# Modelling the effect of energy consumption on different environmental indicators in the United States: The role of financial development and renewable energy innovations

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# Modeling the Effect of Energy Consumption on different Environmental Indicators in the US: The Role of Financial Development and Renewable Energy Innovations.


## Abstract

This study offers new insights into the relationship between energy consumption and environmental degradation in the United States by controlling for financial development, renewable energy innovations, economic expansion, and trade policy uncertainty over the period 1985:Q1 to 2014:Q4. Based on the flexible ARDL model, our findings show that energy consumption deteriorates the environment while renewable energy innovations reduce $CO_2$ emissions, but has no significant effect on ecological footprint. Furthermore, the EKC hypothesis is valid only when ecological footprint is used as an environment indicator. The causality results establish a feedback effect between $CO_2$ emissions and renewable energy innovations, a unidirectional causal flow from financial development to $CO_2$ emissions, energy consumption and economic growth. Also discovered is a unidirectional causal flow from the ecological footprint to energy use and economic growth and from renewable energy innovations and energy consumption to economic growth. Therefore, the policy implications for this study, among others, include the provision of grants and subsidies for research in renewable energy to enhance sustainable environmental quality.



**Keywords**: CO2 emissions; Energy use; Financial development; Trade policy uncertainty; Renewable energy innovations

**JEL Classification:** C22; C32;

## 1. Introduction

Mitigating the adverse effect of environmental damage has increasingly become a herculean commitment especially for advanced economies. From a global perspective, policymakers and intergovernmental agencies such as the United Nations Framework Convention on Climate Change (UNFCCC) are consistently urging for more climate-oriented action and drive towards attaining environmental sustainability targets. Giving the contextual dimensions (such as the socioeconomic, political, ethical and moral aspects) of climate change, the mitigation, adaptation, and climate action plans remain shrouded in complexity (National Aeronautics and Space Administration, 2020). This complex nature of the climate change debacle is responsible for the climate and environmental sustainability targets of intergovernmental agencies and governments across the globe. For instance, the United Nations Development Programme advocates for carbon-neutral economies by 2050 through a deliberate commitment to reduce global emissions by half in 2030 (United Nations Development Programme, 2020). Then, it is not surprising that the development of energy technologies, especially carbon technologies such as the carbon dioxide ($CO_2$) capture and storage (CC-S) and carbon dioxide sequestration (CS) are increasingly gaining global attention.

In the case of the United States, after accounting for $CO_2$ sequestration especially from the land sector, a total record of 6,677 million metric tons of CO2 equivalents of greenhouse gas (GHG) was reported in 2018 (United States Environmental Protection Agency, 2019). The United States Environmental Protection Agency (US-EPA) further indicated that the largest source of anthropogenic GHG emissions in the United States are mainly fossil fuel consumption from electricity (29% share GHG emissions), transportation (28% share GHG emissions), industry (22% share GHG emissions), commercial and residential (12% share GHG emissions), and agricultural activities (10% share GHG emissions). However, the challenge and commitment to attaining a sustainable environment amid increasing economic activities in the United States has remained a subject of keen interest. Considering that the United States became an ecological footprint deficit nation since 14 July 2015 (see the report of Global Footprint Network, 2020), this further supports the argument that the country's ecology cannot sustain the exponential growth of human induced environmental pollution[1]. With the current trend in US consumption patterns (see Table 1) amidst ecological supply deficits, the environmental impact of other factors such as renewable energy development, immigration, and real income growth are increasingly becoming more important (Alola, 2019 a & b; Alola et al., 2020; Alola & Kirikkaleli, 2019; Ike et al., 2020a; 2020b; Usman et al., 2020 a; 2020 b; Iorember et al. 2020; Musa et al. 2021; Ali et al. 2021; Usman et al. 2021).

Table 1: The United States' environmental waste composition from consumption.

| Consumption | Component of waste and description |
|---|---|
| Food items | • In 2015, 22% of food items constitutes landfills across the United States. |
| Water | • In 2015, a total estimate of 322 billion gallons per day of water were withdrawn in the United States. The composition of water usage in the country is mainly through public supply (12%), irrigation (37%), and thermoelectric power (41%). |
| Material use and waste management (MSW) | • In 2000, about 23.7% metric tons of per capita consumption of all materials (52% more than European average) constitutes material use and waste management.<br>• In 2015, about 2.0412 kilograms of MSW (municipal solid waste were generated by the average American. Subsequently, a recycling and composting amounting to 35% of the United States' MSW were made. |
| Total energy expenses | • The total energy expenses in the United States is 1.1 trillion United States dollars (USD), constituting 5.8% of the country's Gross Domestic Product in 2017.<br>• In addition, 2.6 gallons of oil, 11 pounds of coal, and 250 cubic feet of natural gas were consumed per persons in the United States in 2017. |

[1] The large ecological footprint is attributed to excessive use of fuel oil and other traditional energy consumption patterns related to economic growth, which have detrimental effects on the environment.

| | |
|---|---|
| Greenhouse gases (GHG) emissions | • According to the United States Environmental Protection Agency, the United States generated a total of 6,677 million metric tons of CO2 equivalents of GHG emissions in 2018.<br>• In addition, in 2018, the composition of GHG emissions in the United States is 29% from electricity, 28% from transportation, 22% from industrial sector, 12% from commercial and residential. |

**Note**: The information was retrieved from the Center for Sustainable Systems, University of Michigan, and computed by the authors.

Being the world's largest economy and trading country through its operational antecedents in foreign and domestic investments, USA has consistently maintained trade prowess with trading partners like Mexico, Canada, China, Japan, the UK and African countries as well as European countries with evidence of a deficit trajectory for a long timeframe as shown from World Bank data. This trade situation underscores the recent shifts in trade policies by the Trump administration. However, the drive for a more favourable balance of trade could have adverse effect on environmental quality as empirically shown by Alola, (2019a); Usman et al., (2020a). More so, with the upsurge of financial sector development in the USA, one would expect this sector to play an important role in the stability of the whole economy by attracting more foreign direct investments and creating a surge of consumer credits and purchases, which of course may have consequential effects on environmental and ecological quality through the optimization of economic growth as empirically shown by Sadorsky, (2011); Shahbaz et al. (2013a); Shahbaz et al. (2017).

To curb this dilemma, there arises a need to incorporate cutting-edge renewable energy technology within the energy consumption matrix of the US economy. Various studies have isolated the innovation environment nexus with different measures of innovation (Ahmad et al, 2019; Kahouli, 2018; Fernandez et al, 2018). However, most of these studies use a broad-based classification of innovation which do not specifically capture technological innovations in energy utilization.  There are studies that have ascertained the role of energy innovations.

Studies by Álvarez-Herránz et al. (2017), Shahbaz et al (2018), as well as Solarin and Bello (2020) all employ total energy innovation proxies, however the present study follows a similar but different direction by employing a renewable energy innovation proxy which captures innovations specific to renewable energy alone. This is done in order to ascertain if investments in renewable energy specific innovations are environmentally and economically feasible.

Furthermore, given the importance of financial intermediation in various investment undertakings, it becomes important to ascertain the degree to which financial development can affect environmental degradation. Financial development can affect the environment through its effect on economic growth. Empirical evidence on the direction of this effect is largely mixed. According to Xu (2000) effective financial intermediation can affect growth through the domestic investment channel. On the contrary, as aptly uncovered by Cecchetti and Kharroubi (2015, 2019) the financial sector can reduce total factor productivity growth by disproportionally favouring high collateral projects with low productivity. This is due in part to the fact that investors who are likely to be risk averse tend to favour less risky projects with lower returns. If production is environmentally degrading, then financial development in the former scenario (Xu, 2000) would indirectly have a degrading effect on environmental quality. However, if the latter scenario (Cecchetti and Kharroubi, 2015; 2019) is supported then financial development would have an ameliorating effect on the environment. Various studies have uncovered an environment ameliorating effect of financial development (Shahbaz et al., 2013c; 2013d; Bekhet et al., 2017; Zhao and Yang, 2020) as well as an environment degrading effect (Jian et al., 2019; Pata, 2018; Ahmad et al., 2018; Haseeb et al., 2018). It follows from the mixed results that the environmental effects of financial development may depend on the level of development attained in the financial sector. As such, assuming a monotonic relationship may be all too simplistic. The current study examines the environmental impacts of energy use, trade policy uncertainty, renewable energy innovation and the broad-based financial development index from the contextual perspective of the cogency of the Environmental Kuznets Curve (EKC). To achieve this objective, we ask the following salient questions: to what direction does a surge in financial development, trade policy uncertainty, renewable energy innovation and economic expansion affect environmental quality? What are the magnitudes of these effects? We employ two environmental indicators to uncover a wider and a more comparative assessment of the effect of the study variables on the environment. This is because while $CO_2$ emissions capture mainly the atmospheric component of the environment, the ecological footprint additionally captures both the lithosphere, hydrosphere and the biosphere with the implication that both indicators may respond differently to the independent variables.

Therefore, our study contributes not only to the EKC literature especially for the case of the United States of America (USA), but also unveils the underpinning effects of the upsurge of financial development, trade policy and renewable energy innovations on environmental quality in the USA. By incorporating a new broad-based index of financial development and trade policy uncertainty instead of trade volume, the study is different from Alola (2019 a & b), Dogan and Turkekul (2016) and Usman et al., (2020a) and other previous studies in several ways. Unlike previous studies which mostly proxy financial development by the total domestic credit to private sector, the index of financial development employed in this study is generated from nine indices based on the financial institutions and financial markets with focus on their depth, access, and efficiency. These two broad markets (financial institutions and financial markets) and three issue categories (deepness, accessibility and efficiency of the markets) forms the overall new broad-based financial development index. Furthermore, we add the squared term of the broad-based financial development index to ascertain whether the relationship between financial development and the environmental indicators exhibit non-linear relationship(s). This understanding is indeed a required condition for effective and efficient energy/environmental policymaking. Finally, by employing the Autoregressive Distributed Lag (ARDL), we can determine how short-run deviations in both environmental models link with their long-run equilibrium values.

Following the structure of this study, we begin with a synopsis of environmental sustainability determinants in the context of the USA in section 2. In sections 3 and 4, the methodological insight of the study and the discussion of the result are respectively outlined. In the last part, section 5, the conclusion of the study is presented.

## 2. Environmental sustainability in the United States: A synopsis

Studies such as Soytas et al., (2007) and Raza et al., (2019) are among the investigations that have mainly examined the impact of energy utilization and economic expansion in the United States. Specifically, Soytas et al., (2007) employed the Toda and Yamamoto (1995) Granger causality approach by incorporating the gross fixed capital formation and labour in the estimation model for the period 1960–2004. The result found that there is insignificant evidence of Granger causality between income and $CO_2$ emissions for the case of the United States. However, an evidence of Granger causality is found to be significant from energy consumption to carbon emissions. In general, the study posited that income alone is not a good predictor of environmental quality in the United States. By undertaking a similar study, Raza et al., (2019) implemented the wavelength techniques (wavelength coherence spectrum, correlation and covariance), and other wavelength-related techniques, the study found that energy consumption exerts positive impact of emissions of carbon in the short, medium and long terms. Causality results also submitted the same directional outcome but is restricted to a one-way path between the two variables. Several other studies (Ike et al, 2020c; Nwaka et al, 2020; Wang et al, 2020; Dong et al, 2020) have shown how different forms of energy consumption affect the quality of the environment with the general conclusions that fossil-based energy consumption aggravates environmental degradation while renewable energy-based energy consumption ameliorates it.

From the perspective of trade and financial development for the case of the United States especially in the context of environmental sustainability, a handful of studies have linked trade policy with carbon emissions (Alola, 2019 a & b; Alola & Kirikkaleli, 2019). Both studies found a significant relationship between trade policy and carbon emissions in the United States. From a global perspective, Alhassan et al (2020) employing a panel of 79 countries finds that trade impedes environmental performance in countries with lower environmental performance and that the negative environmental effect of trade can be averted with stronger government integrity. Zhao et al (2021) employing a globally representative panel of 62 countries finds that financial risk and innovation impedes environmental degradation in countries with the highest emissions but induces environmental degradation in countries at lower quantiles. Khan et al. (2021) showed that decentralization have a significant impact on CO2 emissions through the institutions and human capita. Furthermore, in the earlier study of Dogan and Turkekul (2016), both trade policy and financial development were investigated in the context of the hypothesis of EKC for the period of 1996-2010. The study employed the bound testing approach of the Autoregressive Distributed lag (ARDL) and found that financial development has no environmental implication for the United States. However, the result showed that the impact of trade on environmental quality is desirable in the country. Besides, and as depicted by the study, energy consumption expectedly aggravates environmental hazard. Interestingly, the study invalidates the hypothesis of EKC for the case of the United States. In addition, there exists bi-directional Granger causality between income and $CO_2$ emissions, energy utilization and $CO_2$, and between urbanization and $CO_2$ emissions.

Moreover, the studies of Apergis and Payne (2017), Dogan and Ozturk (2017), and the more recent works of Sarkodie and Strezov (2018), and Alola and Kirikkaleli (2019) are a few of the other studies that have examined the determinants environmental quality in the United States. Specifically, Apergis and Payne (2017) employed the per capita carbon emissions by fossil fuel sources across the 49 United States and the District of Columbia for the experimental period of 1980-2013. A statistically significant evidence of multiple convergence clubs were found by sector (residential, electric power, transport, industrial, and commercial), for natural gas and coal, and for the aggregate source. Furthermore, the study found a significant evidence of full panel club convergence for petroleum. Similarly, Dogan and Ozturk (2017) examined the validity of the hypothesis of EKC for large economy of the US within the context of real income, conventional energy consumption and other factors for the period of 1980 to 2014. The employed structural break approach of Gregory-Hansen cointegration test revealed a significant evidence of cointegration between CO2 emissions, renewable energy, fossil fuel energy, real income and the square of real income. While the long-run statistical evidence revealed that fossil fuel consumption is detrimental to the environmental quality, the study further aligned with a study like Dogan and Turkekul (2016) by invalidating the hypothesis of EKC for the case of the US. Furthermore, Usman et al., (2020a) examined the role of renewable energy and trade policy on environmental pollution in the USA, and found renewables and trade policy to exert negative pressure on ecological footprints. Within the purview of energy technologies and innovations, Álvarez-Herránz et al. (2017) employ a V-lag distribution model to capture the mitigating effects of energy innovations on greenhouse gases in OECD countries which was observed to be statistically significant. Shahbaz et al. (2018) in their study for France finds that total energy innovations has a negative effect on environmental degradation while financial development as proxied by real domestic credit to private sector has a non-linear inverted U-shape effect on environmental degradation. In addition, Solarin and Bello (2020) employing a

STIRPAT model finds that total energy innovations increases environmental quality in the United States. Our study differs from all three studies due to the fact that we employ a renewable energy innovations proxy instead of total energy innovations as well as augmenting our model with a new broad-based financial development index to determine how financial intermediation can affect environmental degradation. Also, Youssef (2020) finds resident patents to have an increasing effect on carbon emission while non-resident patents dampen carbon emission. Usman et al. (2021) using a panel quantile regression via moments, establish that environmental indicator responds negatively to economic growth and positively to conflicts in the MENA region.

## 3. Data and Methodology

### *3.1 Data*

This study is conducted using US quarterly data from 1985Q1 to 2014Q4. Carbon dioxide ($CO_2$) emission per capita is the dependent variable, which measures environmental quality. The explanatory variables include energy use, measured in terms of metric tonnes of energy consumed per capita in the USA; the broad-based index for financial development measured in terms of financial institutions and financial markets with concentration on the market depth, access, and efficiency. The Financial Development Index Pyramid is shown in the appendix A1.[2] Economic expansion and its squared term are proxied by the Gross Domestic Product (GDP) per capita (constant 2010 US Dollars), while the index for trade policy uncertainty used corresponds to the regulations and agreements that control imports and exports of the USA calculated by Baker et al. (2016)[3]. The selection of the variables are guided by the Sustainable Development Goals (SDGs) outlined by the United Nations (UNs), which are anchored on clean

[2] The depth of the market captures the size and liquidity of markets; market access measures the ability of the individuals and companies alike to access financial services, while market efficiency measures the degree of activity of the capital markets, its ability to provide financial services at low cost as well as sustaining revenues.
[3] The trade policy uncertainty index has been used recently by Usman *et al.,* (2020a, b) to capture uncertainty in trade policy effect on environmental quality in the USA.

energy and water affordability as well as stimulating growth with little or no environmental pollution effects and climate change. The choice of the data length is based on availability as some of the series only available up to the period stated. The GDP, $CO_2$ and energy use variables are all obtained originally as annual frequency and then converted to quarterly frequency via quadratic interpolation available on Eviews 9.5 software. This is because the data length in annual frequency maybe too short for the estimation due to the loss of degrees of freedom.

As shown in Table 2, the data for $CO_2$ emissions, energy use, and real GDP are obtained from the World Bank via the World Development Indicators database. Financial development index is computed by Svirydzenka (2016), directly accessed from the International Monetary Fund (IMF) database. Furthermore, the trade policy uncertainty index is computed by Baker et al. (2016) and collected directly from the Economic Policy Uncertainty (EPU) database via policyuncertainty.com. Data on renewable energy innovations have been obtained from the International Energy Agency via the online data services section while the ecological footprint was obtained from footprintnetwork.org.

Table 2: Descriptive Statistics

| Variables | Measurement Unit | Code | Source | Observation | Mean | Max. | Min. | Std. Dev. |
|---|---|---|---|---|---|---|---|---|
| CO2 Emissions | Metric tons per capita | $lnC_t$ | World Development Indicator | 120 | 2.9369 | 3.0064 | 2.7857 | 0.0627 |
| Ecological footprint | Global hectares per person | $lnEF_t$ | Footprintnetwork.org | 120 | 2.2675 | 2.3483 | 2.1048 | 0.0698 |
| Energy Consumption | Kilo tonnes (kt) of oil equivalent per capita | $lnE_t$ | World Development Indicator | 120 | 9.4433 | 9.5309 | 9.2445 | 0.0783 |
| Renewable energy innovations. | Research design and development expenditure in renewable energy technologies (constant 2019 US$ and exchange rates) | $lnRI_t$ | Iea data services (wds.iea.org) | 120 | 6.0534 | 7.9268 | 5.1616 | 0.6937 |
| Economic expansion | GDP per capita (constant 2010 US$) | $ln\,Y_t$ | World Development Indicator | 120 | 9.1511 | 9.7834 | 8.3516 | 0.4242 |
| Trade Policy Uncertainty | Index | $lnT_t$ | Economic Policy Uncertainty (EPU) Database. | 120 | 4.7541 | 6.9977 | 3.2281 | 0.73 |
| Financial Development | Index | $lnF_t$ | International Monetary Fund (IMF) database | 120 | -0.282 | -0.123 | -0.725 | 0.1749 |

### *3.2 Model Specification via ARDL Bounds Testing Approach*

The conventional model for estimating EKC as provided by Stern (2007); Shahbaz *et al.,* (2013a,b,); Shahbaz et al., (2015); Apergis and Ozturk, (2015); Mesagan et al., (2018), Alola, (2019a); Rafindadi and Usman (2019); Usman et al., (2019; 2020c) is given as:[4]

$$ED_t = \rho_o + \alpha_Y Y_t + \alpha_{Y^2} Y_t^2 + \boldsymbol{X_t} + \mu_t \quad (1)$$

Where $\rho_0$ is the intercept, *ED* which denotes environmental degradation can either be carbon emissions or ecological footprint. $Y$is income while its squared term ($Y_t^2$) is augmented primarily to determine the shape of the EKC, $\boldsymbol{X_t}$ is a vector of macroeconomic variables whose variations can affect environmental degradation. $t$ stands for the time period and $\mu_t$ is the residual term, which is assumed to follow a zero mean white noise process with variance $\sigma^2$, $\varepsilon_t \sim iid(0, \sigma^2)$. Given the US dynamic trade policy, with trade activities with other North American countries and China as well as other trading partners in the world, we employ the trade policy uncertainty index to ascertain how uncertainty in trade-oriented US policies could affect environmental quality. The transmission mechanism of this effect is predicated on the fact that trade-oriented policies would affect multiple variables within the US macro-economy such as domestic manufacturing, trade flows as well as bilateral FDI flows. This comes with varying implications for environmental quality. In this study, we incorporate energy use, trade policy uncertainty, renewable energy innovations and a broad-based financial development index into the standard EKC equation and obtain the long-run and short-run parameters through a dynamic unrestricted error correction model (UECM), resulting from the Autoregressive Distributed Lag (ARDL) approach proposed by Pesaran *et al.* (2001) More so, to eliminate heteroscedasticity problem and interpret results based on elasticities, we take the natural

[4] In this study, we incorporate the squared term of financial development to determine the tolerable threshold level for financial development in the USA.

logarithm of variables. To this end, we obtain the long-run coefficients based on the following conditional error correction model:

$$\Delta lnED_t = \Psi_0 + \rho_1 \, ln\, ED_{t-1} + \rho_2 \, ln\, Y_{t-1} + \rho_3 \, ln\, Y_{t-1}^2$$

$$+ \rho_4 \, lnE_{t-1} + \rho_5 \, T_{t-1} + \rho_6 \, F_{t-1} + \rho_7 \, RI_{t-1} + \sum_{k=1}^{p} \theta_{ED,k} \, \Delta lnED_{t-k}$$

$$+ \sum_{k=0}^{q} \theta_{Y,k} \Delta \, lnY_{t-k} + \sum_{k=0}^{r} \theta_{Y^2,k} \Delta \, lnY_{t-k}^2 + \sum_{k=0}^{s} \theta_{E,k} \Delta \, E_{t-k} + \sum_{k=0}^{u} \theta_{T,k} \Delta \, T_{t-k}$$

$$+ \sum_{k=0}^{v} \theta_{F,k} \Delta \, F_{t-k} + \varepsilon_t \; + \sum_{k=0}^{w} \theta_{RI,k} \Delta \, RI_{t-k} + \varepsilon_t \qquad (2)$$

Where $Y$and its squared term remain as previously defined. $E$ represents the amount of energy consumed; $T$ represents the trade policy uncertainty index, $F$ is a broad-based financial development index while $RI$ denotes renewable energy innovations. $ln$ is the natural logarithm of the variables. $\Delta$ is a differenced operator, which connotes generically $\Delta z_t = z_t - z_{t-1}$. The long-run coefficients are obtained from the first part of Eq. (2), $i = 2{,}3{,}4{,}5{,}6{,}7$. If variables of $lnED,\ lnY, lnY^2, lnE, T,\ F\ and\ RI$ are cointegrated, their short-run deviations would be adjusted so as to maintain an equilibrium level association with long-run coefficients as can be expressed through the error correction model. The error-correction term (ECT) can also be obtained as $ect_{t-1} = lnED_t - ln\, Y_t - ln\, Y_t^2 - ln\, E_t - T_t - F_t - RI_t$. The coefficients $\sigma_2, \sigma_3, \sigma_4, \sigma_5, \sigma_6$ and $\sigma_7$ are the long-run effects on environmental degradation. However, to capture the adjustment speed, which is the lagged error correction term, representing the linear combination of lagged level variables, we reparametrize Eq. (3) to obtain the following equation:

$$\Delta lnED_t = \omega_0 + \sum_{k=1}^{p} \beta_k \, \Delta lnED_{t-k} + \sum_{k=0}^{q} \beta_{Y,K} \, \Delta lnY_{t-k} + \sum_{k=0}^{r} \beta_{Y^2,K} \, \Delta lnY_{t-k}^2$$

$$+ \sum_{k=0}^{s} \beta_{E,K} \, \Delta lnE_{t-k} + + \sum_{k=0}^{u} \beta_{T,K} \, \Delta lnT_{t-k}$$

$$+ \sum_{k=0}^{v} \beta_{F,K} \, \Delta lnF_{t-k} \sum_{k=0}^{w} \beta_{RI,K} \, \Delta lnRI_{t-k} + \lambda(ect_{t-1}) + \epsilon_t \quad (3)$$

where the speed of adjustment is captured by $\lambda$. The short-run coefficients are given by $\beta_k$, $\beta_{Y,k}$, $\beta_{Y^2,k}$, $\beta_{E,k}$, $\beta_{T,k}$ , $\beta_{F,k}$ and $\beta_{RI,k}$. To establish cointegration between the variables, Pesaran et al. (2001) proposed the standard F-test for the joint significance of the lagged level variables from Eq. (3) which is : $H_0\colon \rho_1 = \rho_2 = \rho_3 = \rho_4 = \rho_5 = \rho_6 = \rho_7$ , against the alternative denoted by: $H_A\colon \rho_1 \neq \rho_2 \neq \rho_3 \neq \rho_4 \neq \rho_5 \neq \rho_6 \neq \rho_7$ . The method can also be used to estimate both long-run and associated short-run coefficients. Finally, it performs very well irrespective of the size of the sample.

### *3.3 Lee-Strazicich nonstationarity test*

In order to circumvent the empirical-based problem pertaining to the conventional unit root tests of Augmented Dickey-Fuller (ADF) , Phillips-Perron (PP), Ng-Perron, Kwiatkowski-Phillips-Schmidt-Shin (KPSS) , and the generalized least squares Dickey-Fuller (DF-GLS), we employ a richer minimum LM unit root test with one break by Lee and Strazicich (2003) to check the stationarity properties of the series. The preference of this test against the one proposed by Zivot and Andrews (1992) is based on the fact that it reduces the issue of inaccuracy of the breakpoint when we have a break under the null and alternative hypotheses. To perform this test, we apply only a model referred to as 'crash', which has capacity for a time change in intercept in the alternative hypothesis. The optimal number of lags $k$ is determined from the general to the specific approach as described by Perron (1989), i.e. by beginning the test with the maximum number of lagged first-differenced terms, $k = 8$ and continue to reduce the lagged terms till they all become significant. The null hypothesis for the test is $H_0: \Psi = 0$ which implies that there is a unit root in the presence of a single structural break while the alternative hypothesis, $H_1: \Psi < 0$ implies that there is no unit-root when a single structural break is found.

### *3.4 Causality Test*

For designing appropriate energy and environmental policy frameworks with the aim of mitigating $CO_2$ emissions and aiding sustainable growth, we apply a causality test proposed by Toda and Yamamoto (1995). This is necessary since a cointegrating relationship has been established, it means that causality in at least one direction must be found amongst the series. Within the framework of the Toda-Yamamoto causality test, a causal relationship can be performed irrespective of whether the order of integration of the variables is indeed I(0) or I(1) or mutually cointegrated. Therefore, the test is more advantageous and superior to standard Granger causality tests as well as the VECM causality test which are both limited to I(0) and cointegrated I(1) variables respectively. In performing the test, we estimate a vector autoregressive (VAR) $(k + d_{max})$, with $k$ as an optimal VAR order and $d_{max}$ as the maximum integrating order in the VAR system. A Modified Wald statistic (MWALD) is used to test whether causality holds or not. The T-Y causality test can be modelled as:

$$\begin{bmatrix} \ln ED_t \\ \ln Y_t \\ \ln Y_t^2 \\ \ln E_t \\ \ln T_t \\ \ln F_t \\ \ln RI_t \end{bmatrix} = \begin{bmatrix} \alpha \\ \beta \\ \omega \\ \gamma \\ \varphi \\ \psi \\ \vartheta \end{bmatrix} + \sum_{i-1}^{p} \begin{bmatrix} \rho_{11i}\rho_{12i}\rho_{13i}\rho_{14i}\rho_{15i}\rho_{16i}\rho_{17i} \\ \rho_{21i}\rho_{22i}\rho_{23i}\rho_{24i}\rho_{25i}\rho_{26i}\rho_{27i} \\ \rho_{31i}\rho_{32i}\rho_{33i}\rho_{34i}\rho_{35i}\rho_{36i}\rho_{37i} \\ \rho_{41i}\rho_{42i}\rho_{43i}\rho_{44i}\rho_{45i}\rho_{46i}\rho_{47i} \\ \rho_{51i}\rho_{52i}\rho_{53i}\rho_{54i}\rho_{55i}\rho_{56i}\rho_{57i} \\ \rho_{61i}\rho_{62i}\rho_{63i}\rho_{64i}\rho_{65i}\rho_{66i}\rho_{67i} \\ \rho_{71i}\rho_{72i}\rho_{73i}\rho_{74i}\rho_{75i}\rho_{76i}\rho_{77i} \end{bmatrix} \times \begin{bmatrix} \ln ED_{t-i} \\ \ln Y_{t-i} \\ \ln Y_{t-i}^2 \\ \ln E_{t-i} \\ \ln T_{t-i} \\ \ln F_{t-i} \\ \ln RI_{t-i} \end{bmatrix}$$

$$+\sum_{j=p+1}^{d_{\max}}\begin{bmatrix}\rho_{11j}\rho_{12j}\rho_{13j}\rho_{14j}\rho_{15j}\rho_{16j}\rho_{17j}\\ \rho_{21j}\rho_{22j}\rho_{23j}\rho_{24j}\rho_{25j}\rho_{26j}\rho_{27j}\\ \rho_{31j}\rho_{32j}\rho_{33j}\rho_{34j}\rho_{35j}\rho_{36j}\rho_{37j}\\ \rho_{41j}\rho_{42j}\rho_{43j}\rho_{44j}\rho_{45j}\rho_{46j}\rho_{47j}\\ \rho_{51j}\rho_{52j}\rho_{53j}\rho_{54j}\rho_{55j}\rho_{56j}\rho_{57j}\\ \rho_{61i}\rho_{62i}\rho_{63i}\rho_{64i}\rho_{65i}\rho_{66i}\rho_{67i}\\ \rho_{71j}\rho_{72j}\rho_{73j}\rho_{74j}\rho_{75j}\rho_{76j}\rho_{77j}\end{bmatrix}\times\begin{bmatrix}\ln\mathrm{ED}_{t-j}\\ \ln\mathrm{Y}_{t-j}\\ \ln\mathrm{Y}^2_{t-j}\\ \ln\mathrm{E}_{t-j}\\ \ln\mathrm{T}_{t-j}\\ \ln\mathrm{F}_{t-j}\\ \ln\mathrm{RI}_{t-j}\end{bmatrix}+\begin{bmatrix}u_{1t}\\ u_{2t}\\ u_{3t}\\ u_{4t}\\ u_{5t}\\ u_{6t}\\ u_{7t}\end{bmatrix} \quad (4)$$

Here, the unidirectional causal relationship that flows from $F_t$ to $lnED_t$ means that $\rho_{17i} \neq 0\forall_i$. In the same way, a unidirectional causal relationship that flows from $lnED_t$ to $F_t$ entails that $\rho_{17j} \neq 0\forall_j$.

## 4. Empirical Results

### *4.1 Time plots and descriptive statistics of time series*

We begin our analysis by assessing the visual properties of the variables employ in this study. This is necessitated by the fact that seasonality, drift, trend and structural breaks could possibly exist in the data to distort the estimation results. As can be seen in Figure 1, the time plots of the variables exhibit fluctuations in all the variables. For CO2 emissions, we find that the time plot suggests the fluctuations before 2007 are relatively low. However, there is evidence of structural break in 2008 following the global financial crisis. The ecological footprint follows similar dynamics with CO2 emissions following the 2008/2009 global financial crises with a structural break which begins from 2008 and ends in 2009. Renewable energy innovations on the other hand follows opposite dynamics compared to the two environmental proxies as a steep upward incline is observed between 2008 to 2009. For GDP, the time plots are characterized by upward trends with little fluctuations particularly in 2009 due to the global financial crisis. The plots of energy use and financial development index slope upward up to the year 2000, after which the plots begin to exhibit constant mean with more fluctuations observed in energy use than financial development index. The time plot of trade policy uncertainty is as expected characterized by high level of fluctuations. This is more conspicuous after the global financial crisis due to the trade policy shifts towards recovering from the global financial shocks. Regarding the descriptive statistics, we find that the largest mean for trade policy and smallest mean for financial development. Interestingly, apart from trade policy, the standard deviations of all the series are low, suggesting that the series have low volatilities.

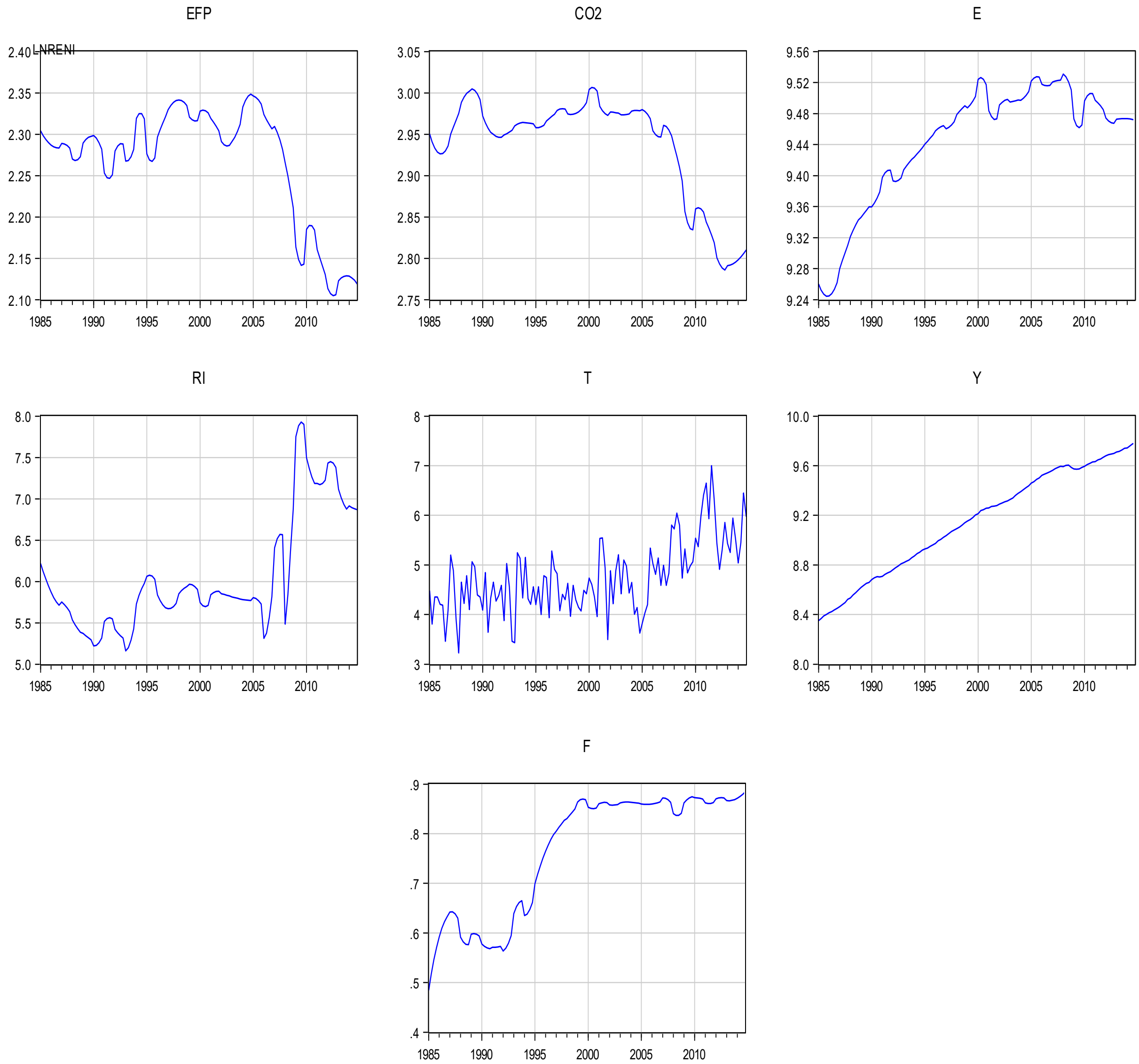


**Figure 1:** Time series plots of the log of CO2 emissions, log of energy use, log of GDP, financial development, and trade policy uncertainty.

*4.2 Nonstationarity test results*

Concerning the results of the minimum LM unit root tests by Lee and Strazicich (2003) (See Table 3), we observe that $CO_2$ emissions, ecological footprint, energy use, economic expansion, financial development and renewable energy innovations are stationary only after their first differences while for the case of trade policy uncertainty, we find evidence that it is stationary at levels. This means that the series employed have mixed integration orders. Furthermore, the results show that the structural break point for $CO_2$ emission is 2009:Q4, GDP and its square are 2008:Q3 and 2008:Q4 respectively. Breakpoints for renewable energy innovations and the ecological footprint were also captured at 2009:Q4 and 2008:Q4 respectively. The results also identified 2009:Q4 for energy use, 1992:Q2 for trade policy and 1994:Q4 for financial development. The break points in 2008 and 2009 are attributed to the effect of global financial crisis that began in the late 2007 while the breaks in trade policy and financial development in 1990s are attributed to the trade policy directive in the USA. The target was to reach multilateral trade agreement with trading partners through general agreement such as Central American Free Trade Agreement (CAFTA), North America Free Trade Agreement (NAFTA) and bilateral agreements with other countries.

Table 3: Results of Lee-Strazicich (LS) Unit Root Test

| | **L-S Test at Level** | | **L-S Test at First Difference** | | **Critical Values (CV)** | | |
|---|---|---|---|---|---|---|---|
| **Variables** | **LM Statistic** | **Break Point** | **LM Statistic** | **Break Point** | **1%** | **5%** | **10%** |
| $lnCO_{2t}$ | -1.615 (4) | 2009Q4 | -3.618$^{**}$ (1) | 2000Q3 | -3.994 | -3.394 | -3.084 |
| $lnEFP_t$ | -1.622 (5) | 2008Q4 | -3.622$^{**}$ (8) | 2004Q3 | -3.994 | -3.394 | -3.084 |
| $ln\,Y_t$ | -1.614 (4) | 2008Q3 | -3.853$^{**}$ (1) | 2010Q3 | -3.994 | -3.394 | -3.084 |
| $ln\,Y_t^2$ | -1.952 (3) | 2008Q4 | -3.893$^{**}$ (1) | 2010Q3 | -3.994 | -3.394 | -3.084 |
| $lnE_t$ | -1.996 (5) | 2009Q4 | -3.395$^{**}$ (8) | 2001Q3 | -3.994 | -3.394 | -3.084 |
| $lnT_t$ | -6.080$^{***}$ (1) | 1992Q2 | -5.921$^{***}$ (0) | 1998Q3 | -3.994 | -3.394 | -3.084 |
| $lnF_t$ | -1.839 (6) | 1994Q4 | -4.007$^{***}$ (1) | 1991Q4 | -3.994 | -3.394 | -3.084 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $\ln RI_t$ | -2.521(8) | 2009Q4 | -6.551*** (4) | 2008Q2 | -3.994 | -3.394 | -3.084 |

Notes: ***, and ** denote 1% and 5% significance levels

Table 4: Results of Cointegration using ARDL Bounds Testing Approach

| **Dependent variables** | $\ln CO_{2t}$ | | $\ln EFP_t$ | |
|---|---|---|---|---|
| | **Model 1** | **Model 2** | **Model 1** | **Model 2** |
| F-Statistics | 4.665** | 3.748** | 3.942** | 9.206*** |
| t-statistics | -5.004** | -4.931** | -4.538** | -5.934*** |
| **Lag order** | 3,3,0,1,3,4,0 | 3,3,0,0,1,1,0,4 | 6,0,5,0,4,1,2 | 3,0,1,1,4,4,2, 2 |
| | **1% critical values** (KS, 2020) | | | |
| Lower bounds F(t) | 3.272(-3.45) | 3.088(-3.45) | 3.29 (-3.46) | 3.473(-3.950) |
| Upper bounds F(t) | 4.787(-5.05) | 4.602(-5.24) | 4.76 (-5.07) | 5.030(-5.507) |
| | **5 % critical values** (KS, 2020) | | | |
| Lower bounds F(t) | 2.493(-2.83) | 2.37 (-2.83) | 2.51 (-2.84) | 2.711 (-3.324) |
| Upper bounds F(t) | 3.801(-4.35) | 3.68 (-4.53) | 3.79 (-4.38) | 4.050 (-4.785) |
| | **10 % critical values** (KS, 2020) | | | |
| Lower bounds F(t) | 2.138(-2.50) | 2.046 (-2.506) | 2.16 (-2.52) | 2.362 (-3.005) |
| Upper bounds F(t) | 3.34(-3.986) | 3.256(-4.156) | 3.34 (-4.02) | 3.595(-4.408) |

Notes: ''***'', ''**'' and ''*'' denotes statistical significance at the 1%, 5% and 10% levels respectively. The critical value is determined where $k = 5$ independent variables for model 1 and $k = 6$ for model 2. The $lnCO_2$ equation follows an unrestricted intercept with no trend for both models while the *lnEFP* equation follows an unrestricted intercept with an unrestricted trend. The maximum lag order is 6 while optimal lag order is selected by the Akaike Information Criterion (AIC). KS (2020) implies that the critical values and the approximate probability values of Kripfganz and Schneider (2020) are employed.

### *4.3 Cointegration test results*

In addition, by applying the ARDL bounds testing cointegration approach, we find evidence of cointegration (long-run relationship) between variables in both models of the two equations, as the estimated F-statistics as well as the t-statistics are greater than the modified critical values (See Table 4).

### *4.4 Long-run ARDL Estimates*

#### *4.4.1 $CO_2$ Equation*

After cointegration has been established between the variables, the long-run parameters are depicted in Table 5. In order to uncover possible non-linear dynamics in the financial development-environmental degradation nexus, we include the squared terms of the financial development variable in a second model (Model 2). This is because higher levels of financial development can have a crowding out effect for productive economic activities and hence have an ameliorating effect on environmental quality. Prior to estimation the model is augmented with the structural break dummy obtained from the Lee and Strazicich (2003) structural break stationarity test. This is done in order to improve its dynamic stability[5].

The outcomes establish that economic expansion in the US has a negative and statistically significant relationship with CO2 emissions during the study period while its quadratic term has no significant relationship with CO2 emissions. This, therefore, fails to validate the $CO_2$ based EKC hypothesis in the long run for the USA over the study period. This finding may be as a result of the data span which falls within the 1985 to 2014 study period. In 1985 the US had already established the environmental protection agency fifteen years prior and thus the enforcement of environmental regulations was already in full gear. However, the results may be quite different if $CO_2$ emissions were to be measured in its extensive form, without normalizing on population. The outcomes of the long run further establish that energy use has a positive, unitary elastic and statistically significant relationship with $CO_2$ emissions in both $CO_2$ models. The effect of trade policy uncertainty on $CO_2$ emissions is negative, inelastic and

[5] A version of this model without the break dummy has been shown—through the CUSUM and CUSUM squared plots to be dynamically unstable. This is however not the case for the ecological footprint model.

statistically significant. This suggests that trade policy uncertainty has a diminishing effect on $CO_2$ emissions. In addition, we can infer that the broad-based financial development index employed is positively and monotonically related to $CO_2$ emissions in such a way that a 1% increase in financial development results to a 0.22% rise in $CO_2$ emissions in Model 1 and a 0.65% rise in $CO_2$ emissions in Model 2. The fact that the quadratic term for financial development in Model 2 is insignificant rejects the non-monotonic financial development-pollutant emissions assumption which was empirically validated by Shahbaz et al. (2018). This result is therefore inconsistent with Shahbaz et al. (2018) in their study for France. Reasons for this may be due to different study locations and different proxies for financial development. Renewable energy innovation is observed to diminish the proliferation of $CO_2$ emissions, an effect which is statistically significant in both models albeit with a small economic significance. A 1% increase in renewable energy innovations corresponds to a 0.029% decrease in $CO_2$ emissions in Model 1 and a 0.035% decrease in Model 2.

The short run analysis as shown in Table 5 reveals that the $ECM_{t-1}$, which represents the speed of adjustment of short-run deviations towards the long-run equilibrium path, has a negative and statistically significant sign for both Models 1 and 2. The interpretation of this result is that the deviations in the short run are corrected by 7.85% every quarter in Model 1 and 7.95% in Model 2 through the dynamic effects of economic expansion, energy use, trade policy, renewable energy innovations and financial development.

*4.4.2 Ecological Footprint Equation*

The EF equation is observed to be vastly different from the $CO_2$ equation. A fundamental difference lies in the energy consumption-ecological footprint relationship in which a negative and statistically significant relationship is uncovered. Though this result may seem counterintuitive, it is however consistent with Ozturk et al. (2016) wherein a negative relationship between energy consumption and the ecological footprint of higher income countries was uncovered. This may arise from the fact that within the study period the US was a net energy importing country and thus domestic energy consumption may induce ecological deterioration in external energy source countries while mitigating ecological deterioration in the United States. Another very interesting finding pertains to the financial development-ecological footprint nexus wherein a statistically insignificant relationship is uncovered between lower levels of financial development and the ecological footprint whilst a negative and statistically significant relationship between higher levels of financial development and ecological footprint is inferred from Model 2. Model 1 also shows that mean values of financial development has no statistical relationship with the ecological footprint. This supports the proposition that higher levels of financial intermediation may crowd out ecologically degrading high-risk real investment undertakings which is consistent with Shahbaz et al. (2018). Similar to the $CO_2$ equation, trade policy uncertainty has a negative and statistically significant relationship with both models of the EF equation with coefficient signs and sizes almost identical with those obtained for Model 1 of the $CO_2$ equation. An ecological footprint based EKC effect is also uncovered for Model 1 and 2 of the EF equation with a higher statistical evidence in Model 1.

Table 5: Long-run ARDL Coefficients with squared term of financial development

| **Independent variables** | **$\Delta lnCO_{2t}$** | | **$\Delta lnEF_t$** | |
|---|---|---|---|---|
| | **Model 1** | **Model 2** | **Model 1** | **Model 2** |
| $lnE_t$ | 0.9742** | 1.079** | -0.791** | -0.813*** |
| $lnF_t$ | 0.2204*** | 0.653** | 0.0871 | -0.183 |
| $lnF_t^2$ | __ | 0.552 | __ | -0.4589** |
| $lnRI_t$ | -0.0285** | -0.0347*** | -0.0118 | 0.0029 |
| $lnT_t$ | -0.0387*** | -0.0182* | -0.035*** | -0.0372*** |
| $lnY_t$ | -0.2503*** | -0.304*** | 4.8718** | 4.0181*** |
| $lnY_t^2$ | 0.1563 | 0.165 | -0.2151* | -0.1658*** |
| Constant | 0.8243 | 0.7219 | -2.922*** | -4.235*** |
| trend | __ | __ | -0.003** | -0.004*** |
| D 2009q4 | 0.00031 | 0.00024 | | |
| $ecm_{t-1}$ | -0.0785*** | -0.0798*** | -0.222*** | -0.352*** |

| Diagnostic Tests | Value (*p*-value) | Value (*p*-value) | Value (*p*-value) | Value (*p*-value) |
|---|---|---|---|---|
| ARCH Test for Heteroscedasticity [3] | 1.53<br>$\chi^2$(0.676) | 1.33<br>$\chi^2$(0.73) | 3.86<br>$\chi^2$(0.125) | 4.5<br>$\chi^2$(0.467) |
| Breusch-Godfrey Serial LM Test [3] | 1.84<br>$\chi^2$(0.604) | 0.54<br>$\chi^2$(0.76) | 1.79<br>$\chi^2$(0.568) | 1.6<br>$\chi^2$(0.124) |
| Ramsey RESET Test [F,1] | 0.063<br>F (0.80) | 0.57<br>F (0.69) | 0.34<br>F (0.4) | 0.64<br>F (0.49) |
| CUSUM | Stable | Stable | Stable | Stable |
| CUSUM SQ. | Stable | Stable | Stable | Stable |

**Note**: $^{***}$, $^{**}$ and $^{*}$ denote significance at 1%, 5%, and 10% significance level, respectively. The maximum lag order selected is 6 based on Akaike Information Criterion [AIC].

The results of the diagnostic tests reveal that the error term of the estimated models are normally distributed with no case of serial correlation and conditional heteroskedasticity. We further observe that the results of the functional form of the model via the Ramsey reset test supports the current specification of the model while tests for the stability of parameters through the cumulative sum (i.e. CUSUM) and the cumulative sum of squares (i.e. CUSUMsq) suggest that the parameters are fairly stable throughout the study period as shown in Figures 2 to 5.

Table 6: Results of Toda-Yamamoto Causality Test

| *Equation 1* ($lnED_t = lnCO_{2t}$) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Endogenous | ← Causal flow (exogenous variables) | | | | | | | |
| Variables | $lnED_t$ | $lnE_t$ | $lnF_t$ | $lnF_t^2$ | $lnRI_t$ | $lnT_t$ | $lnY_t$ | $lnY_t^2$ |
| $lnED_t$ | __ | 4.66 | 56.7$^{***}$ | 54.9$^{***}$ | 14.6$^{**}$ | 8.74 | 2.342 | 2.935 |
| $lnE_t$ | 4.140 | __ | 42.8$^{***}$ | 40.34$^{***}$ | 2.53 | 6.77 | 3.51 | 3.03 |
| $lnF_t$ | 1.56 | 4.69 | __ | 6.33 | 3.09 | 3.15 | 3.12 | 3.07 |
| $lnF_t^2$ | 4.27 | 6.84 | 5.51 | __ | 3.40 | 5.80 | 4.35 | 4.22 |
| $lnRI_t$ | 15.43$^{**}$ | 6.41 | 9.36 | 9.54 | __ | 6.30 | 5.23 | 5.88 |
| $lnT_t$ | 8.43 | 10.03 | 8.19 | 7.61 | 14.20 | __ | 6.21 | 5.48 |
| $ln\,Y_t$ | 6.18 | 7.55 | 8.13 | 9.03 | 16.19$^{**}$ | 8.21 | __ | 7.97 |
| $lnY_t^2$ | 6.35 | 7.67 | 8.27 | 9.09 | 17.41$^{**}$ | 8.16 | 8.10 | __ |
| *Equation 2*($lnED_t = lnEFP_t$) | | | | | | | | |
| $lnED_t$ | __ | 4.40 | 8.51 | 6.10 | 6.92 | 5.14 | 11.93 | 12.48$^{*}$ |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $lnE_t$ | 15.31** | __ | 64.89*** | 62.92*** | 5.72 | 5.21 | 13.96* | 12.81* |
| $lnF_t$ | 3.20 | 12.83* | __ | 9.917 | 6.27 | 3.15 | 6.50 | 6.31 |
| $lnF_t^2$ | 4.75 | 11.55 | 10.53 | __ | 5.72 | 6.08 | 10.07 | 9.69 |
| $lnRI_t$ | 3.83 | 3.92 | 8.09 | 6.60 | __ | 6.57 | 4.03 | 4.47 |
| $lnT_t$ | 3.05 | 7.72 | 4.70 | 4.47 | 8.28 | __ | 3.15 | 2.96 |
| $ln\,Y_t$ | 20.45*** | 31.96*** | 22.97*** | 22.84*** | 27.39*** | 11.31 | __ | 9.26 |
| $lnY_t^2$ | 21.02*** | 33.58*** | 23.97*** | 23.67*** | 29.28*** | 11.47 | 8.87 | __ |

Notes: ***, ** and * denote rejection of the null hypothesis at 1%, 5%, and 10% level of significance.
The maximum lag order is 6 while optimal lag order is selected by the Akaike Information Criterion (AIC).

*4.5 Toda-Yamamoto Granger causality results*

In order the ascertain causal interpretations, we apply the Granger causality test within the framework of Toda and Yamamoto (1995). This test helps to design policies regarding energy-environmental nexus that stimulate sustainable growth. The results as shown in Table 6 provide the existence of a uni-directional causal flow from financial development and its quadratic term to $CO_2$ emissions. We also observe a causal flow from renewable energy innovations to CO2 emissions with a feedback. An innovations led growth effect is also observed via a uni-directional causal flow from renewable energy innovations to economic growth and its quadratic term. Financial development and its squared term has also been observed to have a unidirectional causal effect on energy consumption. Therefore, our findings are consistent with Shahbaz, (2013a); Shahbaz and Leitão, (2013); Dogan and Turkekul (2016); Shahbaz et al. (2017, 2018); Rafindadi and Usman (2019); Usman et al. (2019); Usman et al. (2020a,b). Observations from Equation 2 shows causality flowing from ecological footprint to economic expansion and its quadratic term with a weak feedback from only higher levels of growth. A unidirectional causal flow from ecological footprint to economic expansion is consistent with Usman et al (2020d) for Brazil. Renewable energy innovations has no statistically significant relationship with the ecological footprint showing the fundamental differences between $CO_2$emissions and the ecological footprint. Renewable energy innovations however retains a significant causal effect on economic expansion and its squared term. Another peculiar yet intuitive finding is the fact that the ecological footprint is observed to be endogenous to energy consumption via a unidirectional causal flow from ecological footprint to energy consumption. Financial development and its quadratic term both have predictive content for economic expansion and its quadratic term. Also observed is the fact that energy consumption has a strong causal effect on economic expansion and its squared term with a statistically weak feedback from economic expansion and its squared term. This underlies the major differences between Equation 1 and 2. The fact that this effect is observed in Equation 2 and not in 1 may be because Equation 2 clearly shows energy consumption as the conduit through which the ecological footprint may impact economic expansion. This is further supported by the fact the neutrality hypothesis is observed in the first equation but a weak feedback (strong growth hypothesis) hypothesis is validated in the second equation. Financial development and its quadratic term also retains its unidirectional causal effect on energy consumption albeit with a weak feedback on only the non-quadratic term.

*4.6 Discussion of findings*

The long-run equilibrium results obtained via the ARDL model uncovers the fundamental differences between anthropogenic induced atmospheric pollution and ecological degradation. While renewable energy innovations may mitigate the proliferation of $CO_2$ emissions, it however has no effect on the ecological footprint. This is because renewable energy innovations can affect emissions through the creation and modification of products that can enhance renewable energy utilization and reduce the usage of $CO_2$ emitting fossil fuel-based products. Ecological degradation however may come about by investment projects that affect the earth's topography such as urbanization, deforestation and mining. So, in essence, while renewable energy innovations can enhance atmospheric quality via the creation and modification of products with zero emissions, it however cannot mitigate the modification of the Earth's topography which may only be attained via fiscal intervention.

We found the new broad-based financial development index to have a positive and significant relationship with $CO_2$ emissions and its squared term to have no effect on $CO_2$ emissions. Financial development however has an insignificant effect on the ecological footprint with its squared term having a negative and statistically significant relationship with the ecological footprint. The implication of this result being that financial intermediation may improve the scale of already existing emissions inducing projects but at higher levels may mitigate investment expansions that could modify the Earth's topography. This result supports the earlier postulations of Cecchetti and Kharroubi (2015, 2019) wherein financial development is seen to crowd out real economic activity via investors being less favourably disposed towards high-risk, high-returns projects. It also somewhat concurs with Shahbaz et al., (2018) who found the financial development EKC for France.  The result is also somewhat consistent with Swamy and Dharani (2020) who found that financial development increases economic growth while its square reduces economic growth. The negative effect of trade policy uncertainty entails that uncertainty in trade policy direction can affect trade-based investment decisions which are pollution inducing. The observation of the EKC effect for ecological footprint and not $CO_2$ emissions may be due to the differences in the perception of the harmful effects of atmospheric emissions and the modification of the earth's topography by stakeholders. The energy production/consumption patterns of the US have changed over the years due to the narrowing in the differences between energy production and energy consumption during the study period. As such, pollutant emissions have been perceived by one group to be an economic necessity and by the other more liberal group to be an environmental ticking time bomb. The combination of these two opposing perceptions could modify the energy consumption framework of the US in such a way that while one group favours the utilization of renewable energy fuel sources and technologies, the other more conservative group may favour the use of traditional fossil fuel-based fuel sources and technologies. The negative effect which GDP per-capita has on $CO_2$

emissions may imply that environmental regulations may be very deeply entrenched in the economic policy decision making process of the US within the study period. This may have come about due to the establishment of the Environmental Protection Agency in 1970. Also, the measurement of CO2 emissions in per-capita basis may have also contributed to this and may also indicate that energy intensity per person may have reduced over the years due to a proliferation of energy efficient technologies during the study period. The fact that an ecological footprint based EKC effect has been observed shows that both groups may be unanimous on the condemnation of the ecological degradation of the US by such activities like urbanization induced deforestation. Economic expansion induces ecological degradation up to a certain threshold after which policies are initiated by government and stakeholders to conserve the natural ecology and stem the tide of the modification of the Earth's topography. This result is consistent with Güngör et al. (2021) and Akadiri et al. (2021) while it is not supported by the recent study by Usman et al. (2021).

Causality results show that energy sources for energy consumption in the US are obtained via ecological degradation. Thus, energy consumption is the channel through which the ecological footprint may affect economic growth. A bi-directional causal flow between renewable energy innovations and $CO_2$ emissions can be traced to the fact that innovations in renewable energy technologies has been spurred by the massive atmospheric influx of anthropogenic $CO_2$ emissions and that the use of these innovations also have an effect on $CO_2$ emissions. This however could not be observed for the ecological footprint, which is a fundamentally different form of environmental degradation. Furthermore, while financial development has a unidirectional causal effect on energy consumption in both causality equations, it however only has a causal effect on economic expansion in the first causal equation meaning that atmospheric degradation and not ecological degradation is an important factor to consider in the financial development-growth nexus. Also to be considered, is the fact that only the quadratic term for economic expansion has a weak feedback effect on the ecological footprint. This underscores the fact that economic growth has to supersede a certain threshold before its ecological impact can be felt.

## 5. Conclusion and Policy Implications

United States, being the second largest carbon emitting country after China, suggests the need to revisit the environmental Kuznets curve (EKC) hypothesis of this country especially in the face of financial development upsurge, trade policy uncertainty and renewable energy innovations. To this end, the current study aims to reconsider not only the examination of carbon emission determinants from the perspectives if income (GDP), energy utilization, trade policy, and financial development but also the threshold level of financial development regarding its effects on $CO_2$ emissions and the ecological footprint.

The findings establish the EKC hypothesis only when ecological footprint is used in measuring environmental degradation. Financial development and energy use stimulate carbon emissions while trade policy uncertainty and renewable energy innovation impede it. The effect of renewable energy innovation is not significant when ecological footprint is proxied as environmental degradation. Furthermore, trade policy uncertainty reduces ecological footprint while a non-linear relationship is established between financial development and ecological footprint, suggesting that higher financial development may crowd out real economic activity in the long run. The results of the causality tests reveal a feedback effect between $CO_2$ emissions and renewable energy innovations, a unidirectional causal flow from financial development to $CO_2$ emissions, energy consumption and GDP. Also uncovered is a unidirectional causal flow from the ecological footprint to energy use and GDP and from energy consumption to GDP.

The findings of this study, therefore, have important policy implications for carbon capturing and carbon sequestration in the US. First, the impact of trade policy uncertainty on the environment shows that trade oriented environmental policies could also affect the environment via the same mechanism. Second, to achieve carbon capturing and sequestration, environmental, social, and ecological sustainability are the necessary conditions. By implementing a more aggressive economic approach, the country could be capable of shedding more sources of carbon emissions infrastructures by replacing same with renewable energy-based products for faster transitioning to a low-carbon technologies based green economy. Depending on the peculiarity of the state of the economy, policy trade-off between ensuring huge economic expansion and massive financial development is inevitable. Hence, the drive towards attaining a huge green economic expansion might as well be channelled through policies that are devoid of extensive financial instruments as this may have a deleterious impact on investments in renewable energy innovations. Third, while the current pathway of the country's trade policy could be further harnessed on all fronts, the energy policy of the United States needs a more determined and sustainable energy transition drive. Fourth, renewable energy innovations are economically and environmentally feasible going by the equilibrium and causal effects. To this extent, innovations in renewable energy should be encouraged particularly the renewable energy sources that the country has the cost-advantage. Thus, the stakeholders in government and in private sector should initiate grants and subsidies for research and design of renewable energy technologies to mitigate atmospheric pollution and stimulate green growth. Fifth, environmental regulations in the United States should be enforced to encourage the transition of industries to more sustainable renewable energy technologies. This would lead to an increase in demand and the improvement of the market for renewable energy technologies as well their development. It would also place the world's biggest economy on a more sustainable growth path. However, policymakers should be cautioned by such enforcement not to scarce the investors away from the US.

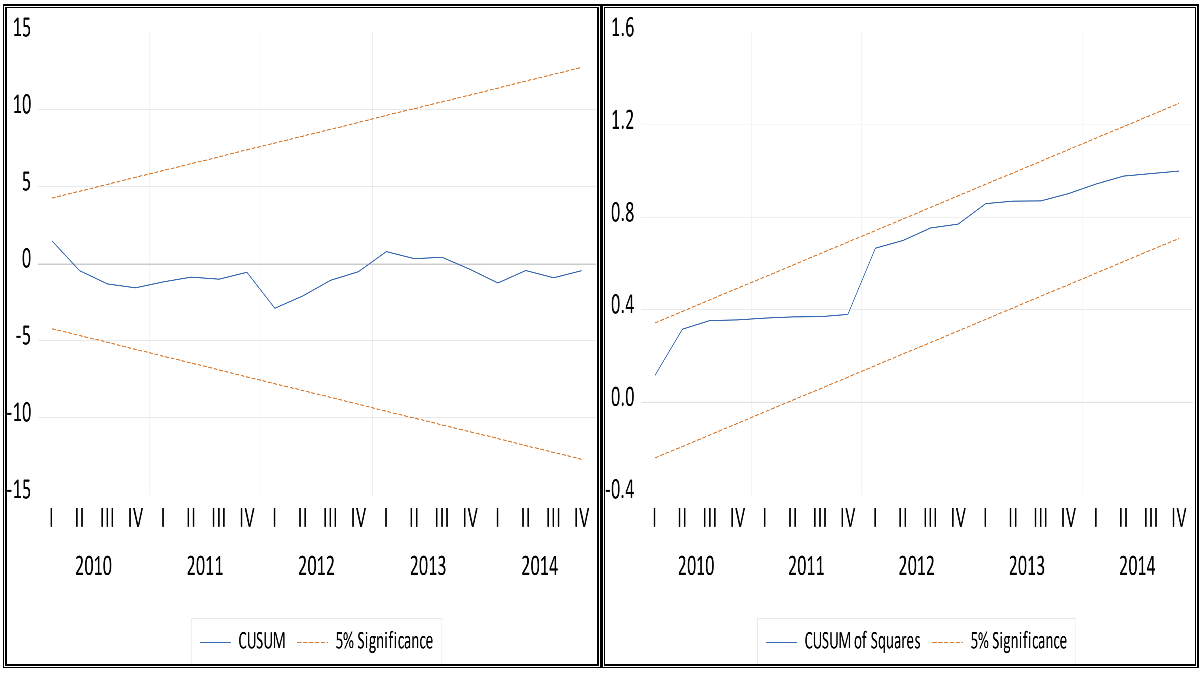


Figure 2: CUSUM and CUSUM of Squares for Model 1 of $CO_2$ equation

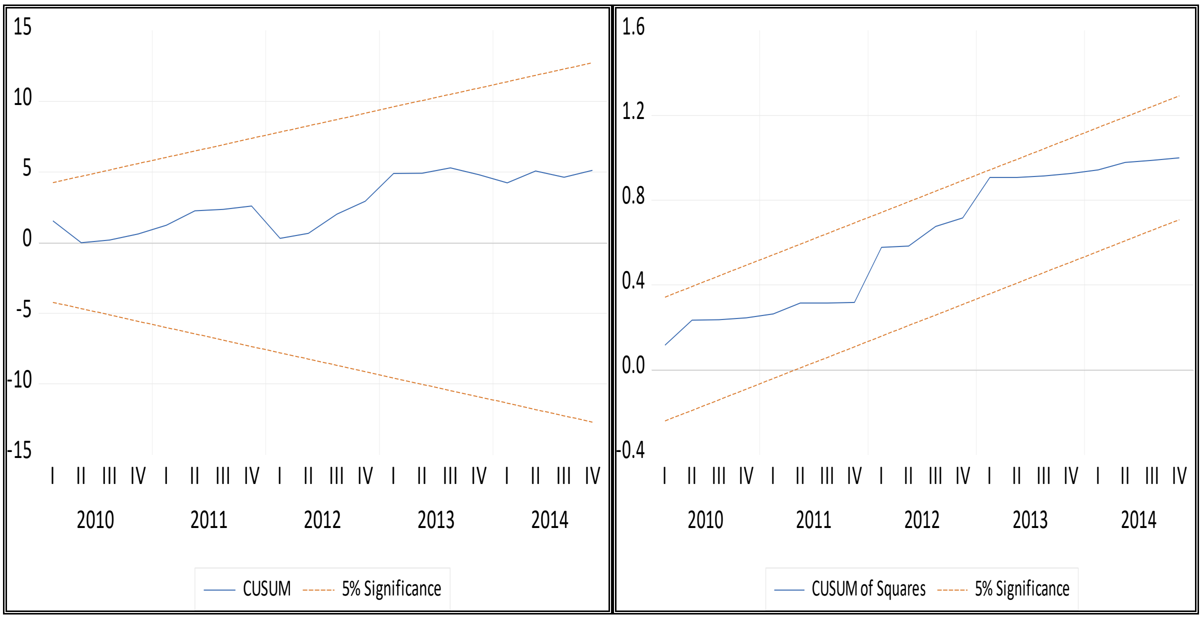


Figure 3: CUSUM and CUSUM of Squares for Model 2 of $CO_2$ equation

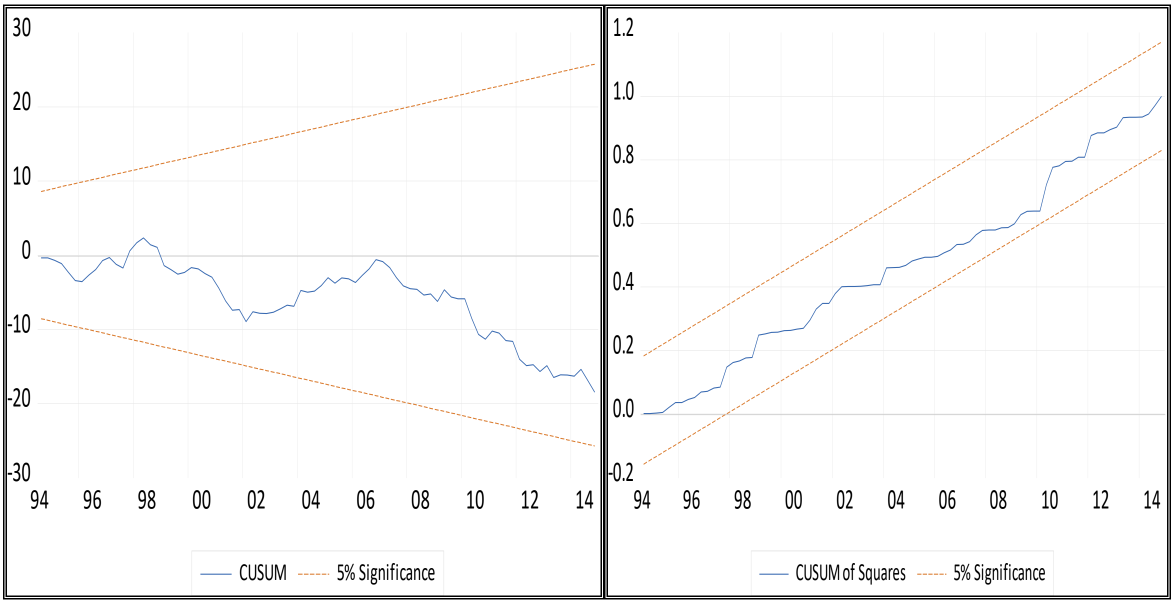


Figure 4: CUSUM and CUSUM of Squares for Model 1 of EF equation

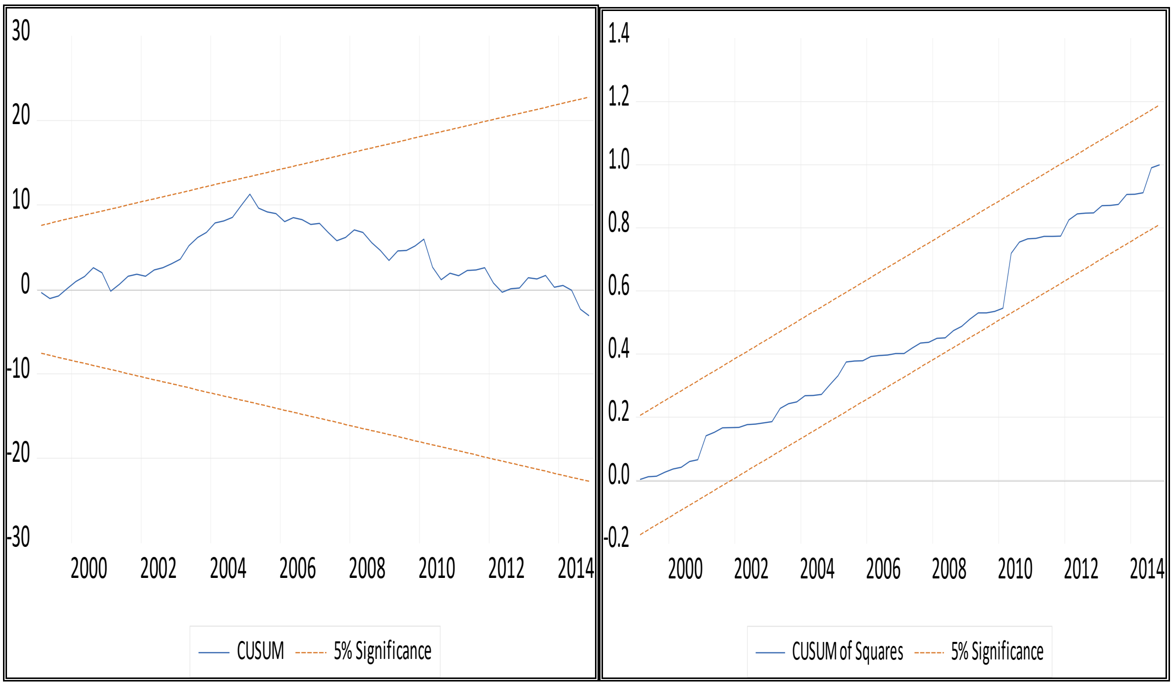


Figure 5: CUSUM and CUSUM of Squares for Model 2 of EF equation.

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APPENDIX A1


Financial development index pyramid

APPENDIX A2

LIST OF ABBREVIATIONS

| | |
|---|---|
| ARDL | Autoregressive Distributed Lag |
| CAFTA | Central American Free Trade Agreement |
| $CO_2$ | Carbon dioxide. |
| CUSUM | Cumulative Sum |
| CUSUMSQ | Cumulative Sum Squared |
| ECM | Error Correction Model |
| EKC | Environmental Kuznets Curve |
| GDP | Gross Domestic Product |
| GHG | Green House Gases |
| IMF | International Monetary Fund |
| MWALD | Modified Wald |
| NAFTA | North America Free Trade Agreement |
| OECD | Organisation for Economic Cooperation and Development |
| SDGs | Sustainable Development Goals |
| STIRPAT | Stochastic estimation of Impact by Regression on Population, Affluence and Technology. |
| UECM | Unrestricted Error Correction Model |
| UN | United nations |

| | |
|---|---|
| UNFCCC | United Nations Framework Convention on Climate Change |
| USA | United States of America |
| US-EPA | United States Environmental Protection Agency |
| VAR | Vector Autoregression |
| VECM | Vector Error Correction Model |