Energy Consumption as a Leading Factor of CO_2 Emissions

Is the EKC still valid for the United States?

Ester Trutwin (980711-4286) & Muhammad Zohaib (950111-6470)

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Supervisor: Joakim Westerlund

Department of Economics

Lund University

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Abstract

The objective of this paper is to examine the long-run relationship between CO_2 *emissions, economic output (GDP), and energy consumption in the US during the period 1960-2015. Energy consumption is investigated in its aggregated and disaggregated form i.e. Fossil Fuel, Nuclear, and Renewable energy to elicit a more precise diagnosis of the emission-energy-GDP nexus. The paper contributes to existing literature by identifying the key drivers of* CO_2 *emissions for the US. To provide evidence that the included variables share a common trend the Johansen cointegration method and a Vector Error Correction Model (VECM) was applied. The long-run estimates obtained from the VECM indicate that an increase in energy consumption contributes positively towards* CO_2 *emissions, whereas an increase in GDP mitigates environmental degradation. Fossil fuel energy consumption is found to be the main culprit for proliferating* CO_2 *emissions. The results for both these cases reveal that the modified Environmental Kuznets Curve (EKC) hypothesis does not hold for the US. However, considering nuclear and renewable energy use, the empirical findings suggest that EKC is valid and the consumption of clean energy sources mitigates environmental degradation significantly. Additionally, we declare that the EKC is rather a long-run phenomena than short-run, as we do not find significant short-run Granger causality running from energy consumption and GDP to* CO_2 *emissions. Thus, the US government should frame policies that promote renewable energy use either by taxing fossil fuel or subsidizing alternative and renewable energy. The government is further advised to increase investment in clean technologies and enhance public awareness on energy consumption to curb the degrading environment.*

Keywords: *EKC,* CO_2 *emissions, GDP, aggregated and disaggregated energy consumption, Cointegration, VECM, Granger causality, US*

Contents

List of Abbreviations

ADF Augmented Dickey-Fuller test.

AIC Akaike Information Criteria.

ARDL Auto Regressive Distributed Lag.

CO_2 Carbon Dioxide.

ECT Error Correction Term.

EIA US Energy Information Administration.

EKC Environmental Kuznets Curve.

EN Total Energy Consumption.

EPA Environmental Protection Agency.

FF Total Fossil Fuels Consumption.

GDP Gross Domestic Product.

LM Lagrange Multiplier test.

NEN Nuclear Electric Power Consumption.

PP Phillips–Perron test.

REN Total Renewable Energy Consumption.

US United States.

VECM Vector Error Correction Model.

WDI World Development Indicator.

1. Introduction

Environmental degradation has been a major issue for more than a few decades, but more importantly climate change is the biggest challenge for the next couple of decades. Deteriorating environmental quality has garnered attention from researchers, ecologists, policymakers, and economists across the globe. There has been a rising trend in global carbon dioxide (CO_2) emissions since 1960. World's CO_2 emissions were recorded as 3.04 metric tons per capita in 1960 and went up to 4.37 metric tons per capita in about 10 years. Thereafter, a cyclical trend can be observed and in 2016 it was recorded as 4.56 metric tons per capita (World Bank, 2021b). Over the span of fifty years, an increase of 51.8% has been observed in world's CO_2 emissions. This has made climate change a burning issue in the global arena and calls for immediate attention to the cause. Keeping in view the severity of the issue, world leaders have joined hands by forming different committees and signing agreements to put forward a collaborative effort to tackle this problem. Such an agreement is the Paris Agreement 2015 whereby the signing countries reinforce the worldwide response to the threat of climate change by maintaining a global temperature such that it does not rise two degrees Celsius above "pre-industrial levels" (United Nations Climate Change, 2021).

The grave consequences of pollution, both in short-run and long-run, have been witnessed by our planet for the last couple of decades. Changing the dynamics of a stable ecosystem disrupts the natural process which sustains life (Watson et al., 2001). Greenhouse gases ultimately cause global warming which in turn raises the sea level (McMichael et al., 2006). This makes many high populated cities situated near coastal areas vulnerable. Global warming increases the chances of drought in areas already affected which makes it a life-threatening situation for the inhabitants (Dai, 2013). These are some of the issues that we collectively face and that affect all of us. Therefore, it is of great significance that the environment is considered as a key factor during policy-making for development. It is not only a question of morals, but it is a matter of human survival on the planet.

The hazardous impacts of rising greenhouse gases have been alarmingly felt in various forms. Emissions from manufacturing plants have a direct impact on human health, causing heat stress, skin diseases, inflammatory problems, and various forms of cancers (Matthews et al., 2017; Pope III & Dockery, 2006). Such diseases have a negative impact on labor productivity and hence the economy (Nasir & Rehman, 2011). Deterioration of the environment not only hurts human life, but also holds grave consequences for a country's economic health. Without a doubt, rapid industrialization is essential for countries to grow at the right pace. Thus, for most economies there is a trade-off between environmental protection and the level of economic growth a country aims for. The issue at hand calls for carefully crafted policies and actions that are only possible if the relationship between environment and economic growth is rightly examined i.e. the social cost of polluting the environment must be rightly allocated. This would allow the world economies to pursue the right direction that leads towards sustainable development and is socially more responsible towards the environment.

The relationship between environmental degradation and economic development was studied by Grossman and Krueger (1991). They concluded that there exist an inverse U-shaped relationship between them. As per the Environmental Kuznets Curve (EKC) hypothesis, the relationship between environmental degradation and economic growth is positive for initial levels of economic growth but becomes inverse as higher levels of economic growth are achieved. Hence, an economy experiencing growth during earlier stages of development faces environmental degradation, until it reaches the maximum point after which the impact becomes positive such that the environment quality starts to improve (Grossman & Krueger, 1991; Kuznets, 1955).

The validity of the EKC hypothesis for the United States (US) has been tested by various researchers making different conclusions. Studies like Aslan et al. (2018a), Congregado et al. (2016), and Dogan and Turkekul (2016) concluded that the EKC is valid for the US, whereas Azam and Khan (2016), Burnett et al. (2013), Sarkodie and Strezov (2018), and Soytas et al. (2007) did not find evidence in favor of the EKC hypothesis. One explanation for the conflicting results might be the existence of different patterns within the data. CO_2 emissions increased rapidly from 1961 onwards and peaked with 22.51 metric tons per capita in 1973. The increase is followed by a decline, denoting 18.59 metric tons per capita in 1982 after which it continued to rise moderately until 2001. Thereafter, it declined and achieved its lowest value of 15.50 metric tons per capita in 2016 (World Bank, 2021a). On the contrary, GDP per capita for the US was continually increasing during this period. However, the positive trend is interrupted by bits up and down (World Bank, 2021c). This pattern indicates that the EKC hypothesis might fit the US data over the specified time span. Hence, examining the data of the US on CO_2 emissions and GDP will give some valuable insights on the interaction between environmental degradation and economic output. The influence of the economic output on the environment is central as the objective of any economy is to enhance economic growth.

Existing literature and research reveal the significance of energy use in this analysis. Various scholarly works state that energy consumption, CO_2 emissions, and economic output are interrelated (Nasir & Rehman, 2011). A study conducted in the US regarding energy consumption, CO_2 emissions, and income concluded that energy consumption was the main cause for CO_2 emissions (Soytas et al., 2007). Besides, the study of Apergis and Payne (2009) reveals that energy consumption has a significant positive relationship with emissions in the long-run. In the short-run, their study shows a uni-directional causality from energy use and real output, respectively, to CO_2 emissions. This result is further supported by Pao and Tsai (2010). It is also of great importance to know the role of energy consumption in CO_2 emissions from a policy perspective. As suggested by Soytas et al. (2007), the variable that is most relevant for controlling emissions is energy consumption. Given that a causal relationship does not exist between economic output and energy consumption, targeting energy consumption rather than reducing economic output would ensure that economic growth, in the long-run, is not affected (Soytas et al., 2007). All this provides sufficient ground to include energy consumption as a variable in our analysis with the purpose to probe if it drives CO_2 emissions in the US.

This study breaks down energy use into its primary sources i.e. fossil fuel, nuclear, and renewable energy consumption. The purpose to do so is to identify the constituents of energy consumption that are the major contributors to CO_2 emissions. To the best of our knowledge it is the first time that such a combination of variables i.e. energy use as per its primary sources has been used in the EKC to get to the root cause of CO_2 emissions in the US. Country-specific research shows that the effects of renewable and non-renewable energy sources on CO_2 emissions vary in nature and magnitude. Bekun et al. (2019) and Sahoo and Sahoo (2020) found that non-renewable energy sources have a positive relation with CO_2 emissions. As suggested by many studies it is of high relevance to investigate the breakdown of energy use for policy recommendations (Pata, 2021; Soytas et al., 2007). Effective policies can be devised to target a more sustainable combination of energy use if the respective contribution of disaggregated source of energy is known (Zaidi et al., 2018). Thus, the inclusion of disaggregated sources of energy allows us to elicit a more precise diagnosis of the emission-energy-GDP nexus, adds great value to our analysis, and contributes to the related literature.

Over the past decade, there has been sustained research to explore key causes of CO_2 emissions across the globe. Most studies emphasized on economic growth, declaring it as the main cause for the deteriorating environment. Some took into account energy use stating it as the key driver for CO_2 emissions. However, only a few studies have considered both variables together under the EKC hypothesis. This study is a continuation of such attempts to probe the key drivers of CO_2 emissions in the US while having both economic output and energy consumption in one model.

The data used for this study contain annual observations for the US and spans from 1960 to 2015. The paper starts off with testing the validity of the EKC hypothesis for the US while incorporating energy use into the model in later stages. Johansen approach is adopted to test for the presence of a cointegrating relationship between the variables. A Vector Error Correction Model (VECM) is applied to look for short-run and long-run relationships, whereas Granger causality tests are employed to further validate the causal relationships between the variables. Furthermore, various robustness checks are conducted to validate our findings. This study aims to add value to existing literature on EKC hypothesis by bringing in energy use to the equation. Our research is unique since no similar study has been conducted before having CO_2 emissions, disaggregated energy use, and output in the model for the US. Most of the existing literature uses aggregated energy data which might not represent the explanatory power of various energy inputs on environmental degradation.

This study is organized as follows: Chapter 2 gives a brief review of existing literature, while Chapter 3 contains some background of the US economy. Further, Chapter 4 describes the data used in this study, while Chapter 5 delivers the methodology used. Empirical results are presented in Chapter 6, whereas Chapter 7 contains a discussion on the results. The study is concluded in Chapter 8.

2. Literature

Environmental degradation has become an alarming concern as CO_2 emissions have reached hazardous levels calling for immediate attention and appropriate action. Energy use, economic activity, and CO_2 emissions are said to be related. Hence, in this paper, their relationship in the context of the US is examined to gain better insight into the main drivers of CO_2 emissions. Since there has been increased emphasis and need for cleaner energy sources, we further disaggregate energy use to study the impact of constituents of energy on CO_2 emissions. This will not only help in effective policy-making, but allow us to discern sources of energy that notably contribute towards environmental degradation.

One of the key resources in literature relevant to the problem at hand is the EKC, representing the relationship between GDP and environment quality throughout the development stages of an economy. The EKC hypothesis states that in the development phase, the relationship between GDP and the environment is negative whereby the environment deteriorates as GDP grows. For higher levels of GDP the relationship becomes positive and the environment starts improving as from a certain income level onwards societies start to care about the environment. This inverted U-shaped relationship was introduced by Grossman and Krueger (1991). The model for EKC presented by Dinda (2005) suggested that capital allocation is in two parts, one for production and one for upgrading the environment. The first part pollutes the environment, while the second improves it (abatement). He concludes that at earlier stages, there is insufficient investment available for the improvement of the environment, but later enough investment becomes available for the improvement of environmental quality in an economy. This production and abatement cause the inverted U-shape of the EKC (Dinda, 2005).

There exists a vast literature about the EKC hypothesis and it has been tested on a variety of countries using various econometric techniques and producing different conclusions. Fosten et al. (2012) using the threshold cointegration method found an inverted U-shape and hence support the EKC hypothesis for the UK. A non-parametric estimation found that the EKC holds for Australia (Churchill et al., 2020). Moreover, a study conducted on 27 advanced economies revealed similar results for most of the advanced economies in the world (Al-Mulali & Ozturk, 2016).

Dogan and Turkekul (2016) found an inverted U-shape relationship for the US and provide evidence that there is strong causal relationship between emissions, real output, energy consumption, and urbanization both in short-run and long-run. Aslan et al. (2018b) examined the validity of EKC for the US using a rolling window estimation method. Their results showed that the US government succeeded to mitigate environmental degradation through adequate economic development. Congregado et al. (2016) concluded that the EKC will only hold for the US when structural breaks are allowed for. On the contrary, many studies conclude that the EKC does not hold for certain economies. Using a non-linear parametric model, He and Richard (2010) showed that CO_2 and GDP have a monotonically increasing relationship for Canada. A study conducted on various countries by Zaman and Abd-el Moemen (2017) found that for high-income countries such as the US, UK, and Australia, the EKC does not hold and form rather a flatter trend. This is because of the use of sophisticated anti-pollutant technologies by developed economies. Azam and Khan (2016), Burnett et al. (2013), and Soytas et al. (2007) found similar results.

These conflicting results show that there exist no consensus on the presence of the EKC in the literature which creates a space for further research on the subject matter. Several studies put much emphasis on energy consumption, considering it as the main cause of CO_2 emissions. Cheikh et al. (2021) found an inverted U-shaped pattern for the impact of energy use on CO_2 in the MENA region. The EKC assumption was supported in a way that the impact of energy on environmental deterioration depends on output. It was found that the growth in energy consumption was the most important factor impacting CO_2 emissions. Ahmad et al. (2018) established a positive and linear relationship between energy consumption and emissions for China. On a similar note, Zhang et al. (2019) observed a uni-directional causality from energy use to CO_2 emissions and economic growth for China concluding that energy consumption was mainly responsible for CO_2 emissions. Richmond and Kaufmann (2006) stated that the notion of output having a favorable impact on the environment does not hold. They recommended to use energy consumption as a measure to control CO_2 emissions. On the other hand, Obradović and Lojanica (2017) showed that CO_2 emissions were not impacted by energy consumption for Greece and Bulgaria. Further, they did not find evidence for short-run causality between energy use and economic output. Similar conclusions are made by Halicioglu (2009), Jalil and Mahmud (2009), and Lean and Smyth (2010). Likewise, Luzzati and Orsini (2009) explored the energy-EKC hypothesis for over a hundred countries. The results were not in favor of the hypothesis and a positive monotone relationship was found for the variables under consideration.

Only a few studies examine the EKC relationship for the US. Soytas et al. (2007) is one of them. They combine energy use, CO_2 emissions, and income in a single model. It was concluded that there is no causality between income and energy in the long-run. However, a long-run causality exists between CO_2 emissions and energy consumption. It was suggested that energy consumption must be targeted to reduce CO_2 emissions. Stern (2000) adopted a similar approach and explored how GDP, energy, labor, and capital stocks are interrelated. He discovered that a mutual causality exists between energy use and GDP, although the relationship between income, emissions, and CO_2 was not specifically tested. Though the findings of these studies vary to some extent, it can be inferred that energy consumption plays an important role in environmental degradation whether directly or indirectly. These varied results are often attributed to differences in data and methodology used in the undertaken research. However, a number of researchers consider the use of aggregated energy consumption data to be the main reason behind it. Soytas et al. (2007) suggested that using aggregated energy data does not allow us to gauge the impact of constituents of energy use on CO_2 emissions. This created a need to explore the EKC hypothesis with disaggregated energy data. Such a study was undertaken by Saboori and Sulaiman (2013b) where the relationship between CO_2 emissions, disaggregated energy consumption, and GDP was explored for Malaysia. Applying the Granger causality approach, the study found a bi-directional causality between CO_2 emissions, coal, gas, electricity, and oil consumption. The empirical findings suggested that coal, gas, and electricity had a positive impact on CO_2 emissions in the long-run, while oil had a negative impact owing to the reduced dependency on oil by Malaysia. Following the same path, Al-mulali (2011) identified a bi-directional causality between oil consumption, CO_2 emission, and GDP when tested through the Granger causality method.

Several other studies that included disaggregated energy use in their analysis provided similar results. Bölük and Mert (2014) used fossil fuel and renewable energy consumption to test the EKC hypothesis for EU countries. They found that renewable energy consumption contributes far less towards CO_2 emissions as compared to the fossil fuel energy consumption. Moreover, no evidence for EKC was found. Similar conclusions have been reached by Danish et al. (2017), Destek et al. (2018), and Jebli et al. (2016). A few studies are conduced on the US too. These include Menyah and Wolde-Rufael (2010) which states that nuclear energy consumption and CO_2 had a unidirectional negative causality. But, no causality was found when tested for renewable energy and CO_2 emissions. Pata (2021) tested the EKC hypothesis by incorporating energy consumption as renewable and non-renewable energy use for the US. He concluded that renewable energy consumption reduce environmental degradation, while non-renewable energy use increase CO_2 emissions. Dogan and Ozturk (2017) made similar conclusions while revealing that EKC hypothesis did not hold for the US. Contrarily, Isik et al. (2019) validated EKC hypothesis by investigating data on 14 states of the US. Despite this all states face a negative impact on the environment due to energy consumption from traditional sources. The conflicting results in the literature persuade us to conduct an in-depth analysis that will enable us to make a concluding remark on the emission-energy-GDP nexus.

3. Background

The US is recognized as one of the most important players in the world (Kose et al., 2017). Besides being the largest economy with a GDP of $21.4 trillion in 2019, the US is also the second-largest exporter in the world and is ranked 7th in terms of Economic complexity Index (OEC, 2017; World Bank, 2019; WTO, 2019). Such high level of economic output and complexity carries the risk of severe environmental problems. Apart from being the largest economy, the US is the second largest CO_2 emitter in the world (Boden et al., 2017). The US tops the energy consumption across the globe as it forms about one-fifth of the world energy demand, putting an increased pressure on the environment (Kose et al., 2017). Primary energy sources include fossil fuels (petroleum, coal, natural gas), nuclear, and renewable energy. Nuclear and renewables are referred as low-carbon energy sources, whereas fossil fuel is considered as a high-carbon energy source. The Environmental Protection Agency (EPA) of the US reports that fossil fuels and industrial processes contribute 78% to total greenhouse emissions which have increased about 90% since 1970 in the US (EPA, 2021).

The annual report of the EPA states the sources of carbon emissions by economic sector in the country. Total emissions amounted to 6,558 million metric tons of CO_2 in 2019 only. It reveals that the transportation sector emitted the largest amount (i.e. 29%) of greenhouse gases in the US. This is primarily due to the fact that the transportation sector makes use of petroleum-based fuel. 62% of the electricity is generated from fossil fuel which makes electricity production as the second most polluting sector in the country. Industry comes next in line which contributes 23% to the total annual carbon emission in the US (EPA, 2020). When it comes to energy consumption the industrial sector is reported to be the leading sector having the largest consumption of energy since the last few decades. According to the analysis of US Energy Information Administration the industrial sector consumed 32% of the total energy (EIA, 2020). The industrial sector is also reported to be the largest contributor to the country's GDP, contributing 68% in 2018 (BEA, 2020). These reports identify key sectors that needs to be targeted during policy- making for environmental protection.

Almost 60% of the American population views climate change as the major threat to the well-being of the US. Around two-thirds of American adults want the government to do more towards curbing environmental issues (Tyson & Kennedy, 2020). This increases the pressure on the US government to enhance efforts and implement more sustainable and energy efficient measures. Addressing the demand of the public, Biden's administration recently rejoined the Paris agreement to collectively come up with a roadmap to curb the drastic environmental degradation across the globe. Alongside, Government's $2 trillion infrastructure plan includes provisions to invest in clean energy and upgrade the existing fossil fuel energy infrastructure (Frazier, 2021). Moreover, the US government aims to reach zero carbon emission by 2050 by moving towards clean energy sources like wind, solar, and hydroelectricity (Diringer et al., 2019).

The US already has been enacting different environmental policies to increase renewable energy consumption. For instance, the government passed the Energy Policy Acts in 2005 and the Federal Energy Independence and Security in 2007, resulting in a massive increase of renewable energy use (Lean & Smyth, 2013). The renewable energy consumption of the US was recorded to increase by 67% from 1980 to 2016 (World Bank, 2021d). This shift is due to the efforts of the policymakers to move towards cleaner energy sources in recent years. More importantly, the US managed to reduce its carbon emission by 2% in 2016 (Olivier, Peters, et al., 2017). With such efforts being undertaken to curtail CO_2 emissions, it is of great significance that detailed insights are available for the policymakers so that the right policy variables can be targeted for achieving the desired results. Though several studies have been conducted to gauge the drivers of CO_2 emissions no conclusive evidence has been made available for the policymakers. Given the limited amount of literature on the US and the difference in the scope of each research, this study analyzes CO_2 emissions, energy consumption, and economic output in a single model to find conclusive answers to the problem. It further incorporates disaggregated energy data on fossil fuel, nuclear, and renewable energy in the analysis to dig deeper into the variables that cause CO_2 emissions. Such an in-depth analysis is of great relevance considering that the policymakers in the US are striving to reduce its environmental footprint.

4. Data

The annual data set used for this study covers the period 1960 to 2015 for the US. This time span has been dictated by availability of the data for the series. Per capita Carbon Dioxide emissions (CO_{2_t}) (measured in metric tons), the per capita real Gross Domestic Product (GDP_t) (measured in constant 2010 US dollars), and per capita Total Energy Consumption (EN_t) (measured in kg of oil equivalent) are collected from the World Development Indicators (WDI) compiled by the World Bank (2021d). Disaggregated level data for the energy consumption and the total population were collected from the US Energy Information Administration (EIA, 2021a). Per capita Total Fossil Fuels Consumption (FF_t), per capita Nuclear Electric Power Consumption (NEN_t), and per capita Total Renewable Energy Consumption (REN_t) are measured in quadrillion British thermal unit (Btu).[1]

All series are converted into their natural logarithmic forms for the usual statistical reasons. The empirical investigation starts by summarizing the descriptive statistics, as presented in Table 4.1 that consists of the mean, standard deviation, minimum, maximum, skewness, and kurtosis for each variable included in the analysis. On a closer examination of the disaggregated level data of energy consumption, it is evidently that fossil fuel denotes the highest mean, followed by renewable and nuclear energy, respectively.

Table 4.1: Descriptive Statistics.

	Mean	SD	Skewness	Kurtosis	Min.	Max.
CO_{2_t} emissions	2.944	0.091	-0.452	2.526	2.752	3.114
GDP_t	10.401	0.326	-0.250	1.866	9.774	10.862
GDP_t^2	108.292	6.750	-0.213	1.833	95.522	117.988
Total Energy Consumption (EN_t)	8.908	0.096	-1.380	4.349	8.633	9.041
Total Fossil Fuels Consumption (FF_t)	19.461	0.088	-0.456	2.567	19.264	19.620
Nuclear Electric Power Consumption (NEN_t)	15.879	1.837	-1.455	3.778	10.415	17.159
Total Renewable Energy Consumption (REN_t)	16.921	0.165	-0.168	2.502	16.593	17.236
Observations	56					

Notes: The data was made available by World Bank and EIA. The annual data set covers the period 1960 to 2015 for the US. GDP_t is measured in constant 2010 US dollar and CO_{2_t}emissions are measured in metric tons. Total energy use is measured in kg of oil equivalent, while energy consumption in its disaggregated level (FF_t, NEN_t, REN_t) is measured in Btu. All time series are measured in per capita and are transformed into natural logarithm.

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[1] To obtain the per capita unit for the disaggregated energy consumption data we use population data from EIA (2021a).

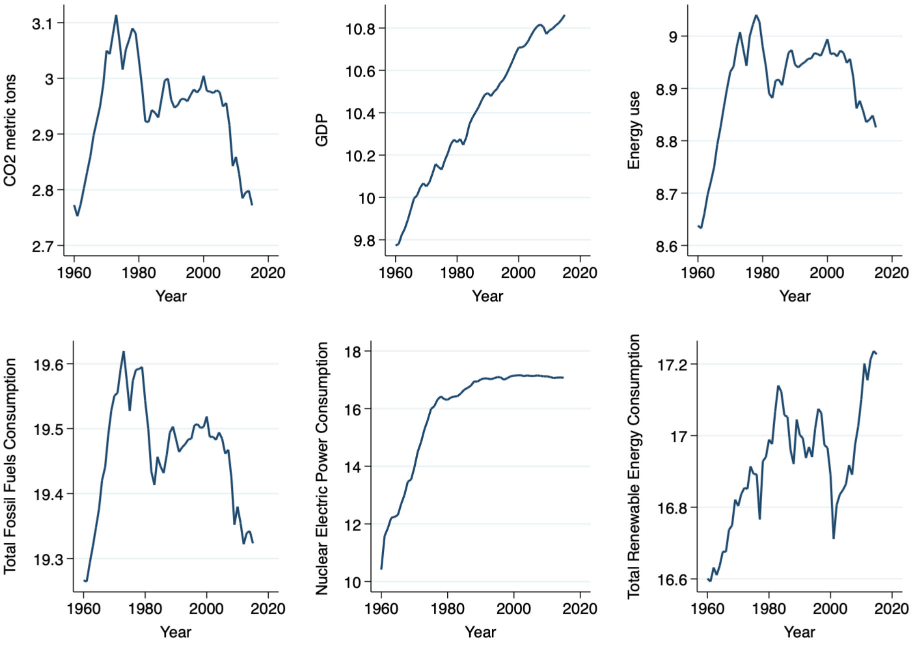

Figure 4.1: Time series plots.
Notes: Time series plots for all variables (after taking natural logarithms) from 1960 until 2015 in the US.

Time series plots for all variables are shown in Figure 4.1. The curve of CO_{2_t} emissions in the US shows three significant drops. Starting in 1960 an increase of emissions is observed. This is followed by a relatively sharp decline in 1973/74 and 1979/80 explained by the two dramatic oil price shocks (Tol et al., 2006). Such variance in data can possibly cause structural breaks that needs to be carefully considered.[2] We further observe a striking decline beginning at the end of the 20^{th} century. The persistent decline in CO_{2_t} emissions can been referred to a series of environmental measures such as the "Clean Air Act“ a program run by the EPA aimed at raising awareness of environmental issues among the population of the US. Moreover, 1997 the Kyoto Protocol was adopted to fight climate change and reduce emissions (Oberthür & Ott, 1999).[3]

We further observe a relatively similar pattern for total energy and fossil fuel consumption. Both, EN$_t$ and FF$_t$ show a sharp increase until the first oil crisis. Compared to the total energy use, the graph of fossil fuel shows a tremendous decrease in the 1980s and from the beginning of the 21^{st} century onwards. Over the last decades energy consumption patterns have changed as new energy sources and their usage have changed. So

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[2] For robustness we also account for structural breaks in Chapter 6.

[3] 1998 President Clinton signed the Kyoto Protocol, however the US Senat did nor ratify it.

has nuclear power consumption made a significant contribution. NEN_t continued to grow throughout the 1960s. The rapid increase between 1970 and 1980 is explained through the increased construction of new reactors (EIA, 2021b). Since then the overall pattern of nuclear energy consumption has remained fairly stable.

Throughout the last decades total renewable energy consumption in the US increased enormously. This is not surprisingly, since that was the time when the US government started setting policy initiatives and the sensitivity for renewable energies has strongly increased within the population. For instance, the Energy Policy Acts of 2002 and 2005, and the Federal Energy Independence and Security Act of 2007 were introduced to increase the consumption of renewable energy (Barros et al., 2012; Lean & Smyth, 2013).

Turning to the economic development of the US, per capita GDP_t increases gradually from 1960. At the beginning of 1980 a small drop of the GDP_t is due to the starting recession in the US. Further, due to the financial crisis in 2007 to 2008 GDP_t decreases slightly, until it continues to increase.

To sum up, Figure 4.1 suggests that a long-run or cointegrating relationship is likely to be present between CO_{2_t} and EN_t. Further, a relatively similar movement for EN_t and FF_t can be observed. This is expected, as fossil fuel accounts for the majority of the US total energy consumption (EIA, 2021c). The dominant share of fossil fuel in the aggregated energy use might have a considerable impact on CO_2 emissions and thus on the environment. However, casual inspection always has its perils and therefore it is necessary to perform a formal testing to confirm our presumptions.

5. Methodology

It is necessary to investigate the EKC hypothesis for the US. Therefore, we examine two different models in this study. First, we consider the traditional EKC (Grossman & Krueger, 1991; Kuznets, 1955) [1]:

$$CO_{2_t} = \beta_0 + \beta_1 GDP_t + \beta_2 GDP_t^2 + \varepsilon_t \tag{Model (I)}$$

where CO_{2_t} is the carbon dioxide emission (measured in metric tons per capita); GDP_t is the real gross domestic product per capita (measured in constant 2010 US dollar); and GDP_t^2 denotes the square of real gross domestic product per capita (measured in constant 2010 US dollar). Due to the usual statistical reasons all variables are transformed into their natural logarithmic forms. Hence, the parameters β_1 and β_2 are interpreted as the long-run elasticities of CO_{2_t} with respect to GDP_t and GDP_t^2. β_0 is the included constant, while ε_t stands for the corresponding error term. Under the traditional EKC of an inverted U-shape relationship between economic output and environmental degradation, β_1 is expected to be positive, whereas β_2 is expected to be negative.

Many studies have found evidence for a causal relationship between EN and CO_2 (Akpan & Akpan, 2012; Dincer & Rosen, 1999; Omer, 2008). Moreover, other studies found that economic development is closely related to energy consumption (Ajmi et al., 2015; Ang, 2007; Baek, 2015; Saboori & Sulaiman, 2013b; Wolde-Rufael, 2004, 2010; Yang, 2000). Since energy consumption is found to be related to both variables in our model, we include energy consumption EN_t (measured in kg of oil equivalent per capita) in our analysis. The transformed model is as follows [2]:

$$CO_{2_t} = \beta_0 + \beta_1 GDP_t + \beta_2 GDP_t^2 + \beta_3 EN_t + \varepsilon_t \tag{Model (II)}$$

The empirical estimation of the long-run relationship between environmental degradation and economic output, in the presence of energy consumption is performed in five different steps. First, we test the integration properties of CO_{2_t}, GDP_t, GDP_t^2, and EN_t.

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[1] For reasons of simplicity we use the letter β_i for the parameters of both models. However, they clearly do not denote the same coefficients. Further, t denotes the time subscript.

[2] EN_t is likewise transformed in natural logarithm.

Second, if all series are integrated of the same order, the long-run relationship among the variables is investigated using the Johansen cointegration method. Third, assuming that the variables have at least one cointegration relationship, short-run and long-run coefficients of the variables used in both models are estimated by using a VECM. A VECM restricts the long-run behaviour of endogenous variables to converge to their co-integrating relationship, while adjusting for short-run dynamics. Hence, we follow Engle and Granger (1987) and incorporate an Error Correction Term (ECT). The multi-variate VECM for Model (II) can be expressed as follows [3]:

$$\begin{aligned}\Delta CO_{2_t} = \alpha_1 + \sum_{i=1}^{p} \beta_{1i} \Delta CO_{2_{t-i}} + \sum_{i=1}^{q} \beta_{1i} \Delta GDP_{t-i} \\ + \sum_{i=1}^{r} \beta_{1i} \Delta GDP^2_{t-i} + \sum_{i=1}^{s} \beta_{1i} \Delta EN_{t-i} + \lambda_1 ECT_{t-1} + u_{1t}\end{aligned} \tag{5.1}$$

$$\begin{aligned}\Delta GDP_t = \alpha_2 + \sum_{i=1}^{p} \beta_{2i} \Delta CO_{2_{t-i}} + \sum_{i=1}^{q} \beta_{2i} \Delta GDP_{t-i} \\ + \sum_{i=1}^{r} \beta_{2i} \Delta GDP^2_{t-i} + \sum_{i=1}^{s} \beta_{2i} \Delta EN_{t-i} + \lambda_2 ECT_{t-1} + u_{2t}\end{aligned} \tag{5.2}$$

$$\begin{aligned}\Delta GDP^2_t = \alpha_3 + \sum_{i=1}^{p} \beta_{3i} \Delta CO_{2_{t-i}} + \sum_{i=1}^{q} \beta_{3i} \Delta GDP_{t-i} \\ + \sum_{i=1}^{r} \beta_{3i} \Delta GDP^2_{t-i} + \sum_{i=1}^{s} \beta_{3i} \Delta EN_{t-i} + \lambda_3 ECT_{t-1} + u_{3t}\end{aligned} \tag{5.3}$$

$$\begin{aligned}\Delta EN_t = \alpha_4 + \sum_{i=1}^{p} \beta_{4i} \Delta CO_{2_{t-i}} + \sum_{i=1}^{q} \beta_{4i} \Delta GDP_{t-i} \\ + \sum_{i=1}^{r} \beta_{4i} \Delta GDP^2_{t-i} + \sum_{i=1}^{s} \beta_{4i} \Delta EN_{t-i} + \lambda_4 ECT_{t-1} + u_{4t}\end{aligned} \tag{5.4}$$

where all variables are defined as stated above. ECT_{t-1} is the error correction term, λ_i denotes the speed of adjustment coefficient and u_{it} is the serially uncorrelated random error term with zero mean. To ensure a long-run relationship among the variables λ_i needs to be negative and statistically significant. Fourth, we test for causal relationship between the analyzed variables and lastly we perform different stability tests to avoid problems of mis-specification.

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[3] VECM for Model (I) is provided in the Appendix A, Equation (A.1) - Equation (A.3).

6. Empirical Results

6.1 Results of Stationarity tests

Stationarity tests are used to identify the order of integration of the time series data. This study implements the following two unit root tests: the Augmented Dickey-Fuller test (ADF) and the Phillips–Perron test (PP) (Dickey & Fuller, 1979; Phillips & Perron, 1988). Both ADF and PP test the null hypothesis that a unit root is present in the time series sample against the alternative hypothesis that the series are stationary. ADF uses additional lags of the first-differenced variable, whereas PP uses Newey and West (1986) standard errors to account for serial correlation and heteroscedasticity in the residuals. The results presented in Table 6.1 indicate that all the series are non-stationary in levels. However, when the first difference is taken these series come out to be stationary. Hence, it can be concluded that all series are integrated of order one (I(1)) at the 1% level of significance.

Table 6.1: Results of unit root tests.

Variable	ADF		PP		Order of Integration
	Level	First difference	Level	First difference	
CO_{2_t}	−2.436	-5.690^{***}	−1.696	-5.653^{***}	$I(1)$
GDP_t	−2.100	-5.790^{***}	−1.832	-5.704^{***}	$I(1)$
GDP_t^2	−2.127	-5.745^{***}	−1.897	-5.656^{***}	$I(1)$
Energy use (EN_t)	−2.635	-5.475^{***}	−1.922	-5.431^{***}	$I(1)$
Total Fossil Fuels Consumption (FF_t)	−2.870	-5.814^{***}	−2.153	-5.788^{***}	$I(1)$
Nuclear Electric Power Consumption (NEN_t)	−3.427	-6.818^{***}	−3.462	-7.991^{***}	$I(1)$
Total Renewable Energy Consumption (REN_t)	−1.929	-7.864^{***}	−1.975	-7.848^{***}	$I(1)$

Notes: The regressions in level and in first difference include intercept and trend. *** indicates the rejection of null hypothesis of non-stationary of the variable at 1% significance levels. The optimal lag length was selected using the AIC.

6.2 Results of Cointegration analysis

Given that all series share a common order of integration the analysis is continued using the Johansen cointegration approach to determine the long-run relationships among the investigated variables. The optimal lag length included is selected using the Akaike Information Criteria (AIC)[1]. The results presented in Table 6.2 indicate that there exist at least one long-run relationship in the specified models at the 1% level of significance. The results are based on both, the Johansen maximum eigenvalue statistic and the trace statistic.

Table 6.2: Results of Johansen test for cointegration - Aggregated Energy Consumption.

	Model I		Model II	
Rank r	Trace statistics	Maximum eigenvalue	Trace statistics	Maximum eigenvalue
$r_0 = 0$	40.690^{***}	33.4395^{***}	70.684^{***}	35.666^{***}
$r_0 \leq 1$	7.251	7.233	35.018	24.489
$r_0 \leq 2$	0.018	0.018	10.529	10.438
$r_0 \leq 3$			0.091	0.091

Notes: *** indicates the rejection of null hypothesis at 1% level of significance. The optimal lag length was selected using the AIC. Hence, Model (I) includes 2 lags while Model (II) includes 4 lags.

Since the Johansen test provides evidence for at least one long-run relationship, the next step is to estimate the long-run and the short-run coefficients of our variables by using a VECM. By normalizing the coefficient of CO_{2_t} to one, Table 6.3 shows that all coefficients of the long-run equation for Model (I) and Model (II) are statistically significant at the 1% level.

Model (I) clearly provides evidence for the existence of the EKC. The signs of the coefficients of GDP_t and GDP_t^2 are consistent with the expectations for the EKC i.e. positive for GDP_t and negative for GDP_t^2 indicating a non-linear curve. We find that an increase of 1% in GDP_t results in an increase of 1.17% points of CO_{2_t} emissions. Our findings suggest that the level of environmental pollution first increases with economic growth, and then stabilizes and declines, which is consistent with most of the literature.

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[1] Since we have a relatively small sample we follow the AIC with the risk of over fitting, but with a decreased risk of leaving dynamics outside the error term and thereby causing the estimates to be biased and inconsistent ((Enders, 2008), p. 70).

Similar results are found by Apergis et al. (2017), Aslan et al. (2018a), Bulut (2019), Koirala and Mysami (2015), and Pata (2021) who also provide evidence that the EKC hypothesis is valid for the US.

Table 6.3: Long-run estimates.

Dependent variable: CO_{2_t}			
Regressors	Coefficients	Standard errors	z-value
$Model(I)$			
GDP_t	1.174^{***}	0.112	-10.49
GDP_t^2	-0.084^{***}	0.011	7.84
$Model(II)$			
GDP_t	-4.105^{***}	0.850	4.83
GDP_t^2	0.215^{***}	0.041	-5.26
EN_t	0.845^{***}	0.059	-14.29

Notes: ***, **, and * indicates the significance of coefficients at 1%, 5%, and 10% levels of significance, respectively. The optimal lag length was selected using the AIC. We include 2 lags in Model (I) and 4 lags in Model (II).

We now turn to Table 6.4 presenting the corresponding ECT_{t-1} and short-run coefficients when ΔCO_{2_t} and ΔGDP_t are the dependent variables. Since our objective is to explore the EKC we mainly focus on the equation when ΔCO_{2_t} is the dependent variable (Equation (A.1)). ECT_{t-1} has the expected negative sign and is statistically significant. Although, the signs of the coefficients of ΔGDP_{t-1} and ΔGDP_{t-1}^2 are the same as in the normalized cointegration vector, they are not statistically significant at conventional levels of significance. Thus, we conclude that in short-run the EKC hypothesis does not hold. We establish that EKC is long-run phenomena rather than short-run. This is in line with Dinda (2004) and Nasir and Rehman (2011) who emphasised that EKC is a long-run appearance and hence, its validity should be judged in long-run.

Further, when ΔGDP_t is the dependent variable, the coefficient of $\Delta CO_{2_{t-1}}$ is negative, however, statistically insignificant. Thus, there is no significant relationship running from carbon dioxide emissions to economic output in short-run.

Table 6.4: Short-run estimates - Model (I).

Regressors	Coefficients	Standard errors	z-value
Dependent variable: Δ CO_{2_t}			
ECT_{t-1}	-0.040^{*}	0.023	-1.72
Δ $CO_{2_{t-1}}$	0.352^{**}	0.146	2.41
Δ GDP_{t-1}	4.215	5.964	0.71
Δ GDP^2_{t-1}	-0.213	0.286	-0.74
Dependent variable: Δ GDP_t			
ECT_{t-1}	-0.078^{***}	0.016	-4.77
Δ $CO_{2_{t-1}}$	-0.041	0.103	-0.40
Δ GDP_{t-1}	-10.405^{**}	4.198	-2.48
Δ GDP^2_{t-1}	0.521^{***}	0.201	2.59

Notes: ***, **, and * indicates the significance of coefficients at 1%, 5%, and 10% levels of significance, respectively. The optimal lag length was selected using the AIC. Short-run coefficients when ΔGDP_t^2 the dependent variable are not reported in here. R^2 is estimated to be 0.26 and 0.61 when ΔCO_{2_t} and ΔGDP_t are the dependent variables.

In order to investigate the key drivers of CO_2 emissions further, energy consumption is included in the initial model. Having EN_t in the model i.e. Model (II), the EKC hypothesis cannot be confirmed. The results state the long-run elasticity of CO_{2_t} with respect to EN_t to be 0.85, meaning that EN_t significantly drives CO_{2_t}. We further provide evidence of a statistically negative effect of GDP_t on emissions in the long-run. In contrast to the initial model, a statistically significant and positive coefficients for GDP_t^2 of approximately 0.22 is observed. This vanishing of the EKC establishes the fact that energy consumption is a key driver of CO_{2_t}. Hence, with the inclusion of EN_t the model shows a positive sign for GDP_t^2 and leads us to conclude that the inverted U-shape relationship between CO_{2_t}, GDP_t, and GDP_t^2 no longer exist. This result goes along with the studies conducted by Dogan and Ozturk (2017), Dogan and Turkekul (2016), and Tzeremes (2018) who also reject a modified form of the EKC hypothesis for the US.

As presented in Table 6.5 the coefficient of ECT_{t-1} is statistically significant and has a negative sign, referring to Equation (5.1). It indicates that after a deviation from the long-run equilibrium more than 85% of the disturbance in the short-run is corrected each year. The absolute value of the coefficient of ECT_{t-1} is quite high, indicating a fairly high speed of adjustment to the long-run equilibrium following short-run deviations (Ang, 2007; Farhani & Ozturk, 2015). Similar to our findings of Model (I) we do not find any significant short-run effects of the included variables. Once more, we conclude that the effect of energy consumption and economic output on environmental degradation is rather long-run phenomena than short-run. As economic development and growth is not a short-run process thus, it will take time and effort for an economy to achieve a specific economic degree where further growth will mitigate environmental degradation in long-run.

As next, we examine the results of Equation (5.2) and Equation (5.4). Table 6.5 illustrates that all coefficients are statistically insignificant in the short-run. For Equation (5.2), when ΔGDP_t is the dependent variable, ECT_{t-1} is negative, however insignificant. This confirms the absence of a significant long-run cointegration. Put differently, the ECT does not push the system towards the equilibrium path in case of a shock in the short-run. The opposite is found for the case when ΔEN_t is the dependent variable (Equation (5.4)).

Table 6.5: Short-run estimates - Model (II), Aggregated Energy Consumption.

Regressors	Coefficients	Standard errors	z-value
Dependent variable: $\Delta\ \mathrm{CO2}_t$			
ECT_{t-1}	-0.855^{***}	0.292	-2.93
$\Delta\ \mathrm{CO2}_{t-1}$	0.111	0.484	0.23
$\Delta\ \mathrm{CO2}_{t-2}$	-0.482	0.448	-1.08
$\Delta\ \mathrm{CO2}_{t-3}$	0.269	0.450	0.60
$\Delta\ \mathrm{GDP}_{t-1}$	-2.080	8.093	-0.26
$\Delta\ \mathrm{GDP}_{t-2}$	-9.626	8.023	-1.20
$\Delta\ \mathrm{GDP}_{t-3}$	-4.086	6.828	-0.60
$\Delta\ \mathrm{GDP}^2_{t-1}$	0.096	0.393	0.24
$\Delta\ \mathrm{GDP}^2_{t-2}$	0.444	0.391	1.13
$\Delta\ \mathrm{GDP}^2_{t-3}$	0.178	0.332	0.54
$\Delta\ \mathrm{EN}_{t-1}$	0.196	0.597	0.33
$\Delta\ \mathrm{EN}_{t-2}$	0.479	0.564	0.85
$\Delta\ \mathrm{EN}_{t-3}$	0.171	0.574	0.30
Dependent variable: $\Delta\ \mathrm{GDP}_t$			
ECT_{t-1}	-0.325	0.240	-1.35
$\Delta\ \mathrm{CO2}_{t-1}$	0.300	0.399	0.75
$\Delta\ \mathrm{CO2}_{t-2}$	-0.017	0.369	-0.05
$\Delta\ \mathrm{CO2}_{t-3}$	0.206	0.371	0.56
$\Delta\ \mathrm{GDP}_{t-1}$	-2.124	6.662	-0.32
$\Delta\ \mathrm{GDP}_{t-2}$	-7.104	6.604	-1.08
$\Delta\ \mathrm{GDP}_{t-3}$	3.491	5.620	0.62
$\Delta\ \mathrm{GDP}^2_{t-1}$	0.108	0.324	0.33
$\Delta\ \mathrm{GDP}^2_{t-2}$	0.336	0.322	1.04
$\Delta\ \mathrm{GDP}^2_{t-3}$	-0.180	0.273	-0.66
$\Delta\ \mathrm{EN}_{t-1}$	-0.217	0.492	-0.44
$\Delta\ \mathrm{EN}_{t-2}$	-0.093	0.464	-0.20
$\Delta\ \mathrm{EN}_{t-3}$	-0.223	0.473	-0.47
Dependent variable: $\Delta\ \mathrm{EN}_t$			
ECT_{t-1}	-0.598^{**}	0.269	-2.22
$\Delta\ \mathrm{CO2}_{t-1}$	-0.018	0.447	-0.04
$\Delta\ \mathrm{CO2}_{t-2}$	-0.277	0.413	-0.67
$\Delta\ \mathrm{CO2}_{t-3}$	0.224	0.415	0.54
$\Delta\ \mathrm{GDP}_{t-1}$	-0.427	7.464	-0.06
$\Delta\ \mathrm{GDP}_{t-2}$	-9.893	7.400	-1.34
$\Delta\ \mathrm{GDP}_{t-3}$	3.083	6.298	0.49
$\Delta\ \mathrm{GDP}^2_{t-1}$	0.015	0.363	0.04
$\Delta\ \mathrm{GDP}^2_{t-2}$	0.460	0.361	1.28
$\Delta\ \mathrm{GDP}^2_{t-3}$	-0.162	0.306	-0.53
$\Delta\ \mathrm{EN}_{t-1}$	0.330	0.551	0.60
$\Delta\ \mathrm{EN}_{t-2}$	0.223	0.520	0.43
$\Delta\ \mathrm{EN}_{t-3}$	0.072	0.530	0.14

Notes: ***, **, and * indicates the significance of coefficients at 1%, 5%, and 10% levels of significance, respectively. R^2 is estimated to be 0.50, 0.62, and 0.46 when $\Delta CO2_t$, ΔGDP_t, and ΔEN_t are the dependent variables.

The finding that energy use is an important and significant driver of emissions is in line with our hypothesis and consistent with related literature (Dogan & Ozturk, 2017; Dogan & Turkekul, 2016; Jalil & Feridun, 2011; Jalil & Mahmud, 2009; Saboori & Sulaiman, 2013a). Therefore, it is valuable to establish that an increase in energy consumption leads to the degradation of the environment in case of the US. As compared to other studies, the estimated effect of EN_t on CO_{2_t} is considered to be small. For instance Nasir and Rehman (2011) found a statistically significant effect of 1.65% points increase for energy consumption on CO_2 emissions in Pakistan. Further, Ang (2007) provides a positive effect of around 2.25% points on environmental degradation for France. Likewise, Baek (2015) estimated a linear model finding that an increase of 1% in energy consumption leads to an increase in CO_2 emissions by 1.01%. While CO_2 emissions decrease by 0.08%, given an 1% increase in income.

The significant reduction in CO_2 emissions with an increase of economic activity can be explained through different channels. The US is one of the most advanced economies in the world having sophisticated anti-pollutant technologies and strict environmental protection laws in place. This ensures that whenever an economic activity is undertaken it must comply to the set standards and must minimally add to the existing CO_2 emissions. Furthermore, the US government also spends a tremendous amount to upgrade old CO_2 emitting infrastructure each year that also helps reducing CO_2 emissions (Frazier, 2021).

Although the results of Johansen cointegration technique confirm the validity of a long-run relationship between the included variables for the US, we use the ARDL approach to check the robustness of our results. We obtain results which are consistent with our findings from the Johansen cointegration approach. Results are presented in Table A.1, Appendix A.

6.3 Disaggregated Energy Consumption

It has been pointed out by Pata (2021) and Soytas et al. (2007) that disaggregated level data on energy consumption may provide further insights regarding the link between energy consumption, economic growth, and environmental degradation. As just showed, including energy use in our model makes us acknowledge it as the key driver of carbon emissions, while rejecting the EKC for the US. Thus, we feel that the usage of energy consumption in its disaggregated level may elicit a more precise diagnosis of the emission-energy-GDP nexus. The utilization of energy consumption in its disaggregated form will indicate the strength and explanatory power of the various energy sources that cause environmental degradation. Same analytical procedure as before is followed whereby each primary energy source, FF_t, NEN_t, and REN_t is considered separately in place of aggregated energy consumption in the VECM.[2] Table 6.6 provides evidence for the presence of a common trend between each of the disaggregated level of energy consumption, CO_2 emissions, and economic output. All cointegration relationships are significant at the 1% level.

Table 6.6: Results of Johansen test for cointegration - Disaggregated Energy Consumption.

	Fossil Fuel		Nuclear		Renewable	
Rank r	Trace statistics	Maximum eigenvalue	Trace statistics	Maximum eigenvalue	Trace statistics	Maximum eigenvalue
$r_0 = 0$	57.858***	41.062***	54.696***	22.941***	49.748***	35.987***
$r_0 \leq 1$	16.796	8.751	31.756	21.983	13.761	8.366
$r_0 \leq 2$	8.045	7.763	9.773	7.432	5.395	5.292
$r_0 \leq 3$	0.283	0.283	2.341	2.341	0.103	0.103

Notes: *** indicates the rejection of null hypothesis at 1% level of significance. The optimal lag length was selected using the AIC.

Table 6.7 presents the long-run estimation results for FF_t, NEN_t, and REN_t, respectively. Our results suggest that CO_{2_t} increases with an increase of FF_t. We find a significant positive coefficient for FF_t. According to the obtained coefficient of fossil fuel, a rise of 1% in FF_t increases CO_{2_t} by around 0.71% points. As fossil fuel accounts for almost 80% of the total energy consumption in the US it is not surprisingly that the effect is relatively similar to the aggregated energy use, where we found evidence for an increase of 0.85 (EIA, 2021c). The signs of the coefficients of GDP_t and GDP_t^2 are likewise not consistent with the expectations of the EKC i.e. we have a negative coefficient for GDP_t and a positive coefficient for GDP_t^2 indicating that there exist no inverted U-shape.

However, the existence of the EKC is detected when we consider the consumption of nuclear and renewable energy. An increase of 1% NEN_t decreases the level of CO_{2_t} emissions by 0.09% points in the long-run. Similarly, an increase of 1% REN_t decreases the level of CO_{2_t} emissions by 0.45% points in long-run.[3] In other words, nuclear and

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[2] FF consists of petroleum, natural gas, and coal.

[3] Both coefficients for NEN_t and REN_t are statistically significant at the 5% level.

renewable energy leads to executing a considerable reduction in CO_2 emissions in long-run. Furthermore, it is important to point out that the coefficient of REN_t is quite large as compared to NEN_t indicating that renewables are more beneficial towards the environment. Nonetheless, our results highlight the importance of clean energy consumption from nuclear and renewable energy sources, respectively. Thus, we conclude that a shift away from the conventional energy sources might be beneficial fighting the degrading environment. Likewise, the studies of Dogan and Ozturk (2017), Lau et al. (2019), Ozcan, Ulucak, et al. (2020), and Pata (2021) found significantly reducing effects of nuclear and renewable energy consumption on emissions. Therefore, the transition towards more clean energy is an issue of great importance with growing debate in climate change mitigation.

Table 6.7: Long-run estimates - Disaggregated Energy Consumption.

Dependent variable: CO_{2_t}			
Regressors	Coefficients	Standard errors	z-value
GDP_t	-1.844^{***}	0.412	4.47
GDP_t^2	0.077^{***}	0.021	−3.70
FF_t	0.709^{***}	0.104	−6.79
GDP_t	1.502^{***}	0.184	−8.14
GDP_t^2	-0.102^{***}	0.016	6.53
NEN_t	-0.093^{**}	0.037	2.55
GDP_t	2.508^{***}	0.583	−4.30
GDP_t^2	-0.142^{***}	0.027	5.18
REN_t	-0.452^{**}	0.188	2.40

Notes: We normalize the coefficient of CO_{2_t} to one. ***, **, and * indicates the significance of coefficients at 1%, 5%, and 10% levels of significance, respectively. The optimal lag length was selected using the AIC.

Tables 6.8a, 6.8b, and 6.9 display the ECTs and short-run estimates using various type of disaggregated energy consumption.

Considering fossil fuel, the negative coefficient of ECT_{t-1} is found to be statistically significant. It shows that the system converges to long-run equilibrium path in case of disturbances in short-run. When ΔCO_{2_t} is the dependent variable, ECT_{t-1} is approximately -0.30, suggesting that if there would be disturbance in the short-run equilibrium, the model will adjust by around 30% within the first year. Ang (2007) and Nasir and

Rehman (2011) found an ECT of above 0.50 for France and Pakistan, respectively. While, Farhani and Ozturk (2015) found an adjustment of around 25% for Tunesia. Thus, the speed of adjustment towards equilibrium is considered as moderate in case of any shock to the emission equation. In contrast to Ang (2007) and Nasir and Rehman (2011), who investigate energy consumption in its aggregated form, we additionally focus on the disaggregated level of energy consumption and, hence, can provide a more detailed analysis.

Equivalently to the aggregated energy consumption we do not find statistically significant short-run effects of ΔFF_{t-i} and ΔGDP_{t-i}. This means that fossil fuel consumption and economic output are not responding on ΔCO_{2_t} in short-run. Nonetheless, as discussed above, in long-run these small contributions of short-run cumulate and have a significant long-run effect.

Further, when ΔGDP_t is our dependent variable we have a negative and statistically significant effect of fossil fuel in short-run. The negative coefficient of the first lag of ΔFF_{t-1} implies a 0.82% decrease in ΔGDP_t due to an increase of 1% in fossil fuel energy consumption. As energy consumption has a harmful effect on the environment, the negative coefficient of ΔFF_{t-1} already indicates how severe the consequences of toxic gases can in turn be for the economy of a country. For instance reduced productivity or raised costs might be consequences due to negative effects on human and environmental health. Moreover, the coefficient of $\Delta CO_{2_{t-1}}$ is positive and statistically significant. This is due to the fact that high levels of production requires more energy consumption leading to a higher GDP. This implies a positive relationship between ΔGDP_t and $\Delta CO_{2_{t-1}}$. On the other hand, in the third equation when ΔFF_t is the dependent variable all coefficients are insignificant in short-run. ECT$_{t-1}$ is reported to be -0.25, indicating a convergence towards the equilibrium path after deviations in the short-run.

Table 6.8: Short-run estimates.

(a) Fossil Fuel Energy Consumption.

Regressors	Coefficients	Standard errors	z-value
Dependent variable: Δ $CO2_t$			
ECT_{t-1}	-0.304^{***}	0.106	-2.88
Δ $CO2_{t-1}$	0.342	0.402	0.85
Δ $CO2_{t-2}$	-0.240	0.422	-0.57
Δ $CO2_{t-3}$	0.326	0.384	0.85
Δ GDP_{t-1}	2.674	7.919	0.34
Δ GDP_{t-2}	-11.589	8.526	-1.36
Δ GDP_{t-3}	-7.948	7.418	-1.07
Δ GDP^2_{t-1}	-0.129	0.384	-0.34
Δ GDP^2_{t-2}	0.548	0.417	1.32
Δ GDP^2_{t-3}	0.373	0.361	1.03
Δ FF_{t-1}	0.016	0.438	0.04
Δ FF_{t-2}	0.130	0.465	0.28
Δ FF_{t-3}	0.031	0.439	0.07
Dependent variable: Δ GDP_t			
ECT_{t-1}	-0.297^{***}	0.075	-3.98
Δ $CO2_{t-1}$	0.723^{**}	0.284	2.54
Δ $CO2_{t-2}$	0.154	0.298	0.52
Δ $CO2_{t-3}$	0.483^{*}	0.272	1.78
Δ GDP_{t-1}	-7.163	5.596	-1.28
Δ GDP_{t-2}	-7.603	6.025	-1.26
Δ GDP_{t-3}	-1.745	5.242	-0.33
Δ GDP^2_{t-1}	0.371	0.272	1.37
Δ GDP^2_{t-2}	0.364	0.294	1.24
Δ GDP^2_{t-3}	0.085	0.255	0.33
Δ FF_{t-1}	-0.820^{***}	0.310	-2.65
Δ FF_{t-2}	-0.286	0.329	-0.87
Δ FF_{t-3}	-0.587^{*}	0.311	-1.89
Dependent variable: Δ FF_t			
ECT_{t-1}	-0.248^{**}	0.107	-2.32
Δ $CO2_{t-1}$	0.583	0.406	1.44
Δ $CO2_{t-2}$	-0.214	0.426	-0.50
Δ $CO2_{t-3}$	0.343	0.388	0.88
Δ GDP_{t-1}	3.116	7.996	0.39
Δ GDP_{t-2}	-11.597	8.609	-1.35
Δ GDP_{t-3}	-1.568	7.491	-0.21
Δ GDP^2_{t-1}	-0.144	0.388	-0.37
Δ GDP^2_{t-2}	0.542	0.421	1.29
Δ GDP^2_{t-3}	0.071	0.365	0.19
Δ FF_{t-1}	-0.319	0.443	-0.72
Δ FF_{t-2}	0.114	0.470	0.24
Δ FF_{t-3}	-0.006	0.444	-0.01

Notes: ***, **,and * indicates the significance of coefficients at 1%, 5%, and 10% levels of significance, respectively. R^2 is estimated to be 0.43, 0.68, and 0.41 when ΔCO_{2_t}, ΔGDP_t, and ΔFF_t are the dependent variables.

(b) Nuclear Energy Consumption.

Regressors	Coefficients	Standard errors	z-value
Dependent variable: Δ $CO2_t$			
ECT_{t-1}	-0.093^{***}	0.0312	-2.98
Δ $CO2_{t-1}$	0.301^{*}	0.175	1.72
Δ $CO2_{t-2}$	-0.175	0.186	-0.94
Δ $CO2_{t-3}$	0.289^{*}	0.174	1.67
Δ GDP_{t-1}	-0.004	8.115	-0.00
Δ GDP_{t-2}	-11.159	8.667	-1.29
Δ GDP_{t-3}	-11.426	8.033	-1.42
Δ GDP^2_{t-1}	0.002	0.394	0.01
Δ GDP^2_{t-2}	0.532	0.422	1.26
Δ GDP^2_{t-3}	0.542	0.390	1.39
Δ NEN_{t-1}	-0.001	0.035	-0.01
Δ NEN_{t-2}	0.005	0.033	0.16
Δ NEN_{t-3}	-0.022	0.026	-0.85
Dependent variable: Δ GDP_t			
ECT_{t-1}	-0.056^{**}	0.025	-2.22
Δ $CO2_{t-1}$	-0.032	0.140	-0.22
Δ $CO2_{t-2}$	-0.242	0.149	-1.62
Δ $CO2_{t-3}$	-0.086	0.139	-0.62
Δ GDP_{t-1}	-5.693	6.508	-0.87
Δ GDP_{t-2}	-10.295	6.950	-1.48
Δ GDP_{t-3}	-0.147	6.442	-0.02
Δ GDP^2_{t-1}	0.295	0.316	0.93
Δ GDP^2_{t-2}	0.502	0.339	1.48
Δ GDP^2_{t-3}	0.007	0.313	0.02
Δ NEN_{t-1}	0.015	0.028	0.55
Δ NEN_{t-2}	-0.001	0.027	-0.02
Δ NEN_{t-3}	0.006	0.021	0.30
Dependent variable: Δ NEN_t			
ECT_{t-1}	-0.243^{*}	0.137	-1.78
Δ $CO2_{t-1}$	0.795	0.764	1.04
Δ $CO2_{t-2}$	-0.489	0.811	-0.60
Δ $CO2_{t-3}$	0.526	0.758	0.69
Δ GDP_{t-1}	-35.391	35.451	-1.00
Δ GDP_{t-2}	18.099	37.862	0.48
Δ GDP_{t-3}	-28.044	35.093	-0.80
Δ GDP^2_{t-1}	1.674	1.723	0.97
Δ GDP^2_{t-2}	-0.787	1.844	-0.43
Δ GDP^2_{t-3}	1.318	1.704	0.77
Δ NEN_{t-1}	0.417^{***}	0.152	2.74
Δ NEN_{t-2}	0.287^{*}	0.146	1.96
Δ NEN_{t-3}	-0.180	0.116	-1.56

Notes: ***, **,and * indicates the significance of coefficients at 1%, 5%, and 10% levels of significance, respectively. R^2 is estimated to be 0.44, 0.60, and 0.71 when ΔCO_{2_t}, ΔGDP_t, and ΔNEN_t are the dependent variables.

Next, we have a closer look on nuclear and renewable energy in short-run. We confirm the existence of the EKC as the coefficients are positive for GDP_t and negative for GDP_t^2 in long-run, illustrated in Table 6.7. However, this pattern cannot be found in short-run, as the coefficients of ΔGDP_{t-i} and ΔGDP^2_{t-i} are not statistically significant when ΔCO_{2_t} is the dependent variable. Thus, in case the of nuclear and renewable energy we reaffirm that the EKC is a long-run phenomena rather than short-run.

As demonstrated in Table 6.8b and Table 6.9 the ECT_{t-1} will push the system towards its equilibrium after disturbances in short-run when ΔCO_{2_t} is the dependent variable. In both cases the ECT_{t-1} is significant but quite small i.e. -0.09 and -0.05 respectively. Similarly, when ΔGDP_t is the dependent variable ECT_{t-1} has the correct sign and is significant. However, Δ $CO_{2_{t-i}}$, ΔNEN_{t-i}, and ΔREN_{t-i}, respectively, do not contribute significantly towards ΔGDP_t in short-run. Contrarily to Table 6.8b in the third part of Table 6.9, when ΔREN_t is the dependent variable, ECT_{t-1} is negative, however, not statistically significant at the conventional levels. Thus, after a deviation in the short-run, the ECT will not push the system towards the equilibrium path again.

Table 6.9: Short-run estimates - Renewable Energy Consumption.

Regressors	Coefficients	Standard errors	z-value
Dependent variable: $\Delta\ \mathrm{CO}_{2_t}$			
ECT_{t-1}	-0.054^{**}	0.0256	-2.11
$\Delta\ \mathrm{CO}_{2_{t-1}}$	0.281^{**}	0.141	2.00
$\Delta\ \mathrm{GDP}_{t-1}$	2.007	6.397	0.31
$\Delta\ \mathrm{GDP}^2_{t-1}$	-0.102	0.308	-0.33
$\Delta\ \mathrm{REN}_{t-1}$	-0.068	0.056	-1.20
Dependent variable: $\Delta\ \mathrm{GDP}_t$			
ECT_{t-1}	-0.077^{***}	0.019	-3.98
$\Delta\ \mathrm{CO}_{2_{t-1}}$	-0.130	0.107	-1.22
$\Delta\ \mathrm{GDP}_{t-1}$	-11.398^{**}	4.857	-2.35
$\Delta\ \mathrm{GDP}^2_{t-1}$	0.577^{**}	0.234	2.47
$\Delta\ \mathrm{REN}_{t-1}$	0.033	0.043	0.76
Dependent variable: $\Delta\ \mathrm{REN}_t$			
ECT_{t-1}	-0.044	0.063	-0.69
$\Delta\ \mathrm{CO}_{2_{t-1}}$	-0.442	0.348	-1.27
$\Delta\ \mathrm{GDP}_{t-1}$	9.180	15.817	0.58
$\Delta\ \mathrm{GDP}^2_{t-1}$	-0.442	0.761	-0.58
$\Delta\ \mathrm{REN}_{t-1}$	-0.099	0.140	-0.71

Notes: ***, **,and * indicates the significance of coefficients at 1%, 5%, and 10% levels of significance, respectively. R^2 is estimated to be 0.31, 0.57, and 0.08 when ΔCO_{2_t}, ΔGDP_t, and ΔREN_t are the dependent variables.

As pointed out in Chapter 4, the issue of possible structural breaks in the data needs to be counted for. Allowing for an endogenously determined structural break Zivot-Andrews test confirmed that all series are integrated of order one (Zivot & Andrews, 2002). This provides evidence for the robustness of our results (Table A.3). To account for the two oil price shocks and the financial crisis, we split our sample into different sub-samples. Results indicate that we do find cointegration for the studied sub-samples (Table A.2). One exception is found for NEN_t, where we cannot provide evidence for a common trend after 1975. Moreover, Gregory and Hansen cointegration test was carried out to control for possible structural breaks (Gregory & Hansen, 1996). Resultantly, we support our previous findings that the linear combination of the variables exhibits stable properties in long-run.

6.4 Results of Granger causality tests

The existence of cointegration implies the existence of causality at least in one direction. It remains to indicate the direction of the causal relationship. To shed more light on the directions of the relationships Granger causality tests are performed. In order to test for short-run causality the statistical significance of the lagged dynamic terms is examined. Therefore, to investigate if energy use does not cause CO_2 emissions in short-run, the statistical significance of the lagged dynamic terms are examined by testing the following null hypothesis $H_0 : all\ \beta_{1i} = 0$ using the Wald test. Rejection of the null implies ΔEN_{t-i} does Granger-cause ΔCO_{2_t} in short-run. Tables 6.10 and 6.11 present our findings.

Table 6.10 shows several interesting facts. We observe no short-run Granger causalities in Table 6.10 depicting that there is no significant short-run relationship between the variables. This finding supports our results reported in Table 6.5 where all the short-run coefficients of the different explanatory variables are statistically insignificant at conventional levels. There is no consensus in the literature on the results of Granger causality. For instance, findings that economic growth and energy consumption Granger causes emissions are found by Dogan and Turkekul (2016). However, similar to our study Dogan and Turkekul found that an increase in the level of energy use does not cause GDP. Suggesting that the US may decrease energy consumption without harming economic growth for the sake of environmental quality.

Table 6.10: Short-run Granger causality tests - Aggregated Energy Consumption.

Variable	$\Delta CO_{2_{t-i}}$	ΔGDP_{t-i}	ΔEN_{t-i}
ΔCO_{2_t}	–	3.46	0.95
ΔGDP_t	0.72	–	0.44
ΔEN_t	0.78	2.16	–

Notes: ***, **, and * denote significance at 1%, 5%, and 10% levels of significance, respectively. Values are based on the chi-square distribution.

The results of the causality tests based on FF_t, NEN_t, and REN_t are reported in Table 6.11. A significant uni-directional short-run causality is running from $\Delta CO_{2_{t-i}}$

and ΔFF_{t-i} to ΔGDP_t. However, we do not find any significant short-run causalities while considering nuclear or renewable energy. This is due to the fact that use of nuclear and renewable energy is quite low and has not yet passed the threshold to make an impact on CO_2 reduction in short-run. Likewise Menyah and Wolde-Rufael (2010) do not found evidence for Granger causality running from renewable energy consumption to CO_2 emissions. However, they found a significant uni-directional causality running from NEN to CO_2.

Table 6.11: Short-run Granger causality tests - Disaggregated Energy Consumption.

Variable	$\Delta CO_{2_{t-i}}$	ΔGDP_{t-i}	$\Delta EN_{k_{t-i}}$
Fossil Fuel			
ΔCO_{2_t}	–	4.50	0.08
ΔGDP_t	8.59**	–	10.19**
ΔFF_t	3.50	2.33	–
Nuclear			
ΔCO_{2_t}	–	5.60	0.85
ΔGDP_t	5.85	–	0.76
ΔNEN_t	1.77	1.40	–
Renewable			
ΔCO_{2_t}	–	0.10	1.44
ΔGDP_t	1.48	–	0.58
ΔREN_t	1.61	0.34	–

Notes: ***, **, and * denote significance at 1%, 5%, and 10% levels of significance, respectively. Values are based on the chi-square distribution. EN_k represents FF, NEN, and REN, respectively.

Further, we perform a pair-wise causality test. Doing so, we test for the joint significance of the lagged terms and the ECT_{t-1}. In particular, ΔEN_{t-i} does cause ΔCO_{2_t} pair-wise if the null $H_0 : all\ \beta_{1i} = \lambda_1 = 0$ is rejected. As previously discussed the ECT is almost always significant, this is supported by our results presented in Table A.4.

6.5 Results of Stability tests

Hansen (1992) provided evidence that estimated parameters might be different in time series data, if the model is incorrect specified. Instability of the model might lead to biased results, which could affect the strength of the empirical findings. Therefore, to avoid mis-specification of our models, we use the Lagrange Multiplier test (LM) in order to test for serial correlation in the residuals. The results for aggregated energy use are shown in Table 6.12. Similarly, Table 6.13 displays results for the disaggregated level data. The results suggest no evidence of serial correlation in the residuals up to the second order for all models. Further, the multivariate normality test shows that the residuals are Gaussian at the 10%, 5%, or 1% level of significance. Therefore, we conclude that we do not find evidence of mis-specification in our models.

Finally, the stability of model is also checked by applying the Cumulative Sum of Squares of Recursive Residual (CUSUMQ) technique. The straight lines in the figures indicate critical bounds at 5% level of significance. It can be observed that the plots of CUSUMQ statistics are well within the critical bounds (Figure A.1). Since the parameters in our model are identified to be stable during the estimation period, results of the cointegration analysis and Granger causality tests based on our model can be used for policy decision-making purposes in Chapter 7.

Table 6.12: Diagnostic test statistics - Aggregated Energy Consumption.

	Model I		Model II	
Diagnostics	Test statistics	p-value	Test statistics	p-value
LM(1)	9.354	0.405	10.266	0.852
LM(2)	11.497	0.243	19.342	0.251
Normality	12.083	0.060	2.395	0.966

Notes: Lagrange Multiplier test (LM): H_0: No serial correlation at lag order. Normality: H_0: Disturbances are normally distributed.

Table 6.13: Diagnostic test statistics - Disaggregated Energy Consumption.

	Fossil Fuel		Nuclear		Renewable	
Diagnostics test statistics	Test statistics	p-value	Test statistics	p-value	Test statistics	p-value
LM(1)	14.297	0.577	12.721	0.693	10.309	0.850
LM(2)	8.187	0.943	6.787	0.977	20.537	0.197
Normality	12.592	0.127	6.766	0.562	6.438	0.598

Notes: Lagrange Multiplier test (LM)): H_0: No serial correlation at lag order. Normality: H_0: Disturbances are normally distributed.

7. Discussion

The findings obtained in Chapter 6 provide support for a robust long-run relationship between the variables, indicating that energy consumption increases CO_2 emissions, while economic activity could mitigate environmental degradation in long-run. Our results demonstrate the importance of policy recommendations and actions to shift energy consumption towards cleaner energy sources in the future.

Examining energy consumption in its aggregated and disaggregated form, an evidence for fossil fuel being a key driver of CO_2 emissions was found. Fossil fuel is considered as one of the major contributor of CO_2 and other greenhouse gases into the atmosphere. The cost of air pollution to the society are many, and a full accounting is beyond the scope of this study. The increased level of CO_2 emissions can be associated with the risk to affect agriculture, water resources, ecological systems, and human health, which in turn could undermine productivity, economic output, and strengthen existing inequalities (Bank et al., 2016; Samet et al., 2000). Precisely, the released pollutants directly and indirectly affect human health, causing various forms of cancer, depression, loss of life due to extreme weather conditions, and an uptake of diseases through food consumption (OECD, 2001). These impacts on public health from degradation of the environment could then in turn have negative effects on our society such as loss of quality of life, increased expenditure on health care but also in terms of loss of output and income. Since the impacts for our society could be very severe and substantial, different approaches are necessary to fight environmental degradation. As fossil fuel accounts for the majority of the total energy consumption, policymakers should target to reduce fossil fuel energy consumption massively (EIA, 2021c). To reduce the dependence on the consumption of fossil fuels, the US public energy policy is advised to take necessary actions such as introduction of appropriate regulations and incentives. This can be done by imposing carbon taxes or giving subsidies that promote green consumption. These interventions could have the potential to change energy consumption behavior and reduce CO_2-based energy consumption.

The second source of energy used in our analysis is nuclear energy consumption. Unlike fossil fuel, it was found to be negatively related with CO_2 emissions. Thus, we conclude that nuclear energy consumption could help reduce CO_2 emissions in the US. Recent studies conducted on nuclear energy consumption suggest that it is a better alternative compared to traditional energy sources when it comes to mitigating environmental degradation. However, the coefficient we obtained for nuclear energy use is quite small indicating a minor reduction in carbon emissions resulting from the use of nuclear energy. Other factors that are disadvantageous to switch to nuclear energy are the costs and technology associated with a nuclear power plant. Nuclear reactors are quite costly and require most sophisticated technologies to be installed and operated. Further, it should be mentioned that nuclear energy use also involves crucial risks such as the creation of radioactive waste if the reactor goes out of control (Ozcan, Ulucak, et al., 2020). Keeping in view the downsides of nuclear energy use, we do not recommend it as an ultimate solution to the problem at hand.

Thus, the most promising way to mitigate emissions in the long-run is the shift towards renewable energy consumption (Jin & Kim, 2018). Our results indicate that renewable energy use is significantly negatively related to CO_2 emissions in the long-run. This implies that renewable energy consumption can play an important role in reducing air pollution. An increase in the use of renewable and alternative energy sources i.e. wind power, hydro power, and solar energy could lead to a significant reduction of CO_2 emissions. It will be a huge step in the right direction to stop and slow down rapid environment degradation. Reduced CO_2 emissions and greenhouse gases will have a positive effect on global warming and will help to cure the deteriorated environment.

Moreover, an increase in economic output could likewise reduce air pollution, by an extended investment in clean, innovative, and more energy efficient technologies. Thus, adequately devised policies that tend to move the economy towards cleaner energy sources are necessary and ought to be devised to curtail carbon emissions. Our finding that an increase of economic activity results in a significant reduction of CO_2 emissions is a promising sign for the US. In the last few years we observed a rapid increase of investment in technology and clean energy infrastructure in the US. Nevertheless, there is still a need for improvement and call for interventions in order to achieve the climate targets such as limiting global temperature increase to 2 degrees Celsius under the Paris Agreement 2015.

Being the largest economy and energy consumer in the world, the US has a crucial role to play in promoting the importance of cleaner energy use and its benefits on the environment (World Bank, 2021e). The US can be a leading example for the world by increasing investment in energy efficient infrastructure and introducing energy conservation policies to reduce unnecessary energy waste. Improvement in energy efficiency means investment in energy efficient buildings, the promotion of the public transportation system and such other initiatives (Shafiei & Salim, 2014; Tzeremes, 2018). Policymakers are advised to take necessary actions and implement innovative technologies to achieve stronger emissions reductions. An increase investment in research & development activities is therefore necessary. More concretely, monitoring systems for CO_2 emissions, adequate environmental planning, development of advanced technologies, and research & development programs regarding pollution control should be introduced and intensified. Though the investment towards more sustainable and environment friendly solutions costs more upfront, they will prove to be fruitful in the long-term.

8. Conclusion

This study examines the relationship between energy consumption (aggregated and disaggregated), economic output, and CO_2 emissions for the US over the period of 1960-2015. More precisely, different models are investigated with the purpose to identify key drivers of CO_2 emissions. Firstly, the traditional EKC hypothesis was examined which provide evidence for the existence of an inverted U-shape curve. Secondly, energy consumption, in its aggregated form, was included in the model as a potential driver for environmental degradation where the presence of EKC was no longer observed. Lastly, constituents of energy consumption i.e. fossil fuel, nuclear, and renewable energy were added in the model to identify the primary source of energy use that causes CO_2 emissions. As most of the existing literature uses only aggregated energy data we make a strong contribution by considering energy consumption in its disaggregated form.

A thorough analytical approach was adopted to examine the long-run relationship between the aforementioned variables. Unit root tests were conducted in order to identify stationary properties of the time series. To discover possible cointegrating relationships, the Johansen cointegration method was exploited and a VECM was used to estimate short-run and long-run coefficients. Furthermore, causality between the variables was investigated using Granger causality tests.

According to the results obtained from the ADF and PP tests we claim that all variables are stationary in their first differences. For all investigated models the Johansen cointegration test indicate that the analyzed variables are cointegrated at 1% level of significance. The short-run and long-run estimates show that energy consumption and economic output are main causes of environmental degradation in the US. Examining energy consumption in its disaggregated form, an evidence for fossil fuel being an important driver of CO_2 emissions was found in the long-run. Including energy consumption or fossil fuel, respectively, we reject the modified form of the EKC hypothesis for the US. Determining the relationship of CO_2 emissions and GDP with nuclear and with renewable energy use we cannot reject the existence of the EKC and further provide evidence that EKC is rather long-run phenomena than short-run. Moreover, a significant negative effect of nuclear and renewable energy consumption on CO_2 emissions was identified. This is likewise supported by the Granger causality test. The stability tests indicate that all estimated models is stable over our sample period.

The results of this study validates the findings of some researches that have been undertaken on this subject, while refute the arguments of other. However, this study considers energy consumption in its disaggregated form and gets to the root of the source of CO_2 emissions. It is recommended that the US government should rightly steer energy consumption and economic output to curb CO_2 emissions. Reducing energy consumption from traditional energy sources (i.e. fossil fuel) and shifting towards renewable energy sources are the necessary steps required to mitigate CO_2 emissions. Introduction of energy efficient policies, the enhancement of alternatives and renewable energy use is likely to contribute to a decrease of carbon dioxide emissions in the US and help improving the deteriorated environment. Efforts must be made to encourage industries to adopt new and innovative technologies that help minimize pollution and abide by the recommendations of the different agreements such as the Paris Agreement 2015.

This analysis provides basis for further research into this topic where it could be extended in several ways. First, different indicators to measure economic activity, emissions, and energy consumption could be included. A promising extension would be to employ sulfur oxide, nitrous oxide, hazardous waste, water pollution, deforestation, and particulate matter as a different measurement of environmental degradation. Second, key source of carbon emissions could be identified by breaking energy consumption by economic sector (industry, transportation, residential etc.) and a detailed analysis can be conducted. Third, there are significant differences in the growth patterns of the eastern, central, and western provinces of the US. Therefore, it is important to expand the work of this study at federal state level to get further insight views. Fourth, as our analysis looks at the development before the US government committed to collectively combat climate change it might be of great interest to examine the period after the Paris Agreement 2015 in more detail.

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A. Appendix

Model (I):

$$\begin{aligned} \Delta CO_{2_t} = \alpha_1 &+ \sum_{i=1}^{p} \beta_{1i} \Delta CO_{2_{t-i}} + \sum_{i=1}^{q} \beta_{1i} \Delta GDP_{t-i} \\ &+ \sum_{i=1}^{r} \beta_{1i} \Delta GDP_{t-i}^2 + \lambda_1 ECT_{t-1} + u_{1t} \end{aligned} \tag{A.1}$$

$$\begin{aligned} \Delta GDP_t = \alpha_2 &+ \sum_{i=1}^{p} \beta_{2i} \Delta CO_{2_{t-i}} + \sum_{i=1}^{q} \beta_{2i} \Delta GDP_{t-i} \\ &+ \sum_{i=1}^{r} \beta_{2i} \Delta GDP_{t-i}^2 + \lambda_2 ECT_{t-1} + u_{2t} \end{aligned} \tag{A.2}$$

$$\begin{aligned} \Delta GDP_t^2 = \alpha_3 &+ \sum_{i=1}^{p} \beta_{3i} \Delta CO_{2_{t-i}} + \sum_{i=1}^{q} \beta_{3i} \Delta GDP_{t-i} \\ &+ \sum_{i=1}^{r} \beta_{3i} \Delta GDP_{t-i}^2 + \lambda_3 ECT_{t-1} + u_{3t} \end{aligned} \tag{A.3}$$

Table A.1: ARDL: Long-run estimates based on Aggregated Energy Consumption.

Dependent variable: CO_{2_t}; Long-run estimates & ECT			
Regressors	Coefficients	Standard errors	t-value
$Model(I)$			
GDP_t	0.876^{***}	0.146	5.99
GDP_t^2	-0.057^{***}	0.014	-4.12
ECT_{t-1}	-0.121^{**}	0.051	-2.37
$Model(II)$			
GDP_t	-1.335^{***}	0.249	-5.379
GDP_t^2	0.059^{***}	0.013	4.43
EN_t	1.171^{***}	0.131	8.97
ECT_{t-1}	-0.204^{**}	0.098	-2.09

Notes: ***, **, and * indicates the significance of coefficients at 1%, 5%, and 10% levels of significance, respectively. The optimal lag length was selected using the Akaike Information Criteria (AIC). Adjusted R^2 is 0.57 and 0.91 for Model (I) and Model (II), respectively.

Table A.2: Results of Johansen test for cointegration - sub-samples.

	Before 1^{st} oil shock	After 1^{st} Oil shock	Before 2^{nd} Oil shock	After 2^{nd} Oil shock	Before Financial Crisis
EN_t	Yes	Yes	Yes	Yes	Yes
FF_t	Yes	Yes	Yes	Yes	Yes
NEN_t	Yes	No	Yes	Yes	Yes
REN_t	Yes	Yes	Yes	Yes	Yes

Notes: The first oil price shock is denoted at 1973/74. Thus, we split the data at 1974. The second oil price shock is denoted around 1979/80. Thus, we divide the sample at 1980. Further, we investigate the period before (until 2007) the financial crisis separately. Due to limited data observations we cannot test for cointegration after the crisis (2007-2015).

Table A.3: Results of Zivot- Andrews unit root tests.

Variable	Level	First difference	Order of Integration
CO_{2_t}	-3.116	-4.831^{*}	$I(1)$
GDP_t	-4.928	-6.120^{***}	$I(1)$
GDP_t^2	-4.984	-6.064^{***}	$I(1)$
EN_t	-3.130	-6.849^{***}	$I(1)$
FF_t	-3.043	-5.220^{**}	$I(1)$
NEN_t	-6.490	-12.031^{***}	$I(1)$
REN_t	-3.553	-8.759^{***}	$I(1)$

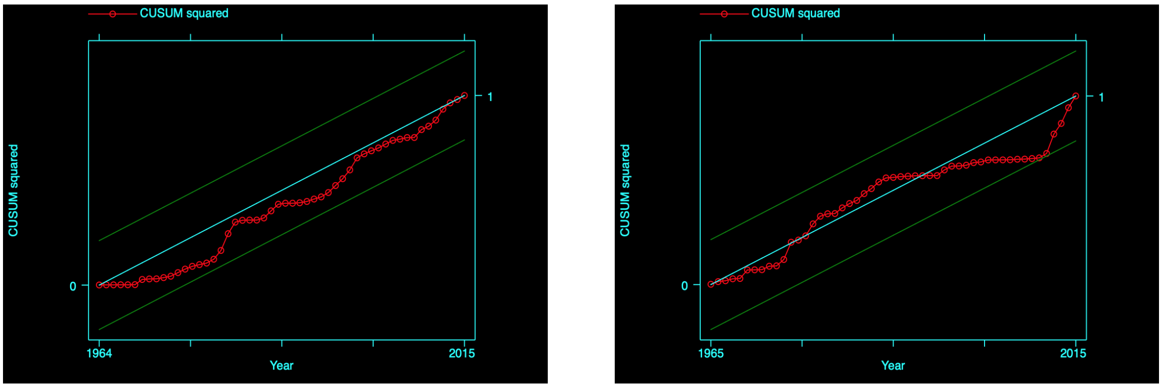
Notes: The regressions in level and in first difference include intercept and trend.***, **, and * indicates indicates the rejection of null hypothesis of non-stationary of the variable at 1%, 5%, and 10% levels of significance, respectively. The optimal lag length was selected using the AIC.

Table A.4: Pair-wise causality tests.

Variable	$\Delta CO_{2_{t-i}}$& ECT_{t-1}	ΔGDP_{t-i}& ECT_{t-1}	$\Delta EN_{k_{t-i}}$ & ECT_{t-1}
Total Energy use			
ΔCO_{2_t}	–	9.62^{**}	13.43^{***}
ΔGDP_t	2.12	–	2.16
ΔEN_t	7.33	6.29	–
Fossil Fuel			
ΔCO_{2_t}	–	12.19^{**}	8.88^{*}
ΔGDP_t	22.12^{***}	–	23.03^{***}
ΔFF_t	8.77^{*}	9.94^{**}	–
Nuclear			
ΔCO_{2_t}	–	11.39^{**}	9.83^{**}
ΔGDP_t	11.54^{**}	–	10.12
ΔNEN_t	5.41	5.00	–
Renewable			
ΔCO_{2_t}	–	11.56^{***}	6.22^{**}
ΔGDP_t	17.88^{***}	–	16.16^{***}
ΔREN_t	2.19	2.94	–

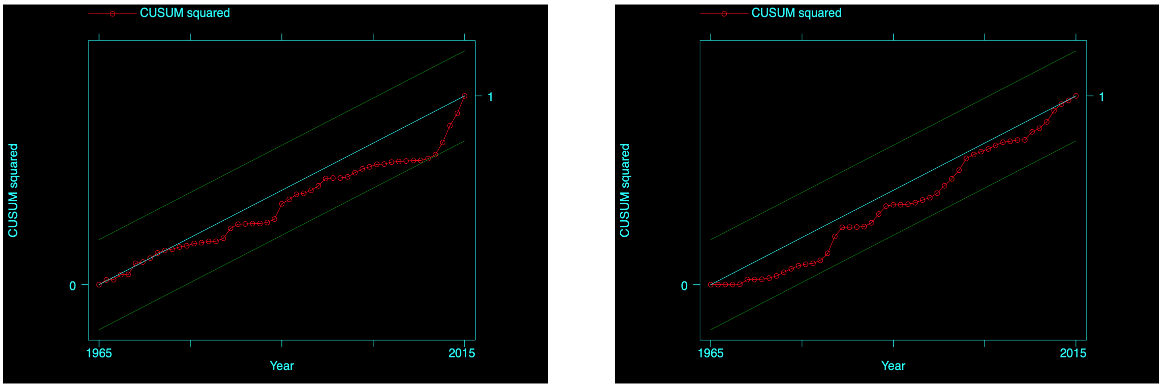
Notes: ***, **, and * indicates the significance of coefficients at 1%, 5%, and 10% levels of significance, respectively.

Figure A.1: CUSUMQ Test.



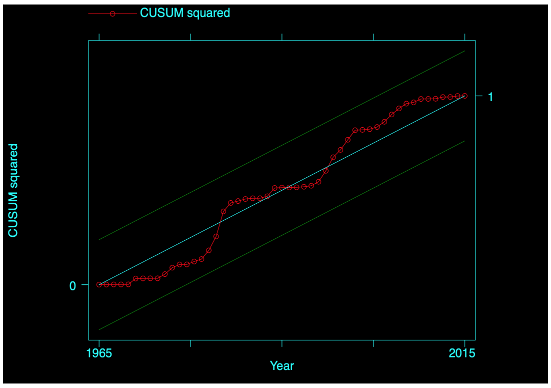
(a) Model (I).

(b) Aggregated Energy Consumption.



(c) Fossil Fuel.

(d) Nuclear.



(e) Renewable.