274^2 - 4 \times (-0.80757) \times (-20.332387) = 1.09 > 0$. \quad (A7)

Hence, the two turning points are computed:

$$X_1 = \frac{-\beta_2 + \sqrt{\beta_2^2 - 3\beta_3 \beta_1}}{3\beta_3} = 4.413 \quad \text{and} \quad X_2 = \frac{-\beta_2 - \sqrt{\beta_2^2 - 3\beta_3 \beta_1}}{3\beta_3} = 5.706 \quad (A8)$$

Figure A3. The inverted N-shaped of the EKC in Vietnam, 1977–2019.
Figure A4. The ratio of total energy consumption in Vietnam, 1977–2019.

Figure A5. The illustration of the correlation between each pair of analyzed variables and the distribution of each variable.

Appendix C

The ARDL’s outputs were calculated based on the long-run form between CO₂ and independent variables. Meanwhile, the BPN was tested by five different numbers of hidden nodes and three different learning rates, which are 0.01, 0.1, and 0.9, respectively. We ran this procedure ten times and the best results were shown in Table A6.
| Year | CO₂ (Actual) | ARDL (Output) | Artificial Neural Networks with Back-Propagation Algorithm—BPN (Output) |
|------|--------------|---------------|---------------------------------------------------------------------|
|      |              |               | Hecht-Nielsen [112] | Turban, Sharda, Delen, Aronson, Liang and King [113] | Zhang, Ma and Yang [114] | Tamura and Tateishi [115] | Sheela and Deepa [107] |
| 1977 | 5.7025       | 5.6766        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 1978 | 5.6899       | 5.6871        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 1979 | 5.7223       | 5.7389        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 1980 | 5.7324       | 5.7726        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 1981 | 5.7621       | 5.7683        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 1982 | 5.7745       | 5.7607        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 1983 | 5.8003       | 5.7526        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 1984 | 5.6799       | 5.7278        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 1985 | 5.8438       | 5.6999        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 1986 | 5.7999       | 5.7229        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 1987 | 5.8970       | 5.7282        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 1988 | 5.8644       | 5.7272        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 1989 | 5.5589       | 5.6858        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 1990 | 5.5734       | 5.7364        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 1991 | 5.7161       | 5.7523        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 1992 | 5.6922       | 5.8092        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 1993 | 5.7413       | 5.9119        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 1994 | 5.8540       | 6.0155        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 1995 | 5.9383       | 6.1288        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 1996 | 6.0992       | 6.2501        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 1997 | 6.3493       | 6.3774        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 1998 | 6.3859       | 6.4618        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 1999 | 6.3762       | 6.5219        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 2000 | 6.4798       | 6.6505        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 2001 | 6.5980       | 6.7654        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 2002 | 6.8263       | 6.9519        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 2003 | 6.9576       | 7.0899        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 2004 | 7.0257       | 7.1607        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 2005 | 7.0605       | 7.1476        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 2006 | 7.0656       | 7.2132        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |
| 2007 | 7.1747       | 7.3427        | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 | 0.01 | 0.1 | 0.9 |

Table A6. The output values from the ARDL and BPN approaches.
| Year | CO₂ (Actual) | ARDL (Output) | Artificial Neural Networks with Back-Propagation Algorithm—BPN (Output) |
|------|--------------|---------------|-------------------------------------------------------------------|
|      |              |               | Hecht-Nielsen [112]                                                |
|      |              |               | Turban, Sharda, Delen, Aronson, Liang and King [113]               |
|      |              |               | Zhang, Ma and Yang [114]                                           |
|      |              |               | Tamura and Tateishi [115]                                          |
|      |              |               | Sheela and Deepa [107]                                             |
|      |              |               | 0.01 0.1 0.9 0.01 0.1 0.9 0.01 0.1 0.9 0.01 0.1 0.9                  |
| 2009 | 7.2462       | 7.3799        | 7.1890 7.2168 7.2246 7.2037 7.1976 7.2185 7.1977 7.2014 7.2129 7.2095 7.2060 7.2286 7.1923 7.2039 7.2456 |
| 2010 | 7.3385       | 7.4420        | 7.2657 7.2927 7.2985 7.2804 7.2731 7.2967 7.2749 7.2789 7.2810 7.2850 7.2813 7.3042 7.2751 7.2813 7.3193 |
| 2011 | 7.3913       | 7.5036        | 7.3420 7.3668 7.3689 7.3552 7.3481 7.3757 7.3496 7.3545 7.3494 7.3547 7.3553 7.3750 7.3536 7.3563 7.3888 |
| 2012 | 7.3110       | 7.5248        | 7.3884 7.4115 7.4127 7.3993 7.3932 7.4065 7.3995 7.3999 7.3982 7.4086 7.3999 7.4188 7.4039 7.4029 7.4319 |
| 2013 | 7.3362       | 7.5766        | 7.4390 7.4579 7.4548 7.4436 7.4433 7.4506 7.4455 7.4461 7.4446 7.4481 7.4478 7.4571 7.4406 7.4481 7.4717 |
| 2014 | 7.4534       | 7.6215        | 7.4954 7.5093 7.5015 7.4945 7.4975 7.4991 7.4989 7.4981 7.4963 7.4965 7.5000 7.5018 7.4911 7.4999 7.5166 |
| 2015 | 7.5867       | 7.6674        | 7.5331 7.5607 7.5472 7.5459 7.5522 7.5478 7.5528 7.5504 7.5468 7.5442 7.5523 7.5455 7.5426 7.5519 7.5604 |
| 2016 | 7.6457       | 7.7182        | 7.6006 7.6012 7.5816 7.5845 7.5966 7.5827 7.5943 7.5906 7.5859 7.5786 7.5939 7.5762 7.5745 7.5915 7.5925 |
| 2017 | 7.6406       | 7.6947        | 7.6376 7.6344 7.6146 7.6196 7.6300 7.5960 7.6393 7.6262 7.6243 7.6320 7.6270 7.6110 7.6269 7.6296 7.6255 |
| 2018 | 7.6933       | 7.7264        | 7.6988 7.6859 7.6588 7.6730 7.6856 7.6427 7.6964 7.6796 7.6687 7.6825 7.6795 7.6539 7.6870 7.6835 7.6681 |
| 2019 | 7.6343       | 7.7279        | 7.7329 7.7124 7.6794 7.6978 7.7157 7.6636 7.7238 7.7056 7.6900 7.7029 7.7070 7.6712 7.7042 7.7089 7.6867 |
Appendix D

To investigate the possible effect of the breakpoint on the outputs, we re-examined Equation (1) by adding the Dummy and the interactive variables:

\[
CO_{2t} = \beta_0 + \beta_1 GDP_t + \beta_2 GDP_t^2 + \beta_3 GDP_t^3 + \beta_4 EC_t + \beta_5 UrB_t + D_t (\beta_0^* + \beta_4^* GDP_t) + u_t \tag{A9}
\]

\[
CO_{2t} = \beta_0 + \beta_1 GDP_t + \beta_2 GDP_t^2 + \beta_3 GDP_t^3 + \beta_4 EC_t + \beta_5 UrB_t + D_t (\beta_0^* + \beta_3^* GDP_t^3) + u_t \tag{A10}
\]

\[
CO_{2t} = \beta_0 + \beta_1 GDP_t + \beta_4 EC_t + \beta_5 UrB_t + D_t (\beta_0^* + \beta_1^* GDP_t) + u_t \tag{A11}
\]

where \(D_t\) is the dummy year variable (\(D_t = 1\) for \(t = 1989, \ldots 2019\), and \(D_t = 0\) otherwise). \(D_t^*GDP_t\) and \(D_t^*GDP_t^3\) are the interactive variables representing the possible effect of economic growth and the breakpoint to CO2 emissions. EC\(_t\) represents energy consumption, and UrB\(_t\) denotes urbanization. The year 1989 was chosen for the breakpoint.

We separate the two terms \(D_t^*GDP_t\) and \(D_t^*GDP_t^3\) for each Equations (A9) and (A10) to investigate the possible effect of the dummy variable on the linear and the cubic forms. Meanwhile, the Equation (A11) shows the possible effect of the structural break on results based on the linear model assumption.

The cointegration tests are presented in Table A7, the long- and short-run estimations are shown in Table A8, and the cumulative sum of recursive residuals (CUSUM) and cumulative sum of squares of recursive residuals (CUSUMSQ) are depicted in Figure A6.

### Table A7. ARDL bounds test for cointegration.

| Dependent Variable, Independent Variables | Optimal ARDL Model | F-Statistic | Cointegration |
|------------------------------------------|---------------------|-------------|--------------|
| CO\(_2\), GDP, GDP\(_2\), GDP\(_3\), EC, UrB, D, D*GDP | 1,0,0,0,0,2,0 | 4.70 \(^a\) | Yes |
| **Significant level** | **Lower Bound (I0 bound)\(^l\)** | **Upper Bound (I1 bound)\(^u\)** |  |
| 10% | 2.03 | 3.13 |  |
| 5% | 2.32 | 3.50 |  |
| 1% | 2.96 | 4.26 |  |
| CO\(_2\), GDP, GDP\(_2\), GDP\(_3\), EC, UrB, D, D*GDP\(_3\) | 1,0,0,0,0,2,0 | 4.71 \(^a\) | Yes |
| **Significant level** | **Lower Bound (I0 bound)\(^l\)** | **Upper Bound (I1 bound)\(^u\)** |  |
| 10% | 2.03 | 3.13 |  |
| 5% | 2.32 | 3.50 |  |
| 1% | 2.96 | 4.26 |  |
| CO\(_2\), GDP, EC, UrB, D, D*GDP | 1,0,0,0,0,2,0 | 3.87 \(^b\) | Yes |
| **Significant level** | **Lower Bound (I0 bound)\(^l\)** | **Upper Bound (I1 bound)\(^u\)** |  |
| 10% | 2.26 | 3.35 |  |
| 5% | 2.62 | 3.79 |  |
| 1% | 3.41 | 4.68 |  |

\(^a,b\) indicate significance at 1%, 5%. \(^l,u\) The critical values are derived from case III: unrestricted intercept and no trend, \(k = 5, N = 40\) in Narayan [90].

The results from Table A7 reveal that the cointegration between analyzed variables was confirmed at 5% level of significance.
Table A8. The long- and short-run estimations.

| Variables | Equation (A7) | Equation (A8) | Equation (A9) |
|-----------|---------------|---------------|---------------|
|           | Coefficient   | t-Statistic   | Coefficient   | t-Statistic   | Coefficient   | t-Statistic   |
| Long-run relationship (dependent variable CO$_2$) | | | | | | |
| GDP       | $-18.807^b$   | $-2.105$      | $-19.141^b$   | $-2.048$      | $-19.624^b$   | $-2.048$      |
| GDP$^2$   | $3.757^b$     | $2.183$       | $3.776^b$     | $2.209$       | $3.776^b$     | $2.209$       |
| GDP$^3$   | $-0.244^b$    | $-2.282$      | $-0.241^b$    | $-2.459$      | $-0.241^b$    | $-2.459$      |
| EC        | $0.822^a$     | $3.653$       | $0.827^a$     | $3.627$       | $0.738^a$     | $2.851$       |
| UrB       | $0.411$       | $0.593$       | $0.408$       | $0.555$       | $1.115$       | $2.902$       |
| D         | 0.8           | 0.304         | 0.161         | 0.174         | $-5.026^a$    | $-2.885$      |
| D*GDP     | $-0.223$      | $-0.384$      | 0             | 0             | $1.026^b$     | $2.454$       |
| D*GDP$^3$ | 0             | 0             | $-0.004$      | $-0.402$      | 0             | 0             |
| Intercept | 30.065        | 2.122         | 30.892        | 2.015         | 4.959         | 2.546         |

Short-run relationship (dependent variable ∆CO$_2$) | | | |
| ∆GDP      | $-12.828^c$   | $-1.866$      | $-13.058^c$   | $-1.829$      | $-2.561^c$    | $-1.201$      |
| ∆GDP$^2$  | 2.563         | 1.936         | 2.576         | 1.959         | 2             | 2             |
| ∆GDP$^3$  | $-0.167^c$    | $-2.028$      | $-0.165^c$    | $-2.159$      | 0             | 0             |
| ∆EC       | 0.561         | 3.416         | 0.564         | 3.403         | 0.437         | 3.02          |
| ∆UrB      | 0.28          | 0.598         | 0.278         | 0.602         | 3.799         | 1.577         |
| ∆D        | 0.419         | 0.234         | $-0.017$      | $-0.027$      | $-3.035^a$    | $-2.762$      |
| ∆D*GDP    | $-0.152$      | $-0.381$      | 0             | 0             | 0.608         | 2.454         |
| ∆D*GDP$^3$| 0.682         | 5.311         | $-0.682^a$    | $-5.316$      | $-0.592^a$    | $-5.155$      |

Residual Diagnostics | F-Statistic (Prob.) | F-Statistic (Prob.) | F-Statistic (Prob.) |
| Jarque-Berra | 2.833 (0.243) | 2.849 (0.240) | 1.466 (0.480) |
| Heteroscedasticity test (BPG) | 0.419 (0.662) | 0.41 (0.661) | 0.649 (0.530) |
| Stability | F-Statistic (Prob.) | F-Statistic (Prob.) | F-Statistic (Prob.) |
| Ramsey reset | 0.711 (0.406) | 0.815 (0.426) | 0.034 (0.085) |
| CUSUM | Portrayed by two lines | Portrayed by two lines | Cross two lines |
| CUSUMSQ | Portrayed by two lines | Portrayed by two lines | Cross two lines |

$^a,b,c$ indicate significance at 1%, 5%, 10%. $^k$ implies the sub-sample (1989–2019).

The results from Table A8 show that in the context of the cubic form (Equations (A9) and (A10)), the terms of dummy time variables (D and D*GDP/D*GDP$^3$) have a statistically insignificant effect on CO$_2$ emissions. The diagnostic and stability tests (lower part of Table A8) confirm that the estimated results are stable. In other words, no difference between the two periods (before and after breakpoint—the year 1989) given the cubic form in the sample. Indeed, the cubic form could describe the change of slopes without breaking.

In the linear form context (Equation (A11)), the results reveal that the dummy time variables have a statistically significant effect on CO$_2$ emissions. The results are as expected because the breakpoint separates two periods into two independent linearities with different slopes. The causality analysis (Table A9) shows the interactive variable positively affects emissions in the long- and short run, indicating that economic growth from 1989 to 2019 positively affects emissions. However, we also note that the GDP regressor is insignificant; the Ramsey reset test indicates the misspecification of the linear function (Table A8); the CUSUM and CUSUMSQ cross the boundaries (Figure A6). In other words, the linear form is not a good fit function to describe data in the sample.
Figure A6. The breakpoint testing for the linear form assumption: (a) CUSUM; (b) CUSUMSQ.

Table A9. Granger causality analysis.

| Variables | \( \Delta CO_2 \) | \( \Delta EC \) | \( \Delta GDP \) | \( \Delta UrB \) | \( \Delta D \) | \( \Delta D^*GDP \) | \( LECT_{t-1} \) |
|-----------|-------------------|----------------|-----------------|----------------|----------------|----------------|----------------|
| \( \Delta CO_2 \) | -                 | 0.31 (0.080) \(^c\) | -0.29 (0.20)    | 2.79 (0.38)    | -3.56 (0.03) \(^b\) | 0.73 (0.046) \(^b\) | -0.703 (4.405) \(^a\) |
| \( \Delta EC \)  | 0.29 (0.031) \(^b\) | -               | 0.05 (0.805)    | -2.34 (0.419)  | -2.78 (0.071) \(^c\) | 0.63 (0.063) \(^c\) | -0.411 (2.451) \(^b\) |
| \( \Delta GDP \) | -0.11 (0.298)     | 0.03 (0.861)    | -               | 6.26 (0.010) \(^b\) | -3.93 (0.000) \(^a\) | 0.87 (0.000) \(^a\) | -0.004 (0.234) |
| \( \Delta UrB \) | 0.01 (0.477)      | 0.01 (0.922)    | 0.06 (0.001) \(^a\) | -              | 0.14 (0.156)    | -0.03 (0.180)   | -              |
| \( \Delta D \)  | -                 | -               | -               | -              | -              | -              | -              |
| \( \Delta D^*GDP \) | 0.14 (0.012) \(^b\) | 0.15 (0.031) \(^b\) | 0.62 (0.001) \(^a\) | -2.36 (0.107)  | 4.51 (0.001) \(^a\) | -              | -              |

\(^{a,b,c}\) indicate significance at 1%, 5%, 10%.

Therefore, the proposed cubic function interpreting the EKC in Vietnam could reflect the two distinct periods without breaking, while the structural change analysis is crucial for the linear assumption. In any given case, an econometric investigation should be carefully examined to describe data in the sample.

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