Bounds Testing Approach to Analyzing the Environment Kuznets Curve Hypothesis: The Role of Biomass Energy Consumption in the United States with Structural Breaks

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Abstract: This paper re-examines the specification of the environmental Kuznets curve (EKC) for the US economy by accounting for the presence of a major renewable energy source and trade openness over the period 1960-2016. Biomass energy consumption and trade openness as well as oil prices are considered as additional determinants of economic growth, and consequentially of CO_2 emissions. The bounds testing approach to cointegration is applied to examine the long-run relationship between the variables in the presence of structural breaks. The causal relationship between the variables is investigated by applying the VECM Granger causality test by accommodating structural breaks. The results confirm the presence of cointegration between the variables. Moreover, the relationship between economic growth and CO_2 emissions is not only inverted-U shaped but also N-shaped in the presence of structural breaks and biomass. Biomass energy consumption lowers CO_2 emissions. Exports, imports and trade openness are also environment- friendly. The causality analysis indicates a feedback effect between biomass energy consumption and CO_2 emissions. Economic growth still Granger causes CO_2 emissions in this new setup.

Keywords: EKC; Biomass energy; Oil prices; Trade openness; Structural breaks.

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1. Introduction

The environment has attracted unprecedented attention from ecologists, researchers and policymakers in recent years. While the objective of the diverse stakeholders is to maintain a high living standard and reduce global poverty, which can be considered justifiable ends in their own right, an unrestricted exploitation of natural resources could also cause an irrevocable loss to the biosphere and hurt the world's long-term economic and social development objectives. The catch lies in the fact that the environment cannot be sustained without sacrificing at least some of long-term growth and development objectives. Consequently, to satisfy some basic human needs, some damage to the environment is inevitable. Attitudes towards the environment vary substantially, particularly among policymakers. Even if the biosphere can be exploited in a variety of ways which lead to a range of consequences, many ecologists believe that the ecosystem could be managed in a way that it can adapt itself to continuously changing conditions (El-Kholy et al. 2012).

The environmental Kuznets curve (EKC), as a theory of the relationship between economic development and environmental quality, hypothesizes that over time that there will be a reduction in the level of emissions for most countries. This reduction can take place possibly because well developed economies should develop and raise sufficient revenues in the long-run to afford newer and cleaner technologies that can help abate pollution. Environmental degradation stands a huge cost in terms of health and life sacrifices. According to recent estimates, outdoor pollution kills more than three million people in the world every year, while many more people suffer from a range of diseases (OECD, 2014).

The prospects of long-term development are also hurt by the degradation of the quality of natural resources. Fisheries for example are damaged because of water pollution, and deforestation leads to erosion siltation, disrupts the hydrological cycle of major watersheds and reduces the productivity and returns of natural resources such as forests, agricultural lands and fisheries translates (Dixon et al., 2013). The catch lies in the fact that the objectives of sustainable development are often inconsistent with the goals of maintaining the affluent lifestyle of the developed world and reducing the poverty of the burgeoning masses in the developing world (See Daly 1991, Arrow et al. 1995). Economic growth is a precondition for effective poverty reduction initiatives (Bourguignon, 2004; Suryahadi et al., 2012; Thorbecke, 2013), but the increased revenues resulting from higher growth are used to pursue overly redistributive policies (Bhagwati and Panagariya, 2014). However, the existing development paradigm is unsustainable because it favors a level of prosperity, which invariably results in more consumption and greater pressure on natural resources (Aşıcı, 2013).

Sustainable economic growth depends on the availability of renewable energy sources, and the integrated development of such sources is essential for an environmentally friendly development of countries or regions. One of the widely used sources of renewable energy in the United States is biomass which is any organic (decomposable) matter derived from plants or animals, and hence is available on a renewable basis. Biomass includes wood and agricultural crops, herbaceous and woody energy crops and municipal organic wastes as well as manure. This renewable source of energy contains a complex mix of carbon, nitrogen, hydrogen and oxygen. Unlike the conventional fossil fuels such as petroleum and coal, biomass is a source of renewable energy based on the carbon cycle. Thus, in virtue of its abundant sources, biomass is likely to be a prevalent option for generating electricity in the future.

The study aims to examine the short- and -long run relationship between carbon emissions and their determinants in the presence of structural breaks and determine whether biomass energy consumption improves environmental quality by reducing carbon pollutants. It particularly seeks to discern whether the EKC hypothesis for economic growth and carbon exists in the presence of biomass consumption and trade openness. Finally, it strives to examine the causality between biomass energy consumption, trade openness and carbon emissions. To our knowledge, these multifaceted relationships of biomass energy consumption have not been addressed adequately in the existing literature. This paper makes the following five-fold contributions to the existing literature. (i) It uses biomass energy consumption as an indicator of renewable energy in an augmented carbon emissions function. (ii) It investigates the quadratic and cubic association between economic growth and carbon emissions in the presence of biomass energy and trade variables. (iii) It applies the single and double unknown structural break unit root test to estimate the unit root properties of the variables. (iv) It uses bounds testing approach to cointegration that accommodates structural breaks in the series to test whether cointegration exists or not. (v) It checks the causality between the variables by applying the VECM Granger causality test in the presence of structural breaks in the series.

The results find cointegration between carbon emissions and their determinants and highlight that biomass energy consumption improves environmental quality by lowering carbon emissions. Moreover, the relationship between economic growth and carbon emissions is inverted U-shaped (i.e. EKC exists) and N-shaped in the presence of biomass energy consumption and structural breaks. Additionally, trade openness (exports, imports) is inversely linked with carbon emissions in the presence of biomass energy consumption. The causality analysis demonstrates a feedback effect between biomass energy consumption and carbon emissions, while economic growth causes CO_2 emissions. The causal association between trade openness (exports, imports) and carbon emissions is bidirectional.

The remainder of study is organized as follows. Section-2 surveys the literature on EKC, biomass energy consumption and trade openness. Section-3 develops the empirical model and Section-4 presents the methodological framework. Section-5 discusses the empirical results. Section 6 provides the conclusion and policy implications.

2. Biomass energy consumption and regulations in the U.S.

In comparison with the other sources of energy, biomass provides a distinctive advantage with respect to maintaining the environment since it is "carbon neutral". Although the combustion of biomass generates as much carbon dioxide as fossil fuels do, CO_2 emissions released is removed when a new plant grows (Agbor et al. 2014; A-Mulali et al. 2016). In other words, some CO_2 emissions from one year's combustion of biomass are captured by future biomass crops through the process of photosynthesis. In relation to its energy uses by industry, biomass energy can be used for heat or power generation or for combined heat and power generation as a direct substitute for fossil fuels. In short, the biomass use is growing in significance as an input to a number of major functions of industries, ranging from research into an application of material inputs to industrial processes through to an implementation of mass produced intermediate and final products (Burritt and Schaltegger, 2012).

The potential benefits of biomass include an increase in the values of agricultural products and a support for farmers and the agricultural sector in both developed and developing countries, a potential reduction in greenhouse gases emissions relative to the petroleum-based fuels and an improved energy security for countries that grow their own feed stocks. Projected increases in biofuel trade are also considered a potential driver of economic growth in the tropics and subtropics regions, which are likely to hold a comparative advantage in feedstock production due to high biomass productivity (Marshall, 2007).

Biomass energy is one of the earliest and most primary sources of energy to provide processing and heat for industrial facilities in the United States. Historically in this country, it has come from three primary sources: wood, waste, and alcohol fuels. More recently, it has come from corn as well. Each of these forms of biomass energy (wood energy, waste energy and biofuel) is used in the United States. Collectively, they represent almost half of the total renewable energy production. Most electricity generation from wood biomass occurs at lumber and paper mills. These facilities use wood waste to provide much of their own steam and electricity needs.

The adoption of biomass has been increasing over the years in the United States. Biofuel production increased from 1,382 ktoe in 1990 to 3,000 ktoe in 2000, and further to 28,440 in 2013 (BP Statistical Review of World Energy, 2014). Over the years, the U.S. government has introduced several policies to improve the share of renewable energy in the total energy mix, including an increase in the use of biomass. For instance, the Renewable Portfolio Standard (RPS) policy, which is a state regulation, calls on electric utilities to ensure that a specific percentage of all produced electricity should come from renewable resources. The first RPS was ratified in Iowa in 1983, under a slightly different name, but with the same basic construction. The 1990s really sparked the adoption of RPS, as seven more U.S. states enacted RPSs of similar varieties. Currently there are 30 states, along with the District of Columbia, that have adopted some form of an RPS policy. RPS allows for ample state flexibility including a variation of different target goals and deadlines, market trading mechanisms and renewable energy types used to comply with the RPS policy. This flexibility makes this particular policy tool especially popular, as evident by the recent exponential increase in RPS adoption. Even though the adoption of RPS is becoming rather common, this policy tool is still relatively new, with few scholarly attempts at ascertaining the results of its implementation (Eastin et al., 2014).

The second policy is the renewable fuel standard (RFS) program, which is a national policy that requires a certain volume of renewable fuels to replace or reduce the quantity of petroleum-based transportation fuel, heating oil or jet fuel. The Congress created this program as part of the Energy Policy Act in 2005 in an effort to reduce greenhouse gases emissions and expand the nation's renewable fuels sector, while reducing reliance on imported oil (Barbos et al., 2011). The RFS program was expanded under the Energy Independence and Security Act of 2007. The RFS was conceived by policy makers as a tool to reduce the demand for transportation fuels derived from foreign oil by stimulating the production of domestic biofuels that could be mixed with or replace gasoline at a time when foreign imports and prices were at or near all-time highs. The RFS, administered by the US Environmental Protection Agency (EPA), mandates the annual minimum volumes of biofuels across four nested categories that must be incorporated into the nation's transportation fuel supply. The biofuel categories include total renewable fuels, advanced renewable fuels, cellulosic biofuel, and biomass-based biodiesel. It also requires electricity providers to acquire specific amounts of renewable energy generation over time which are prevalent within the United States (Barbos et al., 2011).

The government has also introduced several additional policies including the Production Tax Credit or PTC, which is a per-kilowatt-hour tax credit for electricity generated (through renewable energy sources including biomass) by qualified energy resources and is paid for by the U.S. taxpayers. These policies also include the Investment Tax Credit or ITC, which allows the tax credit to be taken based on the amount invested rather than electricity produced. They also include the Modified Accelerated Cost Recovery System Depreciation Schedule or MACRS, which gives bonus depreciations and reduces taxes on large biomass projects (Zhou et al. 2016).

3. Literature review

The issues of climate change and carbon dioxide emissions are at the forefront of policy debates in both developed and developing countries. Correspondingly, there is now a vast literature on the determinants of emissions (including income and energy prices among others), with the majority of the studies utilizing the EKC hypothesis in the analyses, which have often yielded mixed and conflicting results. The literature on EKC has expanded so much that even causality techniques are now used to infer the presence of the EKC (Soytas and Sari 2007; Dogan and Turkekul, 2016). Due to the lack of available data, some studies have traditionally estimated the EKCs with cross-country panel data. Given that the quality of such data is often questionable, the empirical results obtained may be a suspect. Furthermore, since the common method of estimation with panel data assumes that all cross-sections adhere to the same EKC, it may be unreasonable to impose isomorphic EKCs if cross-sections vary in terms of resource endowments, infrastructure, etc. (List and Gallet, 1999)[1]. We classify the considered literature under three strands: income and emissions; energy consumption and income; and energy consumption, income and carbon emissions.

3.1 Income and emissions

This first strand of the literature has considered income as the only determinant of emissions within the EKC framework in the United States. For instance, Unruh and Moomaw (1998) utilize graphical analysis to examine the presence of EKC for 16 countries including the United States. Using a data set for the period 1950-1990, these authors are able to provide evidence of the presence of EKC in the U.S. Subsequently, List and Gallet (1999) analyze the presence of EKC in the 50 U.S. states by using the ordinary least square (OLS) technique for the period 1929-1994. They confirm the presence of EKC in 18 states when income and income squared are entered as independent variables, with the mono-nitrogen oxides serving as the indicator of emissions. However, when income and income squared are entered as independent variables, and with sulfur dioxide serving as the indicator of emissions, they notice the presence of the N-shaped for 10 states.

3.2 Energy and income

The papers on the causal relationship between energy consumption (or its various components) and real GDP constitute the bulk of the existing literature that uses the bivariate and multivariate approaches. This strand is also the earliest part of the literature dating back to 1978. We will focus on this aspect of the literature because it is believed that energy consumption and real income are associated with emissions. The earliest papers have utilized the bivariate approach to consider the relation between energy consumption and economic growth but provided inconclusive empirical results for the US economy [2].

[1] In this paper, we concentrate on the time series literature associated with the concept of EKC in the United States. In the cases where the study involves a multi-country data set, we only report the results for the United States.

[2] For example, Kraft and Kraft (1978), Akarca and Long (1979), Erol and Yu (1987a, b), Yu et al. (1988), Lee (2006), Chiou-Wei et al. (2008), Balcilar et al. (2010), Hatemi-J and Uddin (2012) and Ozcan and Ari (2015).

The earliest studies that also looked at the relationship from a multivariate perspective including Glasure and Lee (1995) which added the ratio of wages and energy prices as control variables for the period 1973:M_1-1984:M_6. Using the Engle and Granger (1987) method, their findings provide evidence that supports the neutrality hypothesis. Similarly, Stern (2000) employs the Johansen (1988) and Johansen and Juselius (1990) to examine the relationship between energy use, capital, labor and real GDP for the period 1947-1994 and the empirical findings provide evidence supporting a unidirectional causality from energy use to economic growth. Thoma (2004) analyzes the causality involving industrial production as well as total electricity usage and electricity usage in commercial, industrial, residential and other sectors for the period 1973M_1-2000M_1. Using the Engle and Granger (1987) method and the Granger causality test, the authors' results support the existence of a unidirectional causality running from economic growth to electrical usage.

Soytas and Sari (2006) utilize the dataset of seven countries to explore the causal relationship between total energy consumption, energy consumption, capital stock, labour force and real GDP per capita during the period 1960-2004. They use the Johansen and Juselius (1990) approach to show a unidirectional causality running from energy consumption to real GDP. Narayan and Prasad (2008) investigate the causal relationship between electricity consumption and real GDP, using the Hacker and Hatemi-J (2006) causality test but find no causality between the variables. In a series of related papers, Bowden and Payne (2009) and Payne (2009a) use different indicators of energy consumption such as primary energy (and usage in various sectors), renewable and non-renewable energy consumption; and nuclear energy, respectively. Their empirical findings provide evidence of no causality in the case of the total and transportation primary energy consumption, renewable and non-renewable energy consumption and nuclear energy. There is a unidirectional causality running from industrial production to primary energy consumption and a bidirectional causality in the case of commercial and residential primary energy consumption. Payne (2009b) supports the growth-hypothesis i.e. energy consumption causes economic growth in the case of the U.S. state of Illinois.

Wolde-Rufael and Menyah (2010) utilize the Toda and Yamamoto (1995) to examine the causality involving nuclear energy consumption and economic growth, while controlling for capital stock and labour in nine developed countries for the period 1971-2005. Their results yield support for a bidirectional causality in the United States. Lee and Chiu (2011) show no support for a causality between nuclear energy consumption and economic growth, but a support for the growth hypothesis in the case of oil consumption. Gross (2012) uses total energy consumption, and energy consumption in the industrial, commercial and transportation sectors as indicators for energy consumption. The results suggest no causality in the total energy consumption, the industrial sector and the commercial sector but a bidirectional causality in the transportation sector. Tugcu et al. (2012) provide mixed evidence of no causality and a bidirectional causality. Kum et al. (2012) consider the causal relationship between natural gas consumption and economic growth in the G-7 countries during the period 1970-2008. By using the Hacker and Hatemi-J (2006) causality tests, their results reveal evidence of a bidirectional causality between natural gas consumption and economic growth.

Yildirim et al. (2012) utilize the Hacker and Hatemi-J (2006) method to examine the causal relationship in various indicators of energy consumption, employment, investment and real GDP for the period 1949–2010. The empirical findings reveal a unidirectional causality from energy consumption to economic growth in the case of the biomass-waste-derived energy consumption and no causality in the case of the total renewable energy consumption, geothermal energy consumption, hydro-electric energy consumption, biomass energy consumption and biomass-wood-derived energy consumption. Tiwari (2014) provides similar evidence for coal consumption, natural gas consumption, primary energy consumption, total renewable energy consumption and total electricity consumption as indicators of energy consumption in the U.S.

3.3 Energy, income and emissions

The most comprehensive strand in the existing literature is the one that integrates energy consumption, income and emissions into the same model. However, this strand has only gained popularity recently, with very few studies in this area. Conventional studies have used the normal regression and also causality analysis to infer the existence of EKC. Soytas et al. (2007) is one of the earliest studies to integrate energy consumption, income and emissions in one function for the U.S. The authors utilize the Toda and Yamamoto (1995) method to explore the relationship between income, energy consumption, carbon emissions, labor and capital. There is evidence of a causality flowing from energy consumption to emissions but no causality between real GDP and emissions, and between energy consumption and real GDP. Since no causality flows from real GDP to emissions, the authors conclude that there is no EKC in the U.S. Menyah and Wolde-Rufael (2010) analyze the causal relationship between CO_2 emissions, renewable and nuclear energy consumption and real GDP and the results support the presence of a bidirectional causality between CO_2 emissions and income. Burnett et al. (2013) utilize a dataset of the U.S. for the period $1981Q_1$-$2003Q_4$ to examine the relationship between carbon dioxide emissions, personal income and energy production. Using the Dynamic OLS of Stock and Watson (1993), the results show there is no EKC.

In another recent study, Dogan and Turkekul (2016) examine the existence of EKC in the U.S. for the period 1960–2010 in a multivariate framework that includes emissions per capita, energy consumption per capita, real output per capita, trade openness, urbanization and financial development by employing the ARDL bounds testing approach of Pesaran et al. (2001) and the Granger causality test. Their results suggest a bidirectional causality between energy consumption and emissions and between income and emissions. The coefficient suggests that income decreases emissions but income square increases emissions.

None of the foregoing papers examines the EKC hypothesis in the presence of biomass energy consumption. With the exception of Dogan and Turkekul (2016), none of the previous papers have utilized both the regression analysis and causality analysis. Table-1 presents a summary of studies investigating association between economic growth and carbon emissions in the case of the U.S. economy for the three strands of the existing literature.

Table-1: Summary of literature review

Panel A: Income and emission							
No.	Authors	Dataset	Period	Method	Variables	EKC	Causal relationship
1	Unruh and Moomaw (1998)	16 countries	1950–1992	Descriptive analysis	CO2 emissions per capita, real GDP	Yes	N/A
2	List and Gallet (1999)	50 states	1929–1994	OLS	Mono-nitrogen oxides; Sulfur dioxide; real GDP; real GDP square; real GDP cubic	Yes in 18 states for mono-nitrogen oxides without a real GDP cubic; 0 in mono-nitrogen oxides with real GDP cubic 16 in Sulfur dioxide without real GDP cubic; 10 in Sulfur dioxide with real GDP cubic	
Panel B: Energy and income							
No.	Authors	Dataset	Period	Method	Variables	EKC	Causal relationship
3	Kraft and Kraft (1978)	U.S.	1947–1974	Sims causality	Energy consumption; GNP	N/A	Y→E
4	Akarca and Long (1979)	U.S.	1973:M1-1978:M3	Granger causality test	Energy consumption; Employment	N/A	E→Y
5	Erol and Yu (1987a)	U.S.	1973:M1-1984:M6	Sims causality test	Energy consumption; employment	N/A	E‡Y
6	Yu et al. (1988)	U.S.	1973:M1-1984:M6	Sims causality test; Granger causality test	Energy consumption; total employment; non-farm employment	N/A	E‡Y for total employment; Mixed result for non-farm employment
7	Glasure and Lee (1995)	U.S.	1973:M1-1984:M6	Engle-Granger	Energy consumption; total employment; non-farm employment; Ratio of wages; energy prices	N/A	E‡Y
8	Stern (2000)	U.S.	1947-1994	Johansen test	Energy use, capital; labour inputs; real GDP	N/A	E→Y
9	Thoma (2004)	commercial, industrial, residential other sectors; and total electrical energy usage	1973M1–2000M1	Engle and Granger; Granger causality test	Electrical energy usage; industrial production	N/A	Y→E for commercial, industrial, and total electrical energy usage; E‡Y for residential and other electrical energy usage
10	Lee (2006)	G-11	1960–2001	Toda and Yamamoto	Energy consumption; real GDP per capita	N/A	E↔Y
11	Soytas and Sari (2006)	G-7	1960-2004	Johansen; VECM Granger causality test	Energy consumption; capital; labour force; real GDP per capita	N/A	E→Y

12	Chiou-Wei et al. (2008)	9 countries	1954-2006	Johansen test; Hiemstra and Jones causality test,	Energy consumption; real GDP.	N/A	E‡Y
13	Narayan and Prasad (2008)	30 OECD countries	1970–2002	Hacker and Hatemi-J	Electricity consumption; real GDP.	N/A	E‡Y
14	Bowden and Payne (2009)	U.S.	1949-2006	Toda and Yamamoto	Industrial energy consumption; commercial energy consumption; residential energy consumption; and transportation consumption; total energy consumption; capital; labor; real GDP.	N/A	E→Y\for industrial energy consumption; E↔Y for commercial energy consumption; residential primary energy consumption E‡Y for total energy consumption; transportation primary energy consumption; renewable and non-renewable energy consumption.
15	Payne (2009a)	U.S.	1949-2006	Toda and Yamamoto	Renewable energy consumption; non-renewable energy consumption; capital; labour; real GDP.	N/A	E‡Y
16	Payne (2009b)	Illinois	1976-2006	Toda and Yamamoto	Illinois total energy consumption; Illinois total nonfarm employment; US total nonfarm employment.	N/A	E→Y
17	Balcilar et al. (2010)	G-7	1960-2006	Toda and Yamamoto	Total energy consumption; real GDP.	N/A	E‡Y
18	Wolde-Rufael and Menyah (2010)	Nine Developed countries	1971-2005	Toda and Yamamoto	Nuclear energy consumption; capital; labor; real GDP	N/A	E↔Y
19	Lee and Chiu (2011)	G-6	1965–2008	Johansen test; Toda and Yamamoto (1995)	Nuclear energy consumption; real oil price; oil consumption; real GDP.	N/A	E‡Y for nuclear consumption; E→Y for oil consumption.
20	Gross (2012)	Industry sector, commercial sector, transport sector, as the macro level	1970-2007	ARDL bounds testing approach; VECM Granger causality	Final energy consumption; trade; capital; real GDP; sectoral value added.	N/A	E‡Yfor Industry sector, commercial sector, macro level; E↔Y for transport sector.
21	Tugcu et al. (2012)	G-7	1980–2009	ARDL bounds testing approach; Hatemi-J	Real GDP; physical capital; labour force; research and development; human capita;	N/A	E↔Y for classical production function; E‡Y for augmented

					renewable energy consumption; non-renewable energy. consumption		production function.
22	Kum et al. (2012)	G-7	1970–2008	Hacker and Hatemi-J	Natural gas consumption; capital; GDP.	N/A	E↔Y
23	Yildirim et al. (2012)	U.S.	1949–2010	Hacker and Hatemi-J	Total renewable energy consumption; geothermal energy consumption; hydroelectric energy consumption; biomass energy consumption; biomass-wood-derived energy consumption; Employment; capital; real GDP.	N/A	E→Y for biomass-waste-derived energy consumption E‡Y for total renewable energy consumption; geothermal energy consumption; hydroelectric energy consumption; biomass energy consumption and biomass-wood-derived energy consumption.
24	Hatemi-J, and Uddin (2012)	U.S.	1960-2007	Hatemi-J	energy consumption per capita; real GDP per capita.	N/A	E→Y
25	Tiwari (2014)	U.S.	1973M1-2011M10	Granger Causality	coal consumption; natural gas consumption; primary energy consumption; total renewable energy consumption; total electricity end use; real GDP.	N/A	E↔Y
26	Ozcan and Ari (2015)	15 OECD countries	1980-2012	Hacker and Hatemi-J	Nuclear energy consumption; real GDP	N/A	Y→E
Panel C: Energy, income and emission							
No.	Authors	Dataset	Period	Method	Variables	EKC	Causal relationship
27	Soytas et al. (2007)	U.S.	1960–2004	Toda and Yamamoto	energy consumption; carbon emissions; labor; capital; real GDP.	No	E→C Y‡C E‡Y
28	Menyah and Wolde-Rufael (2010)	U.S.	1960-2007	Toda and Yamamoto	Emission; renewable energy consumption; nuclear energy consumption; real GDP.	N/A	Y↔C E→C for nuclear consumption; C→E for renewable consumption; E‡Y for nuclear consumption; Y→E for renewable consumption.
29	Burnett et al. (2013)	U.S.	1981Q1-2003Q4	DOLS	Emissions; personal income; energy production	No	N/A
30	Dogan and Turkekul (2016)	U.S.	1960–2010	ARDL bounds testing	Emissions per capita; energy consumption per	No	Y↔C E↔C Y→E

				approach; VECM Granger causality	capita; real GDP per capita; square of real GDP; trade openness ratio; urbanization ratio; financial development;.		

3.4 Biomass energy and emissions

Very few studies have investigated the association between biomass energy consumption and carbon emissions for Turkey and U.S. economies, using trivariate and bivariate models accordingly. For instance, Katircioglu (2015) employs the carbon emissions function by including biomass energy and fossil fuel consumption. The empirical evidence indicates that the use of biomass energy is environment-friendly, but on the other hand fossil fuel consumption adds to carbon emissions. Bilgili et al. (2016) apply the wavelet coherence approach to investigate the impact of biomass energy consumption on CO_2 emissions, and their empirical results show that biomass energy consumption improves environmental quality by lowering carbon emissions after 2005. Using a trivariate model, Bilgili (2016) validates that biomass energy consumption reduces carbon emissions but fossil fuels consumption increases it. We may note that empirical findings of such studies are ambiguous due to the negligence of other potential variables such as economic growth and trade openness that are relevant in the analysis. This study fulfils a gap in the literature by investigating the association between biomass energy consumption and carbon emissions and incorporating economic growth and trade openness as additional determinants of carbon emissions in a multivariate framework.

4. Data and model construction

The study covers the period 1960-2016 to investigate the presence of the environmental Kuznets curve in the presence of biomass energy consumption and trade openness for the U.S. economy. We have utilized the World Development Indicators (WDI, 2016) to collect data on real GDP (constant 2010 US$), exports (constant 2010 US$), imports (constant 2010 US$) and trade (export + imports)[3]. The data on CO_2 emissions (metric tons) is also collected from World Development Indicators (WDI, 2016). Biomass energy consumption is collected from

[3] We have used three indicators of trade openness i.e. exports, imports and trade.

materialflows.net. We have transformed all the variables into the log-form after converting all the series into per capita unit following Ahmed et al. (2015) and others.

Katircioglu (2015), Bilgili (2016) and Bilgili et al. (2016) investigate the impact of biomass energy consumption on CO_2 emissions. Their analysis may provide misleading results because it does not incorporate the other relevant factors of CO_2 emissions such as exports, imports and trade openness, along with energy consumption and economic growth. We have incorporated biomass energy consumption, oil prices and trade openness into the carbon emissions function as potential determinants of CO_2 emissions. Trade openness affects carbon emissions via income, technique and composition effects (Ling et al. 2015). Oil prices may affect carbon emissions positively or negatively. A rise in oil prices increases the demand for other fossil fuels and renewable energy giving rise to mixed results. If the rise in oil price increases the demand for coal, carbon emissions will rise because coal generates more emissions than oil. If the rise in oil prices increases demand for renewable energy, carbon emissions might fall because renewable energy inclusive of biomass generate less emissions than oil (Chai et al. 2016).

This study fills the gap in the existing energy literature by investigating the environmental Kuznets curve in the presence of biomass energy consumption, oil prices and trade openness for US economy. The general functional form of the model is constructed as follows:

$$C_t = f(E_t, Y_t, Y_t^2,\ \mathrm{O_t}, \mathrm{TR_t},\ \mathrm{TR_t^2}) \tag{1}$$

where is C_t stands for CO_2 emissions per capita , E_t is biomass energy consumption per capita, Yt is real GDP per capita, Y_t^2 is square of real GDP per capita, O_t is oil prices, TR_t is real trade per capita and TR_t^2 is the square of real trade per capita.

The log-linear specification is employed to examine the presence of the environmental Kuznets curve. The empirical equation of the general carbon emissions function is formulated as follows:

$$\ln C_t = \alpha_1 + \alpha_E \ln E_t + \alpha_Y \ln Y_t + \alpha_{Y^2} \ln Y_t^2 + \alpha_o \ln O_t + \alpha_{TR} \ln TR_t + \alpha_{TR^2} \ln TR_t^2 + \mu_t \tag{2}$$

where $\ln$, C_t, E_t, $Y_t\,(Y_t^2)$, O_t and $TR_t\,(TR_t^2)$ indicate the natural-log of those variables as defended earlier,[4] while μ_t is the error term which is assumed to have a normal distribution.

We expect $\alpha_E < 0$ if biomass energy consumption is environment friendly; otherwise $\alpha_E > 0$ which makes biomass consumption hurting the environment (Katircioglu 2015, Bilgili 2016). The relationship between economic growth and carbon emissions is viewed as an inverted-U shaped if $\alpha_Y > 0$ and $\alpha_{Y^2} < 0$, but it will be seen as a U-shaped if $\alpha_Y < 0$ and $\alpha_{Y^2} > 0$. Moreover, the relationship between trade openness and carbon emission is U-shaped if $\alpha_{TR} < 0$ and $\alpha_{TR^2} > 0$ otherwise inverted U-shaped[5]. We expect $\alpha_O < 0$ if oil prices are inversely linked with carbon emissions, otherwise $\alpha_O > 0$.

Cole et al. (2006) claim that a quadratic specification on the relationship between economic growth and carbon emissions provides ambiguous empirical results. They argue that carbon emissions or environmental degradation may likely become zero or negative after a new threshold level of income per capita is reached[6]. This quadratic relationship between economic growth and environmental degradation is termed 'symmetric' by Sengupta (1996), which argues that after a threshold level of real income per capita, a rise or a fall in CO_2 emissions remains the same. Therefore, Moomaw and Unruh, (1997) recommend to use the cubic specification of the relationship between economic growth and carbon emissions. The augmented EKC empirical equation is modeled as follows:

$$\ln C_t = \beta_1 + \beta_E \ln E_t + \beta_Y \ln Y_t + \beta_{Y^2} \ln Y_t^2 + \beta_{Y^3} \ln Y_t^3 + \beta_o \ln O + \beta_{TR} \ln TR_t + \beta_{TR^2} \ln TR_t^2 + \mu_t \quad (3)$$

The association between economic growth and CO_2 emissions is an N-shaped if $\beta_Y > 0$, $\beta_{Y^2} < 0$, $\beta_{Y^3} > 0$. Moomaw and Unruh (1997) and Friedl and Getzner (2003) argue that after, a second threshold level of real income per capita, if CO_2 emissions start to increase then a N-shaped relationship between economic growth and carbon emissions exists. This reveals that an

[4] We have also used exports and imports as indicators of trade openness to test the robustness of empirical results.

[5] If the technique effect dominates the scale effect then trade openness improves the environment; otherwise trade openness worsens environmental quality if the scale effect is more than the technique effect.

[6] Hence, we have not seen any nation who grows rapidly with zero carbon emissions.

increase in carbon emissions would be temporary and may be due to factors other than growth contributing to a rise in CO_2 emissions (Friedl and Getzner, 2003).

5. Methodological strategy

5.I ARDL bounds testing approach

Although the applied economics literature provides many approaches to examining cointegration between energy variables, we prefer to use the autoregressive distributed lag or the ARDL model or the bounds testing approach to cointegration to avoid the criticism of using conventional cointegration tests due to their shortcomings. It also captures short run and long run relationships. This approach is also flexible regarding the order of integration of the variables. We may apply the bounds testing approach to cointegration if the variables are integrated of I(1) or I(0) or I(1) / I(0). Pesaran and Shin (1999) also posit that this Monte Carlo approach is more efficient than conventional cointegration approaches. This approach provides more consistent empirical results for small samples (Pesaran and Shin, 1999). The ARDL bounds testing via simple linear transformations is used to reach the dynamic unrestricted error-correction model (UECM). The UECM presents the short-run dynamics and long-run equilibrium path without affecting the long-run information.

The empirical equation of the ARDL bounds testing approach under the UECM framework is presented below:

$$
\begin{aligned}
\Delta \ln C_t &= \alpha_1 + \alpha_T T + \alpha_Y \ln Y_{t-1} + \alpha_{Y^2} \ln Y_{t-1}^2 \left[\alpha_{Y3} \ln Y_{t-1}^3\right] + \alpha_E \ln E_{t-1} + \alpha_O \ln O_{t-1} + \alpha_{TR} \ln TR_{t-1} \\
&+ \alpha_{TR^2} \ln TR_{t-1}^2 + \sum_{i=1}^{p} \alpha_i \Delta \ln C_{t-i} + \sum_{j=0}^{q} \alpha_j \Delta \ln Y_{t-j} + \sum_{k=0}^{r} \alpha_k \Delta \ln Y_{t-1}^2 \left[\sum_{k=0}^{r} \alpha_k \Delta \ln Y_{t-1}^3\right] + \sum_{l=0}^{s} \alpha_l \Delta \ln E_{t-l} \qquad (4) \\
&+ \sum_{j=0}^{s} \alpha_j \Delta \ln O_{t-j} + \sum_{l=0}^{s} \alpha_l \Delta \ln TR_{t-l} + \sum_{m=0}^{s} \alpha_m \Delta \ln TR_{t-m}^2 + \mu_t
\end{aligned}
$$

The next step is to compute the F-statistic for comparison with the critical bounds generated by Pesaran et al. (2001) in order to make decisions on the existence of cointegration. The appropriate choice of the lag length also matters. The F-statistic varies at various lag orders. In doing so, we have used the Akaike Information Criterion (AIC) due to its superior power properties. The Wald-test is used to compute the ARDL-F statistics. We test the null hypothesis i.e. $H_0 : \alpha_c = \alpha_Y = \alpha_{Y^2}[\alpha_{Y^3}] = \alpha_E = \alpha_O = \alpha_{TR} = \alpha_{TR^2} = 0$ of no cointegration for Equation (4) against the alternative hypothesis $H_a : \alpha_c \neq \alpha_Y \neq \alpha_{Y^2}[\alpha_{Y^3}] \neq \alpha_E \neq \alpha_O \neq \alpha_{TR} \neq \alpha_{TR^2} \neq 0$).

The test will favor the presence of cointegration between the variables if the computed ARDL-F statistic is more than the upper critical bound. However, the decision would be no cointegration between the variables if the lower critical bound is greater than the calculated ARDL-F statistic and would be inconclusive if the computed ARDL-F statistic is between the lower and upper critical bounds. We use the critical bounds generated by Narayan (2005) because the data sample is small (i.e. 54 observations) and in this case the critical bounds tabulated by Pesaran et al. (2001) are not suitable. The stability of the bounds testing approach estimated is tested by applying CUSUM and CUSUMsq suggested by Brown et al. (1975).

We apply the ARDL bounds testing approach in order to examine the presence of cointegration between the variables. If the existence of cointegration between the variables is confirmed, we then estimate the long-run impact of economic growth (Y_t), biomass energy consumption (E_t), oil prices (O_t) and trade openness (TR_t) on carbon emissions (C_t) by following Equation (5):

$$\ln C_t = \theta_0 + \theta_1 \ln Y_t + \theta_2 \ln Y_{t-1}^2 [Y_{t-1}^3] + \theta_3 \ln E_t + \theta_4 \ln O_t + \theta_5 \ln TR_t + \theta_6 \ln TR_t^2 + \mu_i \qquad (5)$$

where

$\theta_0 = -\alpha_1 / \alpha_C, \theta_1 = -\alpha_Y / \alpha_1, \theta_2 = -\alpha_{Y^2[Y^3]} / \alpha_1, \theta_3 = -\alpha_E / \alpha_1, \theta_4 = -\alpha_O / \alpha_1, \theta_5 = -\alpha_{TR} / \alpha_1, \theta_6 - \alpha_{TR^2} / \alpha_1$ and μ_t is the error term assumed of having normal distribution. We apply a similar approach with various proxies of trade openness (exports, imports, trade) to examine the association between CO_2 emissions, economic growth, biomass energy consumption, oil prices and trade openness for the U.S. economy.

4.2 The VECM Granger causality approach

We apply the vector error correction model (VECM) version of Granger causality to test the direction of the causal relationship after confirming the long-run association between the variables. The empirical equation of the VECM Granger causality is modelled as follows:

$$(1-L)\begin{bmatrix}\ln C_t\\ \ln Y_t\\ \ln Y_{t-1}^2[Y_{t-1}^3]\\ \ln E_t\\ \ln O_t\\ \ln TR_t[\ln TR_t^2]\end{bmatrix}=\begin{bmatrix}a_1\\ a_2\\ a_3[a_4]\\ a_5\\ a_6\\ a_7[a_8]\end{bmatrix}+\sum_{i=1}^{p}(1-L)\begin{bmatrix}b_{11i}b_{12i}b_{13i}b_{14i}\,b_{15i}\,b_{16i}\\ b_{21i}b_{22i}b_{23i}b_{24i}\,b_{25i}\,b_{26i}\\ b_{31i}b_{32i}b_{33i}b_{34i}\,b_{35i}\,b_{36i}\\ b_{41i}b_{42i}b_{43i}b_{44i}\,b_{45i}\,b_{46i}\\ b_{51i}b_{52i}b_{53i}b_{54i}\,b_{55i}\,b_{56i}\\ b_{61i}b_{62i}b_{63i}b_{64i}\,b_{65i}\,b_{66i}\end{bmatrix}\times\begin{bmatrix}\ln C_t\\ \ln Y_t\\ \ln Y_{t-1}^2[Y_{t-1}^3]\\ \ln E_t\\ \ln O_t\\ \ln TR_t[\ln TR_t^2]\end{bmatrix}+\begin{bmatrix}\alpha\\ \beta\\ \delta[\phi]\\ \Phi\\ \theta\\ \omega[\lambda]\end{bmatrix}ECT_{t-1}+\begin{bmatrix}\varepsilon_{1t}\\ \varepsilon_{2t}\\ \varepsilon_{3t}[\varepsilon_{4t}]\\ \varepsilon_{5t}\\ \varepsilon_{6t}\\ \varepsilon_{7t}[\varepsilon_{8t}]\end{bmatrix}\quad(6)$$

where $(1-L)$ is the difference operator. The lagged residual term i.e. ECT_{t-1} is derived from the long-run relationship. The error terms are shown by $\varepsilon_{1t},\varepsilon_{2t},\varepsilon_{3t},\varepsilon_{4t},\varepsilon_{5t},\varepsilon_{6t},\varepsilon_{7t}$ and ε_{8t}. The long-run causality is derived from the significance value of the coefficient for ECM_{t-1} through using the *t*-test statistic. The direction of the short-run causality between the variables is judged through using the *F*-statistic for the first differenced lagged independent variables.

6. Empirical results

Table 2 presents the descriptive statistics and the historical correlation analysis. We note that all the variables have normal distributions as confirmed by the Jaque-Bera test. In the correlation analysis, the presence of negative correlation is noted between biomass energy consumption and CO_2 emissions, indicating that this renewable energy consumption lowers carbon missions due to the absorption of CO_2 emissions by new tree growth. On the other hand, a positive correlation exists between economic growth and CO_2 emissions. Further, oil prices and CO_2 emissions are positively correlated. The correlations of exports, imports and trade with CO_2 emissions are also negative, again highlighting the importance of trade to environment by providing better technologies to control pollution. Biomass energy consumption as well as exports, imports and trade is positively correlated with economic growth, underlying the fact that biomass energy consumption is a normal good. Exports, imports and trade are also positively correlated with biomass energy consumption. A negative correlation exists for oil prices with economic growth, exports, imports and trade openness. Finally, biomass energy consumption is positively correlated with oil prices.

Table-2: Descriptive statistics and correlation analysis

Variables	$\ln C_t$	$\ln E_t$	$\ln Y_t$	$\ln O_t$	$\ln TR_t$	$\ln EX_t$	$\ln IM_t$
Mean	2.9543	16.1201	10.3118	3.6190	8.0047	7.2466	7.3632
Median	2.9626	16.2037	10.3688	3.5973	8.3148	7.5057	7.7257
Maximum	3.1139	16.5582	10.7802	4.7468	9.9645	9.1528	9.3773
Minimum	2.7042	15.7242	9.6252	2.3786	4.6319	4.2223	3.5415
Std. Dev.	0.0821	0.2602	0.3392	0.7523	1.3873	1.3028	1.4726
Skewness	-0.7035	-0.2402	-0.3305	-0.1123	-0.5188	-0.4736	-0.5786
Kurtosis	3.9470	1.7445	1.9400	1.7531	2.1741	2.0998	2.3177
Jarque-Bera	4.0322	4.2916	3.7063	3.8122	4.1776	4.0558	4.2865
Probability	0.1328	0.1169	0.1567	0.1486	0.1238	0.1316	0.1172
$\ln C_t$	1.0000						
$\ln E_t$	-0.0298	1.0000					
$\ln Y_t$	0.1881	0.4272	1.0000				
$\ln O_t$	0.1318	0.3560	-0.3575	1.0000			
$\ln TR_t$	-0.1918	0.5728	0.4586	-0.5290	1.0000		
$\ln EX_t$	-0.1804	0.6762	0.5465	-0.4300	0.9991	1.0000	
$\ln IM_t$	-0.2067	0.4682	0.4980	-0.3266	0.9992	0.9968	1.0000

Note: C_t is CO_2 emissions per capita, E_t is biomass energy consumption per capita, Y_t is real GDP per capita, O_t is real oil prices, EX_t is exports, IM_t is imports and TR_t is trade.

In order to examine the unit root properties of the variables, we have applied the Ng-Perron unit root test (2001) which provides efficient empirical results for small samples such as in our case[7]. The empirical results indicate that all the series are non-stationary in the level by using the intercept and time trend but are stationary in the first difference of the variables[8]. The Ng-Perron unit root test provides ambiguous empirical results due to their low explanatory power since this unit root test does not accommodate information about unknown structural break dates stemming from the series, which further weakens the stationarity hypothesis.

To resolve this issue, we employ the Clemente-Montanes-Reyes (1998) unit root test which contains information about single and double unknown structural breaks occurring in the

[7] Testing the unit root properties of a variable is necessary to apply any standard cointegration methods such as the bounds testing or the Johansen methods to cointegration.

[8] We have not provided the results of the Ng-Perron (2001) unit root test to conserve space but they are available upon request from the authors.

series during the sample period. Table 3 details the results of the CMR (Clemente-Montanes-Reyes) unit root test. We note that the variables are non-stationary in the level in the presence of structural breaks. The structural breaks are found in CO_2 emissions, economic growth, biomass energy consumption, oil prices, trade openness, exports and imports for the years of 1978, 1981, 1974, 1971 and 1970, respectively. These years are associated with major events in the economy and the oil market. For example, 1973-1974 are the years of OPEC oil embargo, 1980 is a year of a major economic recession in the United States. The break point in 1978 for carbon emissions signifies the implementation of Water Pollution Control Act Amendments (WPCAA, 1977) which is also commonly known as Superfund Act in 1980 (SA, 1980). This act helped in regulating public drinking water systems, toxic substances, pesticides, and ocean dumping; and protected wildlife, wilderness, and wild and scenic rivers. This series of new laws provided for conducting pollution research, improve standard setting, contaminated site cleanup, monitoring, and enforcement. We may conclude that the implementation of WPCAA not only affected energy but also environmental quality in 1978.

We note that all the variables are stationary in their first difference form. This indicates that all the series are integrated of I(1). The robustness of stationarity properties of the variables is checked by applying the CMR (1998) test that accounts for information for double unknown structural breaks in the series. The results display in Table 3 unveil that all the series have a unit root problem in the level but show stationary in the first difference. It is noted that all the variables have unique order of integration[9].

Table 3: Unit root analysis with structural breaks

Variable	Innovative Outliers				Additive Outlier			
	T-statistic	TB1	TB2	Decision	T-statistic	TB1	TB2	Decision
$\ln C_t$	-3.051 (2)	1978	…	I(0)	-6.218 (2)*	1972	…	I(1)
	-3.987 (2)	1967	1978	I(0)	-7.141 (3) *	1972	1981	I(1)
$\ln Y_t$	-3.743 (1)	1981	…	I(0)	-5.442 (1) *	2007	…	I(1)
	-3.858 (2)	1974	1981	I(0)	-6.243 (2) *	1981	2007	I(1)
$\ln E_t$	-4.088 (2)	1974	…	I(0)	-7.199 (4) *	2000	…	I(1)
	-5.396 (3)	1974	2000	I(0)	-7.464 (2) *	1974	1983	I(1)

[9] The graphical presentation of CMR unit root test with indication of structural break is given in Appendix-A for all the variables.

$\ln O_t$	-2.710 (2)	1971	…	I(0)	6.609 (2) *	1977	…	I(1)
	-3.470 (3)	1977	2009	I(0)	-7.247 (3) *	1977	1996	I(1)
$\ln TR_t$	-2.920 (1)	1971	…	I(0)	-14.496 (1) *	1979	…	I(1)
	-4.162 (2)	1971	1992	I(0)	-17.236 (2) *	1979	2008	I(1)
$\ln EX_t$	2.122 (3)	1971	…	I(0)	-11.343 (2) *	1979	…	I(1)
	-3.959 (2)	1971	1985	I(0)	-11.728 (1) *	1970	1979	I(1)
$\ln IM_t$	-3.029 (2)	1970	…	I(0)	-16.579 (2) *	1979	…	I(1)
	-4.616 (2)	1971	1992	I(0)	-9.703 (3) *	1979	2008	I(1)

Note: * and** represent significance at the 1% and 5% levels, respectively. () shows the lag length of the variables. *TB1* and *TB2* refer to structural break dates.

After investigating the integrating order of the variables, the next step is to examine the presence of cointegration between carbon emissions and their determinants. In doing so, we apply the bounds testing approach to examine cointegration between the variables. The ARDL bounds testing approach is sensitive to the selection of lag order, and thus we rely on the AIC for selecting the appropriate lag order selection due to its superior power properties as suggested by Lütkepohl, (2006). The appropriate selection of the lag order helps in capturing the dynamic association between the variables (Lütkepohl, 2006). The empirical results are shown in Table 4.

We find that the computed ARDL-F statistic is greater than the upper critical bounds at the 1% and 5% significance levels as we have found for carbon emissions, biomass energy consumption and exports serving as dependent variables. This shows the existence of three cointegrating vectors, which validates the occurrence of cointegration between carbon emissions and this variable's determinants. A similar outcome is noted as we use imports and trade standing as indicators of trade openness. This confirms that carbon emissions, economic growth, biomass energy consumption, oil prices and exports (imports, trade) of the US economy have a long-run relationship during the period 1960-2016.

Table 4: The results of the ARDL cointegration test

Bounds Testing to Cointegration				Diagnostic tests			
Estimated Models	Optimal lag length	Structural Break	F-statistics	χ^2_{NORMAL}	χ^2_{ARCH}	χ^2_{RESET}	χ^2_{SERIAL}
$C_t = f(Y_t, Y_t^2, E_t, O_t, TR_t, TR_t^2)$	2, 2, 1, 2, 2, 2, 2	1978	6.829 **	0.3116	1.9105	1.8169	2.5191
$Y_t = f(C_t, Y_t^2, E_t, O_t, TR_t, TR_t^2)$	2, 2, 2, 1, 2, 2, 1	1981	4.062	0.5111	0.2212	0.5518	4.7101
$Y_t^2 = f(Y_t, C_t, E_t, O_t, TR_t, TR_t^2)$	2, 2, 2, 1, 2, 2, 2	1981	4.170	0.1171	0.3292	0.5373	1.2710
$E_t = f(C_t, Y_t, Y_t^2, O_t, TR_t, TR_t^2)$	2, 2, 2, 2, 2, 1, 2	1974	6.997 *	1.2311	2.1322	2.5252	0.4000
$O_t = f(C_t, Y_t, Y_t^2, E_t, TR_t, TR_t^2)$	2, 2, 2, 1, 1, 2, 2	1971	7.797 *	1.3311	2.1421	1.5441	0.4000
$TR_t = f(C_t, Y_t, Y_t^2, E_t, O_t, TR_t^2)$	2, 2, 2, 2, 2, 2, 2	1971	6.341 **	0.1332	0.3424	0.5055	0.4004
$TR_t^2 = f(C_t, Y_t, Y_t^2, E_t, O_t, TR_t)$	2, 2, 2, 2, 2, 2, 2	1971	6.640 **	0.1312	0.3224	0.5657	0.4074
$C_t = f(Y_t, Y_t^2, E_t, O_t, EX_t, EX_t^2)$	2, 2, 1, 2, 2, 2, 2	1978	8.837 *	0.6313	2.6332	0.1831	1.9127
$Y_t = f(C_t, Y_t^2, E_t, O_t, EX_t, EX_t^2)$	2, 2, 2, 1, 2, 2, 1	1981	2.112	1.2323	1.3446	2.1762	0.9012
$Y_t^2 = f(Y_t, C_t, E_t, O_t, EX_t, EX_t^2)$	2, 2, 2, 1, 2, 2, 2	1981	2.317	1.1304	0.3134	2.1609	0.8207
$E_t = f(C_t, Y_t, Y_t^2, O_t, EX_t, EX_t^2)$	2, 2, 2, 2, 2, 1, 2	1974	7.789 **	0.1608	0.3401	1.4653	1.5850
$O_t = f(C_t, Y_t, Y_t^2, E_t, EX_t, EX_t^2)$	2, 2, 2, 1, 1, 2, 2	1971	7.927 *	1.3611	2.3423	1.5346	0.4000
$EX_t = f(C_t, Y_t, Y_t^2, E_t, O_t, EX_t^2)$	2, 2, 2, 2, 2, 2 , 2	1971	9.818 *	0.2430	0.4423	0.2929	2.3021
$EX_t^2 = f(C_t, Y_t, Y_t^2, E_t, O_t, EX_t)$	2, 2, 2, 2, 2, 2 , 2	1971	6.749 **	0.2140	0.3324	0.1912	2.3021
$C_t = f(Y_t, Y_t^2, E_t, O_t, IM_t, IM_t^2)$	2, 2, 1, 2, 2, 2, 2	1978	6.395 **	0.2015	2.4181	2.4161	0.2370
$Y_t = f(C_t, Y_t^2, E_t, O_t, IM_t, IM_t^2)$	2, 2, 2, 1, 2, 2, 1	1981	2.873	0.3050	1.2002	2.2104	0.1502
$Y_t^2 = f(Y_t, C_t, E_t, O_t, IM_t, IM_t^2)$	2, 2, 2, 1, 2, 2, 2	1981	3.901	1.1561	0.1221	0.3480	2.5501
$E_t = f(C_t, Y_t, Y_t^2, O_t, IM_t, IM_t^2)$	2, 2, 2, 2, 2, 1, 2	1974	7.670 **	0.6344	0.4316	1.5191	2.8101
$O_t = f(C_t, Y_t, Y_t^2, E_t, IM_t, IM_t^2)$	2, 2, 2, 1, 1, 2, 2	1971	7.476 **	0.7891	0.8976	1.8971	0.8716
$IM_t = f(C_t, Y_t, Y_t^2, E_t, O_t, IM_t^2)$	2, 2, 2, 2, 2, 2 , 2	1970	7.974 **	0.9130	0.2949	1.2901	2.6627
$IM_t^2 = f(C_t, Y_t, Y_t^2, E_t, O_t, IM_t)$	2, 2, 2, 2, 2, 2 , 2	1970	9.990 **	0.8971	0.8761	0.5687	0.9871

$C_t = f(Y_t, Y_t^2, Y_t^3, E_t, O_t, TR_t, TR_t^2)$	2, 2, 1, 2, 2, 2, 2	1978	9.151 *	1.6564	0.1613	2.4080	0.2502
$Y_t = f(C_t, Y_t^2, Y_t^3, E_t, O_t, TR_t, TR_t^2)$	2, 2, 2, 1, 2, 2, 1	1981	3.701	1.8464	0.1313	2.4811	0.2501
$Y_t^2 = f(C_t, Y_t, Y_t^3, E_t, O_t, TR_t, TR_t^2)$	2, 2, 2, 1, 2, 2, 2	1981	2.105	1.6040	0.1260	2.3801	0.0221
$Y_t^3 = f(C_t, Y_t, Y_t^2, E_t, O_t, TR_t, TR_t^2)$	2, 2, 2, 1, 2, 2, 2	1981	3.272	1.4049	0.1409	2.3038	0.1245
$E_t = f(C_t, Y_t, Y_t^2, Y_t^3, O_t, TR_t, TR_t^2)$	2, 2, 2, 1, 1, 2, 2	1974	6.538 **	1.4044	0.4609	2.3679	0.1450
$P_t = f(C_t, Y_t, Y_t^2, Y_t^3, O_t, TR_t, TR_t^2)$	2, 2, 2, 2, 2, 2, 2	1971	8.901 *	0.8976	0.8765	0.5436	0.3456
$TR_t = f(C_t, Y_t, Y_t^2, Y_t^3, E_t, O_t, TR_t^2)$	2, 2, 2, 2, 2, 2, 2	1971	9.231*	2.1421	1.0309	2.4260	1.1550
$TR_t^2 = f(C_t, Y_t, Y_t^2, Y_t^3, E_t, O_t, TR_t)$	2, 2, 2, 2, 2, 2, 2	1971	9.018 *	1.0989	0.8971	1.0879	0.8956
$C_t = f(Y_t, Y_t^2, Y_t^3, E_t, O_t, EX_t, EX_t^2)$	2, 2, 1, 2, 2, 2, 2	1978	9.135 *	2.3431	2.0204	2.6525	2.3635
$Y_t = f(C_t, Y_t^2, Y_t^3, E_t, O_t, EX_t, EX_t^2)$	2, 2, 2, 1, 2, 2, 1	1981	3.751	1.2810	0.4202	2.1432	0.3501
$Y_t^2 = f(C_t, Y_t, Y_t^3, E_t, O_t, EX_t, EX_t^2)$	2, 2, 2, 1, 2, 2, 2	1981	2.112	1.3212	0.3202	2.4142	0.5303
$Y_t^3 = f(C_t, Y_t, Y_t^2, E_t, O_t, EX_t, EX_t^2)$	2, 2, 2, 1, 2, 2, 2	1981	3.070	1.1209	0.3602	2.3434	0.2124
$E_t = f(C_t, Y_t, Y_t^2, Y_t^3, O_t, EX_t, EX_t^2)$	2, 2, 2, 1, 1, 2, 2	1974	6.598 **	2.0409	1.3209	1.4060	1.0313
$P_t = f(C_t, Y_t, Y_t^2, Y_t^3, O_t, EX_t, EX_t^2)$	2, 2, 2, 2, 2, 2, 2	1971	8.808 *	1.1010	2.1021	2.4302	2.2130
$EX_t = f(C_t, Y_t, Y_t^2, Y_t^3, E_t, O_t, EX_t^2)$	2, 2, 2, 2, 2, 2, 2	1971	9.131*	1.2102	2.2003	1.4021	2.0312
$EX_t^2 = f(C_t, Y_t, Y_t^2, Y_t^3, E_t, O_t, EX_t)$	2, 2, 2, 2, 2, 2, 2	1971	9.218 *	1.0261	1.0203	2.1011	0.1021
$C_t = f(Y_t, Y_t^2, Y_t^3, E_t, O_t, IM_t, IM_t^2)$	2, 2, 1, 2, 2, 2, 2	1978	9.445 *	0.6302	0.1032	2.2035	0.5032
$Y_t = f(C_t, Y_t^2, Y_t^3, E_t, O_t, IM_t, IM_t^2)$	2, 2, 2, 1, 2, 2, 1	1981	2.075	1.2040	0.2023	2.3031	0.2030
$Y_t^2 = f(C_t, Y_t, Y_t^3, E_t, O_t, IM_t, IM_t^2)$	2, 2, 2, 1, 2, 2, 2	1981	3.132	2.2101	1.1301	0.6515	0.0552
$Y_t^3 = f(C_t, Y_t, Y_t^2, E_t, O_t, IM_t, IM_t^2)$	2, 2, 2, 1, 2, 2, 2	1981	3.175	1.2152	1.0050	0.2519	0.5305
$E_t = f(C_t, Y_t, Y_t^2, Y_t^3, O_t, IM_t, IM_t^2)$	2, 2, 2, 1, 1, 2, 2	1974	7.190 **	0.8970	0.9817	0.1234	0.9801
$P_t = f(C_t, Y_t, Y_t^2, Y_t^3, O_t, IM_t, IM_t^2)$	2, 2, 2, 2, 2, 2, 2	1971	8.868 *	0.7654	0.2389	0.8712	0.2348
$IM_t = f(C_t, Y_t, Y_t^2, Y_t^3, E_t, O_t, IM_t^2)$	2, 2, 2, 2, 2, 2, 2	1970	9.535 *	0.1978	0.4567	0.0980	0.1350
$IM_t^2 = f(C_t, Y_t, Y_t^2, Y_t^3, E_t, O_t, IM_t)$	2, 2, 2, 2, 2, 2, 2	1970	9.458 *	0.3457	0.8912	0.6780	0.8017
	Critical values (T= 57)						

	Lower bounds $I(0)$	Upper bounds $I(1)$					
	7.227	8.340					
	5.190	6.223					
	4.370	5.303					
Note: Significance at 1% and 5% levels is shown by * and **. The optimal lag length is determined by AIC.							

We find a unique level of integration for all variables, so we can move to apply the Johansen and Juselius, (1990) maximum likelihood cointegration test in order to test the robustness of cointegration results. The results of Johansen cointegration test reported in Table 4 reveal that the null hypothesis of no cointegration is rejected because the trace statistic and maximum Eigen value show the presence of one cointegrating vector between the variables as we measure trade openness by exports, imports and trade using squared and cubic functions of carbon emissions. The presence of a cointegrating vector confirms the existence of a long-run cointegration between the variables. This finding underscores the robustness of the empirical results of a long-run cointegration association between the variables.

Table 5: Results of the Johansen cointegration tests with squared and cubic specifications

Hypothesis	Trace Statistic	Maximum Eigen Value	Trace Statistic	Maximum Eigen Value
$C_t = f(E_t, Y_t, Y_t^2, O_t, TR_t, TR_t^2)$			$C_t = f(E_t, Y_t, Y_t^2, Y_t^3, O_t, TR_t, TR_t^2)$	
$R = 0$	250.4464 *	46.2314 *	361.5025 *	114.2808 *
$R \leq 1$	167.6963 *	40.0775 *	247.2217 *	69.2183 *
$R \leq 2$	107.3465 *	33.8768 *	178.0033 *	67.8709 *
$R \leq 3$	64.9437 *	27.5843 **	110.1324 *	51.0452 *
$R \leq 4$	33.0077 **	21.1316	59.0871 **	28.5930
$R \leq 5$	14.7909	14.2646	30.4941	16.0193
$R \leq 6$	0.4337	3.8414	14.4746	12.8163
$R \leq 7$	…	…	1.6584	1.6584
$C_t = f(E_t, Y_t, Y_t^2, O_t, EX_t, EX_t^2)$			$C_t = f(E_t, Y_t, Y_t^2, Y_t^3, O_t, EX_t, EX_t^2)$	
$R = 0$	254.8348 *	78.8268 *	318.7486 *	86.6317 *
$R \leq 1$	176.0080 *	63.6650 *	232.1169 *	69.5309 *
$R \leq 2$	112.3430 *	39.3047 *	162.5859 *	53.2441 *
$R \leq 3$	73.0382 *	35.6900 *	109.3418 *	48.1110 *
$R \leq 4$	37.3482 *	23.7827 **	61.2307 *	28.8295 **
$R \leq 5$	13.5654	13.5281	32.4012 **	19.1251
$R \leq 6$	0.0372	0.0372	13.2760	13.2400
$R \leq 7$	…	…	0.0359	0.0359
$C_t = f(E_t, Y_t, Y_t^2, O_t, IM_t, IM_t^2)$			$C_t = f(E_t, Y_t, Y_t^2, Y_t^3, O_t, IM_t, IM_t^2)$	
$R = 0$	272.8178 *	91.1898 *	344.7629 *	94.4201 *
$R \leq 1$	181.6280 *	61.8528 *	250.3428 *	86.4238 *
$R \leq 2$	119.7751 *	47.8955 *	163.9189 *	54.0829 *
$R \leq 3$	71.8795 *	34.0217 *	109.8360 *	45.0981 *

$R \leq 4$	37.8578 *	24.4507 **	64.7377 *	33.2065 *
$R \leq 5$	13.4071	11.9902	31.5312 **	18.1224
$R \leq 6$	1.4168	1.4168	13.4088	13.3327
$R \leq 7$	…	…	0.0760	0.0760
Note: * and ** indicate significance at the 1% and 5% levels, respectively.				

The presence of cointegration between the variables paves the way to examine the long-run and short-run dynamic relationships between the variables. The long-run results reported in Table 6 show that biomass energy consumption has a negative impact on carbon emissions, which highlights that biomass energy is good for the environment. For instance, we observe that a 1% increase in biomass energy consumption will decrease emissions by 0.25-0.31%. This evidence is similar to that found by Bilgili et al. (2016) and Bilgili (2016) for the US economy.

Oil prices are positively and significantly linked with carbon emissions. This finding implies that oil prices increase CO_2 emissions. A 1% rise in those prices leads carbon emissions to increase by 0.03-0.04%. This empirical evidence is consistent with the results of Chai et al. (2016), which indicate that higher oil prices make firms use other fossil fuel substitutes such as dirty coal that increase carbon emissions.

The association between economic growth and carbon emissions has an inverted U-shaped when exports, imports and trade are used as measures of trade openness. We find that a 1% increase in real GDP would increase carbon emissions by 15.10%-16.06%, using the three different measures of trade openness. The negative sign of the squared term of real GDP in the carbon emissions function corroborates the delinking of carbon emissions at a higher level of real GDP, while again controlling for exports, imports and trade as measures of trade openness. This is evidence for the existence of EKC in the United States. This empirical evidence is similar to that of Unruh and Moomaw (1998) and Roach (2013) which underscores the presence of the EKC hypothesis for the US economy.

The relationship between trade openness (as measured by exports, imports and trade) and carbon emissions has a U-shaped. We note that exports (imports) have a negative and significant impact on CO_2 emissions, suggesting that international trade is good for the environment. A 1% increase in exports (imports) would produce a 0.17% (0.09%) decrease in carbon emissions. Moreover, total trade also decreases carbon emissions significantly, where a 1% increase in trade would dampen emissions by 0.13%. The negative sign of the squared term of trade openness (exports, imports and trade) also corroborates the positive linking of carbon emissions with trade openness at a higher level of real trade, while controlling biomass energy consumption, oil prices and economic growth. This finding is evidence of the existence of a U-shaped association between trade openness and carbon emission in the United States[10]. The dummy variable has a positive and significant effect on carbon emissions. This shows that the implementation of Water Pollution Control Act Amendments (WPCAA) could not improve the environmental quality by lowering CO_2 emissions in the US economy.

Table 6: Long run and stability analysis for carbon emissions

Dependent Variable: $\ln C_t$						
Variable	Coefficient	Coefficient	Coefficient	Coefficient	Coefficient	Coefficient
Constant	-72.2159*	-77.4234*	-76.1664*	-84.5825*	-94.3031*	-95.8409*
$\ln E_t$	-0.2578*	-0.2620*	-0.2465*	-0.3112*	-0.2488*	-0.2462*
$\ln Y_t$	15.1023*	16.0611*	15.6710*	231.4294*	278.6781*	285.7061*
$\ln Y_t^2$	-0.7131*	-0.7559*	-0.7359*	-21.5281*	-26.6005*	-38.3676*
$\ln Y_t^3$	…	…	…	1.1812**	1.1934*	1.2443*
$\ln O_t$	0.0335*	0.0373	0.0378*	0.0274*	0.0237*	0.0560**
$\ln TR_t$	-0.1296**	…	…	-0.1499*	…	…
$\ln TR_t^2$	0.0056**	…	…	0.0132**	…	…
$\ln EX_t$	…	-0.1656*	…	…	-0.1896*	…
$\ln EX_t^2$	…	0.0095**	…	…	0.0152**	…
$\ln IM_t$	…	…	-0.0901**	…	…	-0.1049*
$\ln IM_t^2$	…	…	0.0030***	…	…	0.0110***
D_{1978}	0.0305**	0.0464**	0.0402**	0.0113*	0.0144**	0.0151**
R^2	0.7693	0.7742	0.7789	0.7933	0.8417	0.8581
F-stat	27.247*	28.002*	28.7801*	26.326*	31.2505*	35.545*
D.W Test	1.5842	1.6275	1.5686	1.6687	1.8616	1.9356
Stability Analysis						
Test	F-stat	F-stat	F-stat	F-stat	F-stat	F-stat
χ^2_{Normal}	0.6191	1.0433	0.8702	1.5381	0.8888	1.1037
χ^2_{serial}	0.4537	0.3934	0.4517	0.5105	0.4546	0.5440

[10] We find similar empirical results by using three indicators of trade openness which indicates the resilience and consistency of empirical analysis.

χ^2_{ARCH}	0.1098	0.1192	0.1276	1.6957	0.2311	0.2437
χ^2_{Hetero}	1.3881	1.0774	1.1921	1.2435	1.7666	1.8117
χ^2_{Remsay}	2.5762	2.1808	2.4613	1.1164	1.3562	2.2833
CUSUM	Stable[11]	Stable	Stable	Stable	Stable	Stable
CUSUM	Stable	Stable	Stable	Stable	Stable	Stable
Note: Asterisk *, ** and *** indicate significance at the 1%, 5% and 10% levels.						

Following Moomaw and Unruh (1997) and later on, Friedl and Getzner (2003), we insert a cubic term of real GDP per capita to examine whether the relationship between economic growth and carbon emission is N-shaped or inverted N-shaped. We find that the linear, quadratic and cubic terms of real GDP per capita affect carbon emissions positively, negatively and positively. This result shows the presence of an N-shaped relationship between economic growth and CO_2 emissions. It implies that an increase in carbon emissions would be a temporary outcome generated by factors contributing to CO_2 emissions other than economic growth (Friedl and Getzner, 2003).

Table 7 shows the short-run results. These results reveal that biomass energy consumption is negatively but insignificantly linked to carbon emissions. However, the association between economic growth and carbon emissions is significant and is inverted-U shaped, which validates the existence of the EKC hypothesis. Oil prices are negatively but insignificantly linked with carbon emissions. The linkage between trade openness (measured by exports, imports and trade) and carbon emissions is inverted-U shaped but statistically insignificant. The cubic relationship between economic growth and CO_2 emissions is N-shaped but insignificant. The impact of the dummy variable is positive and significant. This again indicates that implementation of Water Pollution Control Act Amendments (WPCAA) degrades environmental quality.

The sign of the ECM_{t-1} estimate is negative and statistically significant for the long run at the 1% level. The coefficients of ECM_{t-1} are -0.21, -0.12 and -0.17, responding to the use of exports, imports and trade as indicators of trade openness in the quadratic carbon emissions function, respectively. Concerning the cubic carbon emissions function, the ECM_{t-1} coefficients are -0.30, -0.13 and -0.19 according to using trade openness variables of the US economy. The

[11]The diagrams of CUSUM and CUSUMsq are available upon request from authors.

statistical significance of ECM_{t-1} corroborates the established long-run association between carbon emissions and their determinants. It reveals that the short-run adjustments towards the long-run equilibrium path are corrected by 21.26%, 12.45% and 16.67% for exports, imports and trade for the quadratic carbon emissions function, respectively. For the cubic carbon emissions function, the short-run adjustments to the long-run equilibrium path are corrected by 30.08%, 13.44% and 19.17% for exports, imports and trade models, respectively. Furthermore, the diagnostic tests reveal the absence of serial correlation, ARCH and white heteroscedasticity effects in the short run model(s). This well-characterization of the specification(s) of the short-run(s) is confirmed by the Remsay reset test. The normal distribution of the error term is also validated. The CUSUM and CUSUMsq (except Figure-2B, 6B and 10B) tests corroborate the stability of the short-run and long-run estimates (See Appendix-B). The instability of CUSUMsq in Figure-2B, 6B and 10B intends us to apply the Chow forecast test in order to test stability of estimates[12]. The results are reported in Table-1B, 2B and 3B. We find that F-statistic confirms the stability of estimates. This corroborates the stability of long-run and short-run estimates.

Table 7: Short run analysis

Dependent Variable: $\Delta \ln C_t$						
Variable	Coefficient	Coefficient	Coefficient	Coefficient	Coefficient	Coefficient
Constant	-0.0248*	-0.0213*	-0.0237*	-0.0300**	-0.0261**	-0.0323*
$\Delta \ln E_t$	-0.0364	-0.0045	-0.0295	-0.0635	0.0259	-0.0630
$\Delta \ln Y_t$	1.1978*	1.2870*	1.7707*	0.1287*	0.1318**	0.1242**
$\Delta \ln Y_t^2$	-5.3803***	-7.8338**	-6.0782***	-0.5124	-0.0845	-0.7751
$\Delta \ln Y_t^3$	…	…	…	25.7710	17.3947	29.5007
$\Delta \ln O_t$	-0.0053	-0.0040	-0.0076	-0.0037	-0.0062	-0.0106
$\Delta \ln EX_t$	0.0959	…	…	0.1318	…	…
$\Delta \ln EX_t^2$	-0.0688	…	…	-0.0916		
$\Delta \ln IM_t$	…	0.0321	…	…	0.0667	…
$\Delta \ln IM_t^2$	…	-0.0031	…		-0.0304	
$\Delta \ln TR_t$	…	…	0.0841	…	…	0.1493
$\Delta \ln TR_t^2$	…	…	-0.0492	…	…	-0.1171

[12] The Chow forecast test is more reliable compared to CUSUMsq test.

$\ln D_{1978}$	0.0124**	0.0131**	0.0138**	0.0115***	0.0141**	0.0152**
ECM_{t-1}	-0.2126*	-0.1245*	-0.1667*	-0.3008*	-0.1344*	-0.1917*
R^2	0.7010	0.6592	0.6778	0.7446	0.6644	0.6920
F-stat	13.775*	11.338*	12.359*	14.907*	10.119*	11.484*
D.W Test	1.6205	1.6199	1.6014	1.7132	1.6537	1.6258
Stability Analysis						
Test	F-stat	F-stat	F-stat	F-stat	F-stat	F-stat
χ^2_{Normal}	0.1449	0.1666	0.1616	1.5381	0.6476	0.7818
χ^2_{serial}	1.4732	1.5914	1.5290	0.5105	1.0361	1.4259
χ^2_{ARCH}	0.5424	0.4734	0.5304	1.6957	1.1213	0.0949
χ^2_{Hetero}	0.4578	0.3937	0.4060	1.2435	1.9386	1.3990
χ^2_{Remsay}	0.8820	1.6080	1.9072	1.1164	1.0212	2.3520
CUSUM	Stable[13]	Stable	Stable	Stable	Stable	Stable
CUSUM	Stable	Stable	Stable	Stable	Stable	Stable
Note: Asterisk *, ** and *** indicate significance at the 1%, 5% and 10% levels.						

The causal relationship between the variables is tested by applying the VECM Granger causality. The VECM supports a causality relationship both for the short-run and the long-run. We have provided empirical results separately for the squared and the cubic carbon emissions functions[14]. In the long-run, we note that biomass energy consumption causes carbon emissions, while carbon emissions cause biomass energy consumption in the Granger sense (Tables 8 and 9). The unidirectional causality running from economic growth to carbon emissions confirms the presence of the EKC hypothesis in the United States. This empirical finding is different from that of Soytas et al. (2007) which posits a neutral effect between economic growth and carbon emissions. On the other hand, Dogan and Turkekul (2016) validate the presence of a feedback effect between both variables.

Biomass energy consumption is Granger caused by economic growth. The feedback effect exists between exports (imports) and carbon emissions. The relationship between exports (imports) and biomass energy consumption is bidirectional. Similarly, trade openness causes carbon emissions, while carbon emission causes trade openness in the Granger sense. The feedback effect is noticed between biomass energy consumption and trade openness. The results

[13] The diagrams of CUSUM and CUSUMsq are available upon request from the authors.

[14] The inverted-U relationship between economic growth and carbon emissions is tested by examining non-linear (squared) relationship between economic growth and CO_2 emissions and the N-shaped relationship is investigated by the non-linear (cubic) relationship between both variables.

of the cubic model (N-shaped) reported in Table 8 show a unidirectional causality running from economic growth and carbon emissions. The relationship between oil prices and carbon emissions is bidirectional. Oil prices cause biomass energy consumption and biomass energy consumption causes oil prices in the Granger sense. The feedback effect exists between trade openness (measured by exports, imports and trade) and oil prices. The unidirectional causality is also found running from economic growth to oil prices.

In short run, the unidirectional causality running from economic growth and exports to carbon emission is found, while exports Granger cause biomass energy consumption, and the same narrative is true from the opposite side. Economic growth is Granger caused by carbon emissions. The feedback effect is noted between imports and carbon emissions. Further, biomass energy consumption causes carbon emissions. Similarly, carbon emissions are Granger caused by trade openness, and trade openness is Granger caused by carbon emissions. The bidirectional causal relationship exists between trade openness and biomass energy consumption. Moreover, economic growth Granger causes oil prices. Table 7 reports the results of N-shaped (cubic) model using exports, imports and trade as indicators of trade openness, and we find that the results of the inverted-U (squared) model are almost similar. This implies the robustness of the short-run causality results.

Table-8: VECM Granger causality analysis (inverted U-shaped model)

Dependent Variable	Type of causality						
	Short Run						Long Run
	$\sum\Delta\ln C_{t-1}$	$\sum\Delta\ln E_{t-1}$	$\sum\Delta\ln Y_{t-1}, \sum\Delta\ln Y^2_{t-1}$	$\sum\Delta\ln O_{t-1}$	$\sum\Delta\ln EX_{t-1}, \sum\Delta\ln EX^2_{t-1}$	Break Year	ECT_{t-1}
$\Delta\ln C_t$	…	0.5224 [0.5965]	34.9033* [0.0000]	0.4856 [0.6186]	2.9050*** [0.0695]	1978	-0.3712* [-4.9345]
$\Delta\ln E_t$	1.0700 [0.3512]	…	0.9179 [0.5685]	0.0185 [0.9816]	3.1951** [0.0513]	1974	-0.2137** [-2.7125]
$\Delta\ln Y_t, \Delta\ln Y^2_t$	10.8851* [0.0000]	0.5984 [0.5585]	…	3.2345** [0.0521]	0.4116 [0.6695]	1981	…
$\sum\Delta\ln O_{t-1}$	0.0511 [0.9502]	0.6591 [0.5223]	5.9719* [0.0051]	…	0.7085 [0.5867]	1971	-0.2424** [-2.6789]
$\sum\Delta\ln EX_{t-1}, \sum\Delta\ln EX^2_{t-1}$	0.1850 [0.8395]	9.9189* [0.0002]	0.6126 [0.7189]	0.4050 [0.6200]	…	1971	-0.2236* [-3.1665]
	$\sum\Delta\ln C_{t-1}$	$\sum\Delta\ln E_{t-1}$	$\sum\Delta\ln Y_{t-1}, \sum\Delta\ln Y^2_{t-1}$	$\sum\Delta\ln O_{t-1}$	$\sum\Delta\ln IM_{t-1}, \sum\Delta\ln IM^2_{t-1}$	Break Year	ECT_{t-1}
$\Delta\ln C_t$	…	3.7449** [0.0321]	35.0291* [0.0000]	0.5489 [0.6089]	0.3839 [0.6965]	1978	-0.0366*** [-2.6983]
$\Delta\ln E_t$	1.3766 [0.2765]	…	1.0913 [0.4305]	0.1056 [0.9087]	4.7100** [0.0201]	1974	-0.1908** [-2.4080]
$\Delta\ln Y_t, \Delta\ln Y^2_t$	8.9391* [0.0009]	2.1419 [0.1423]	…	3.4567** [0.0451]	0.8801 [0.3865]	1981	…
$\sum\Delta\ln O_{t-1}$	0.2019 [0.8236]	0.7651 [0.4971]	6.7891* [0.0037]	…	0.6578 [0.5978]	1971	-0.2435* [-4.5678]
$\sum\Delta\ln IM_{t-1}, \sum\Delta\ln IM^2_{t-1}$	0.4504 [0.5808]	18.0091* [0.0000]	0.4803 [0.6704]	0.4415 [0.6160]	…	1970	-0.2660* [-2.9573]
	$\sum\Delta\ln C_{t-1}$	$\sum\Delta\ln E_{t-1}$	$\sum\Delta\ln Y_{t-1}, \sum\Delta\ln Y^2_{t-1}$	$\sum\Delta\ln O_{t-1}$	$\sum\Delta\ln TR_{t-1}, \sum\Delta\ln TR^2_{t-1}$	Break Year	ECT_{t-1}
$\Delta\ln C_t$	…	3.8471** [0.0254]	8.9822* [0.0002]	0.4409 [0.6182]	5.5506* [0.0044]	1978	-0.0815** [-2.7058]

$\Delta \ln E_t$	1.1121 [0.3209]	…	0.9801 [0.4608]	0.1156 [0.8908]	4.8909** [0.0211]	1974	-0.1750** [-2.5667]
$\Delta \ln Y_t, \Delta \ln Y_t^2$	8.6035* [0.0009]	1.4209 [0.2695]	…	3.5507** [0.0444]	0.7524 [0.4795]	1981	…
$\sum \Delta \ln O_{t-1}$	0.2419 [0.8031]	0.7056 [0.5008]	8.7809* [0.0009]	…	0.6607 [0.5865]	1971	-0.2305* [-4.0678]
$\sum \Delta \ln TR_{t-1}, \sum \Delta \ln TR_{t-1}^2$	0.1101 [0.8518]	14.6332* [0.0000]	0.4439 [0.6205]	0.5445 [0.6010]	…	1971	-0.2043* [-3.1360]

Note: The asterisks *, ** and *** denote the significance at the 1, 5 and 10 per cent level, respectively. The numbers in [] are probability-values.

Table-9: VECM Granger causality analysis (N-shaped model)

Dependent Variable	Type of causality						
	Short Run						Long Run
	$\sum \Delta \ln C_{t-1}$	$\sum \Delta \ln E_{t-1}$	$\sum \Delta \ln Y_{t-1}, \sum \Delta \ln Y_{t-1}^2, \sum \Delta \ln Y_{t-1}^3$	$\sum \Delta \ln O_{t-1}$	$\sum \Delta \ln EX_{t-1}, \sum \Delta \ln EX_{t-1}^2$	Break Year	ECT_{t-1}
$\Delta \ln C_t$	…	1.2361 [0.8934]	7.9897* [0.0001]	0.4757 [0.6201]	2.4989*** [0.0942]	1978	-0.4310* [-5.1570]
$\Delta \ln E_t$	0.8995 [0.3808]	…	1.1828 [0.2904]	0.0205 [0.9808]	6.9555* [0.0217]	1974	-0.1076** [-2.4320]
$\Delta \ln Y_t, \Delta \ln Y_t^2, \Delta \ln Y_t^3$	15.2106* [0.0000]	0.2509 [0.8601]	…	3.2545** [0.0519]	0.5275 [0.5902]	1981	
$\sum \Delta \ln O_{t-1}$	0.2313 [0.8054]	0.7506 [0.4988]	8.8808* [0.0007]	…	0.6906 [0.5805]	1971	-0.1922** [-2.5546]
$\sum \Delta \ln EX_{t-1}, \sum \Delta \ln EX_{t-1}^2$	0.1608 [0.9202]	11.1083* [0.0001]	1.7105 [0.2333]	0.4501 [0.6109]	…	1971	-0.2095* [-3.3829]
	$\sum \Delta \ln C_{t-1}$	$\sum \Delta \ln E_{t-1}$	$\sum \Delta \ln Y_{t-1}, \sum \Delta \ln Y_{t-1}^2$	$\sum \Delta \ln O_{t-1}$	$\sum \Delta \ln IM_{t-1}, \sum \Delta \ln IM_{t-1}^2$	Break Year	ECT_{t-1}
$\Delta \ln C_t$	…	3.5484* [0.0100]	2.9794** [0.0321]	0.507 [0.6149]	0.2382 [0.8676]	1978	-0.4305 * [-4.4574]

$\Delta \ln E_t$	0.8909 [0.3765]	…	3.8594** [0.0110]	0.0232 [0.9765]	4.5410* [0.0108]	1974	-0.1023* [-3.8827]
$\Delta \ln Y_t, \Delta \ln Y_t^2, \Delta \ln Y_t^3$	18.9060* [0.0000]	1.5354 [0.2164]	…	3.5546** [0.0510]	0.3563 [0.7220]	1981	…
$\sum \Delta \ln O_{t-1}$	0.3303 [0.7945]	0.7651 [0.4809]	9.8008* [0.0006]	…	0.6016 [0.6005]	1971	-0.2302** [-2.6546]
$\sum \Delta \ln IM_{t-1}, \sum \Delta \ln IM_{t-1}^2$	0.2646 [0.7633]	13.2208* [0.0000]	0.4045 [0.5943]	0.4051 [0.6309]		1970	-0.2035* [-2.9863]
	$\sum \Delta \ln C_{t-1}$	$\sum \Delta \ln E_{t-1}$	$\sum \Delta \ln Y_{t-1}, \sum \Delta \ln Y_{t-1}^2$	$\sum \Delta \ln O_{t-1}$	$\sum \Delta \ln TR_{t-1}, \sum \Delta \ln TR_{t-1}^2$	Break Year	ECT_{t-1}
$\Delta \ln C_t$	…	2.9767*** [0.0678]	12.9007* [0.0000]	0.5707 [0.6165]	2.9186*** [0.0649]	1978	-0.3075* [-4.0032]
$\Delta \ln E_t$	2.0025 [0.1405]	…	2.2198 [0.1120]	0.0215 [0.9785]	7.9141* [0.0013]	1974	-0.1687** [-2.5207]
$\Delta \ln Y_t, \Delta \ln Y_t^2, \Delta \ln Y_t^3$	19.9900* [0.0000]	1.8078 [0.1807]	…	3.4546** [0.0513]	0.1180 [0.8807]	1981	…
$\sum \Delta \ln O_{t-1}$	0.3403 [0.7933]	0.7757 [0.4769]	9.8348* [0.0005]	…	0.6676 [0.5987]	1971	-0.2106** [-2.6657]
$\sum \Delta \ln TR_{t-1}, \sum \Delta \ln TR_{t-1}^2$	0.1803 [0.8703]	13.3696* [0.0000]	0.5446 [0.5932]	0.5506 [0.6009]	…	1971	-0.2795* [-3.7971]

Note: The asterisks *, ** and *** denote the significance at the 1, 5 and 10 per cent level, respectively. The numbers in [] are probability-values.

7. Conclusion and policy implications

This study has employed augmented squared and cubic carbon emissions functions to investigate the existence of the EKC hypothesis in the presence of biomass energy consumption, oil prices and trade openness over the period 1960-2016. The integrating properties of the variables are investigated by applying the CMR unit root test which caters for single and double structural breaks. The cointegration between carbon emissions and their determinants is examined by applying the bounds testing approach to cointegration while considering structural breaks in the series. The VECM Granger causality test is also applied in order to test the existence of a dynamic causal relationship between the variables.

The bounds analysis confirms the existence of cointegration between carbon emissions and their determinants including biomass energy consumption, oil prices and trade openness, while also accommodating structural breaks in the series. Moreover, biomass energy consumption is negatively linked with carbon emissions, underscoring the importance of harnessing renewable energy to help combat carbon emissions emanating from fossil fuels. The association between economic growth and CO_2 emissions has an inverted-U shaped, which attests to the presence of the EKC hypothesis in the quadratic carbon emissions hypothesis, and it is also N-shaped in the cubic carbon emissions hypothesis.

These results confirm the findings reached by other studies in the literature, but our results are acquired in the presence of biomass energy consumption which is not a fossil fuel consumption in the carbon emissions functions. Biomass consumption in the presence of other control factors is good to the environment. The policy implication of this finding is that policy makers should introduce regulations that gradually include this renewable and clean source in the energy mix that is dominated by fossil fuels.

The relationship between trade openness (measured by exports, imports and trade) and carbon emissions is U-shaped, which reveals that carbon emissions are negatively linked with trade openness. But after a threshold level of trade openness, trade raises CO_2 emissions. The policy implication of this result is that any regulations or legislations at the US or state level in this regard should make sure that going deeper into the globalization process in the longer run will not raise CO2 emissions. Otherwise, tools of commercial policy should be invoked to fine tune globalization in order to safeguard environmental quality.

The causality result shows the presence of a feedback effect between biomass energy consumption and carbon emissions. The policy implication of this finding is that any policies or shocks that affect biomass consumption, whether in terms of conservation or augmentation, should into account changes in CO_2 emissions and vice versa.

Moreover, economic growth causes CO_2 emissions in the Granger sense, and the unidirectional causality runs from exports (imports) and trade openness to biomass energy consumption and carbon emissions. The policy implication is that shocks to economic growth or changes in the commercial policy have an impact on carbon emissions. Finally, the feedback effect is present between oil prices and carbon emissions. This result and its implications are well known in the existing literature.

The message from this research to policy makers is that our findings highlight the importance of biomass energy as a renewable energy source in reducing carbon emissions. This source of energy is plentiful in the United States. It has come from primary sources including wood, waste, alcohol fuels and corn and these sources generate wood energy, waste energy and biofuel in the country which collectively represents almost half of the total renewable energy production. One great advantage of the combustion of biomass with respect to the environment is that it is "carbon neutral". Re-growing plants recapture or requester a quantity of CO_2 emissions equivalent to the amount released to the atmosphere by burning biomass energy, and thus net carbon emissions are zero.

Based on those facts, policy makers should introduce legislations and set regulations that support the production and consumption of biomass energy but they should be aware of its relations with other economic variables. It seems that this energy source is a better friend to the environment, which has been supported by subsidies and tax credits but it still consumes a considerable amount of fossil fuels in its production. But a significant amount of research should be conducted before any legislation is enacted and there should be a demonstration that the sustainability criteria have been met.

Appendix A

Figure-1A

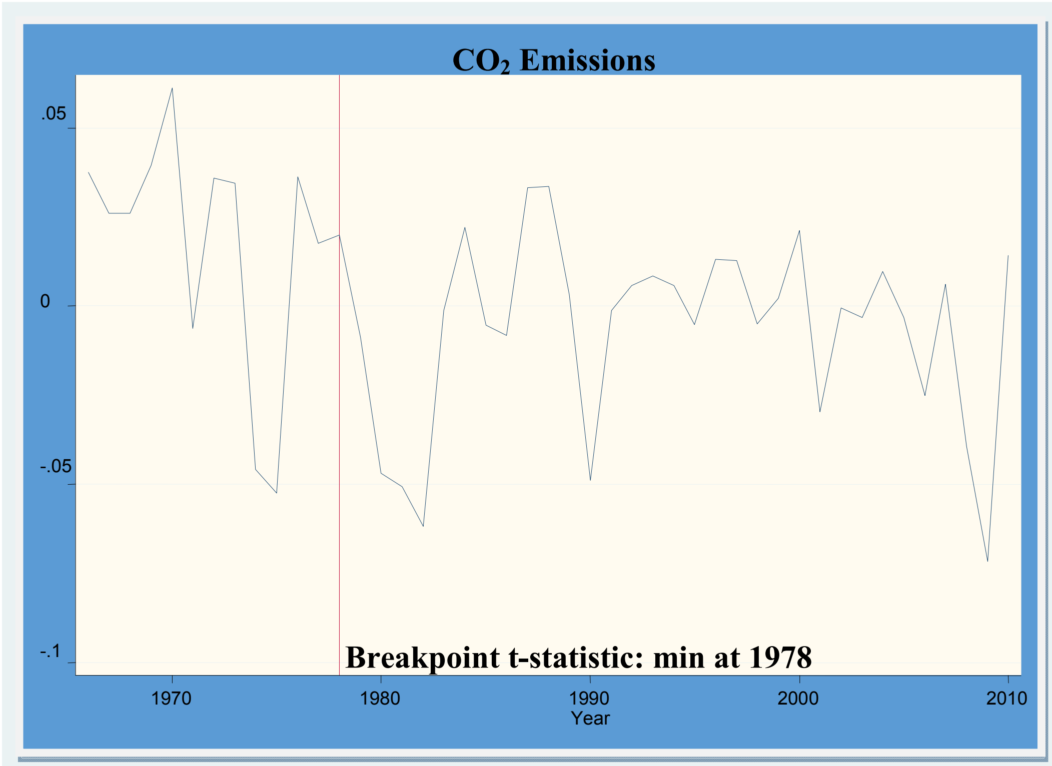


Figure-2A

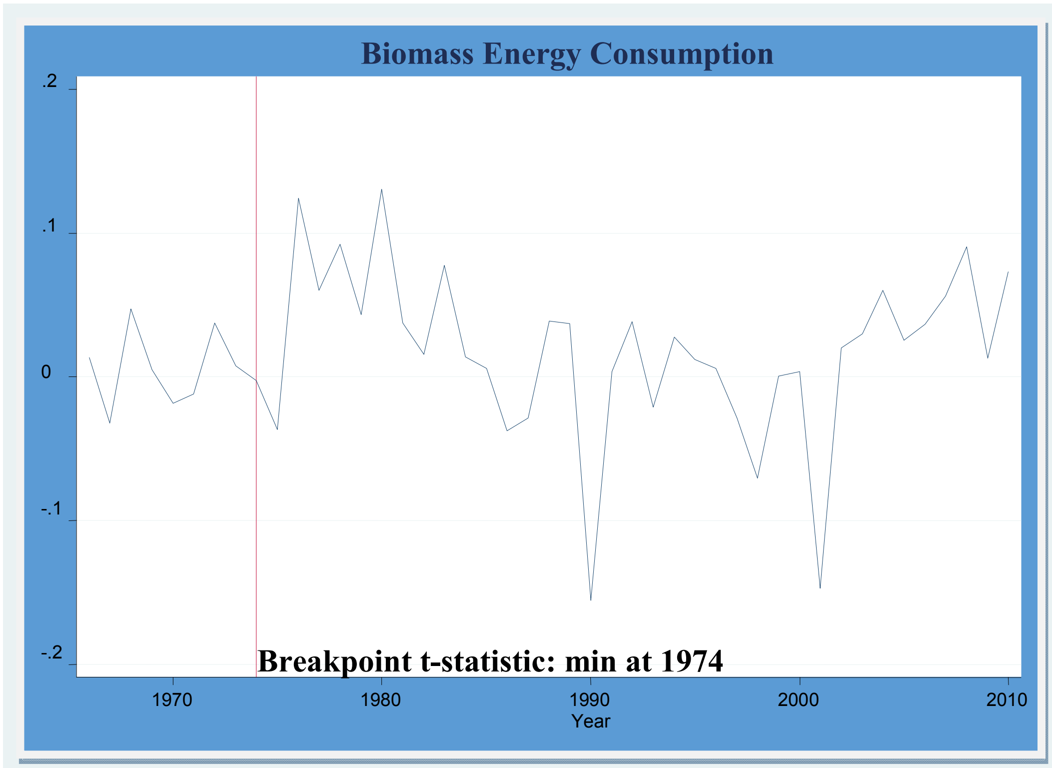


Figure-3A

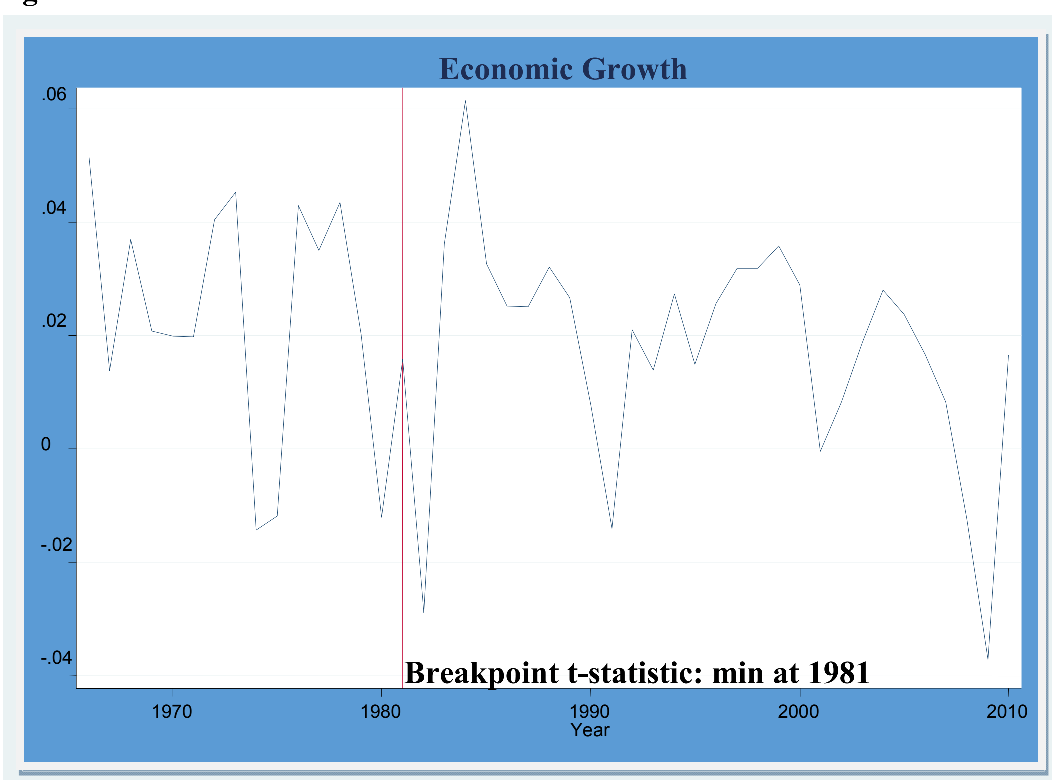


Figure-4A

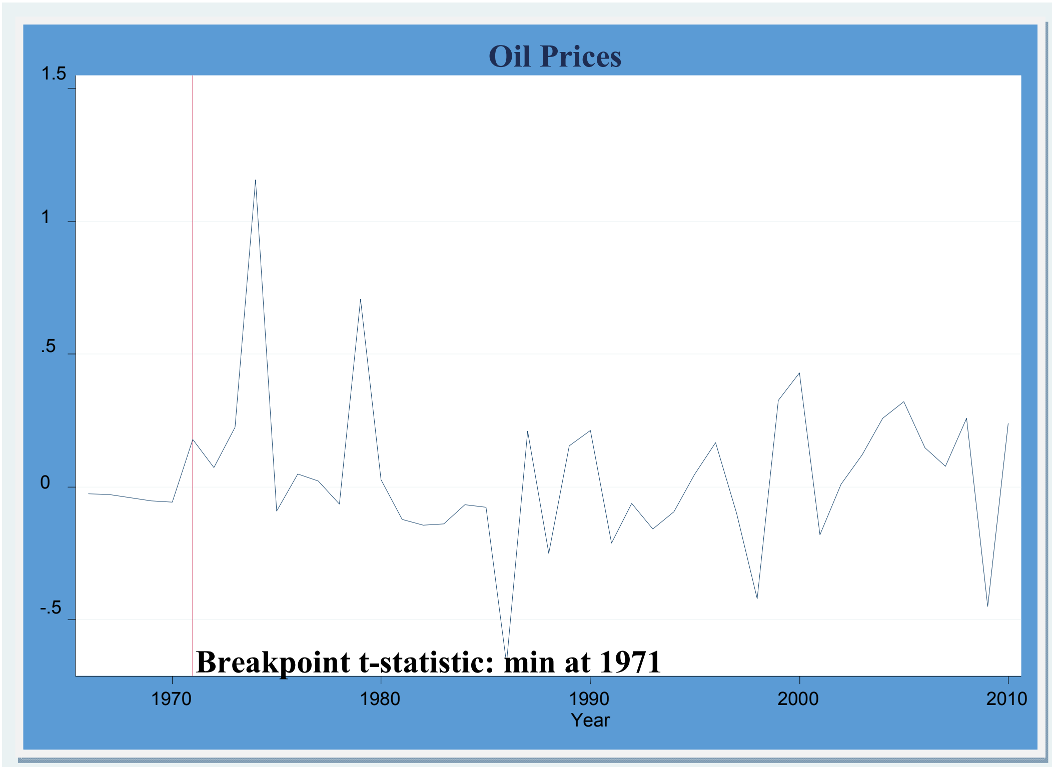


Figure-5A

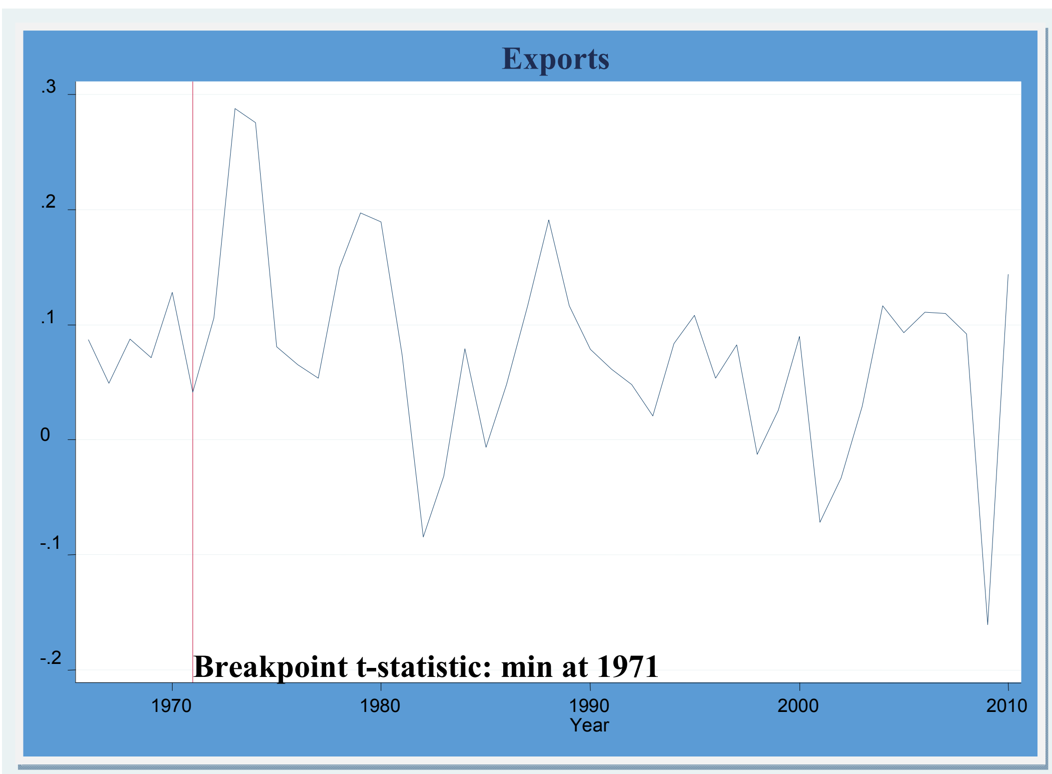


Figure-6A

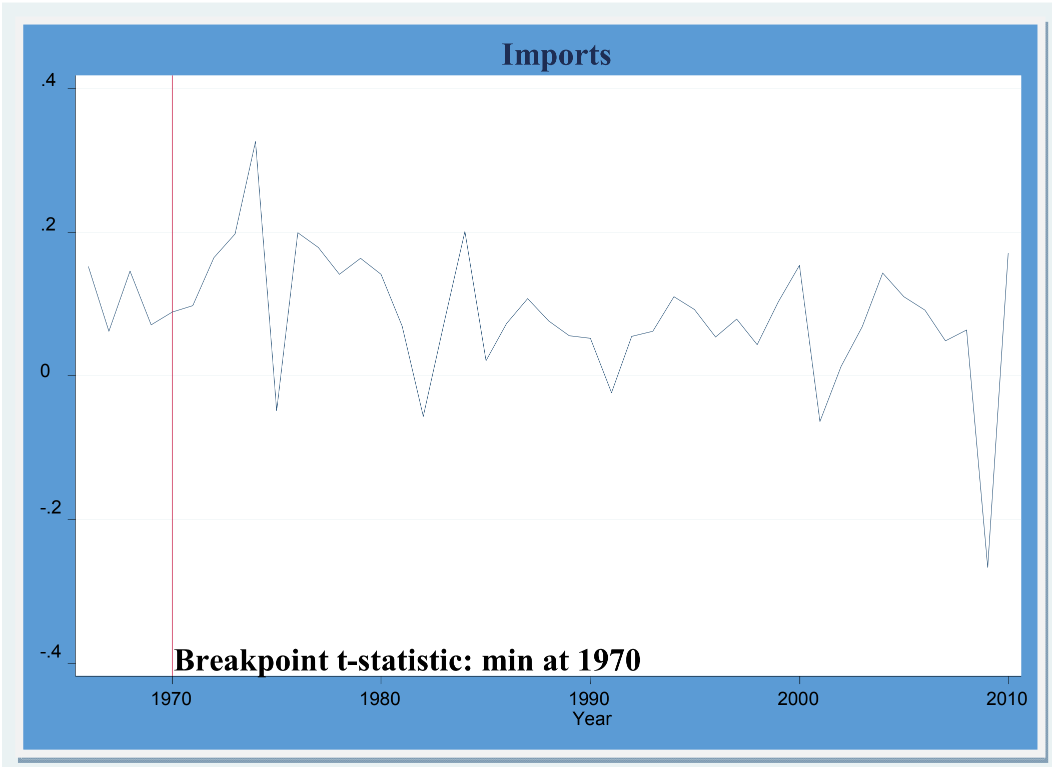
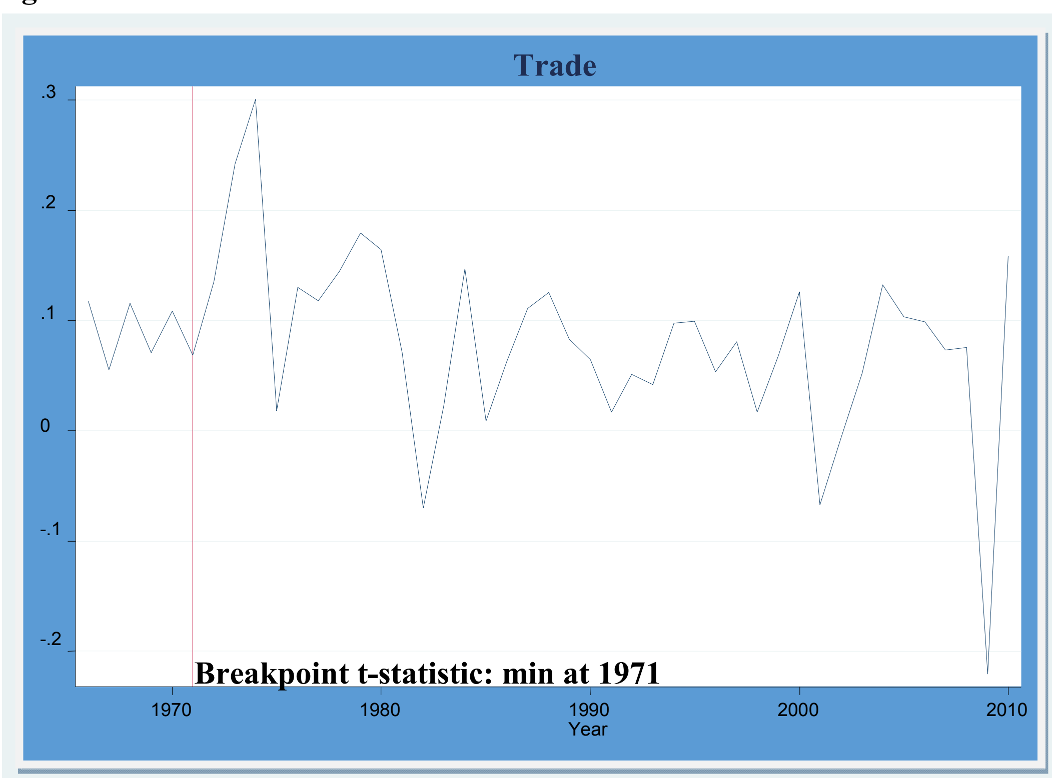


Figure-7A



Appendix-B

I. Quadratic Carbon Emissions Function

The Exports Model

Figure 1B: CUSUM

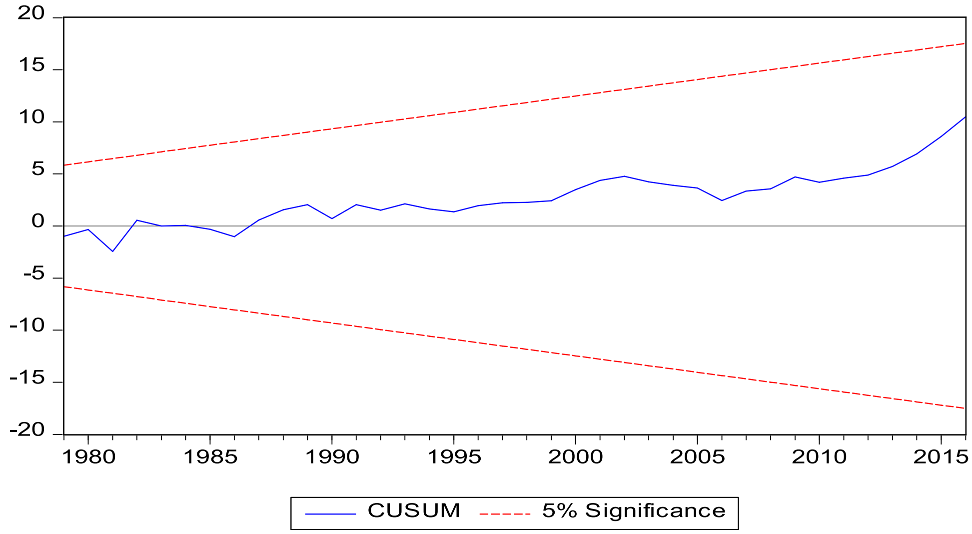


Figure 2B: CUSUMsq

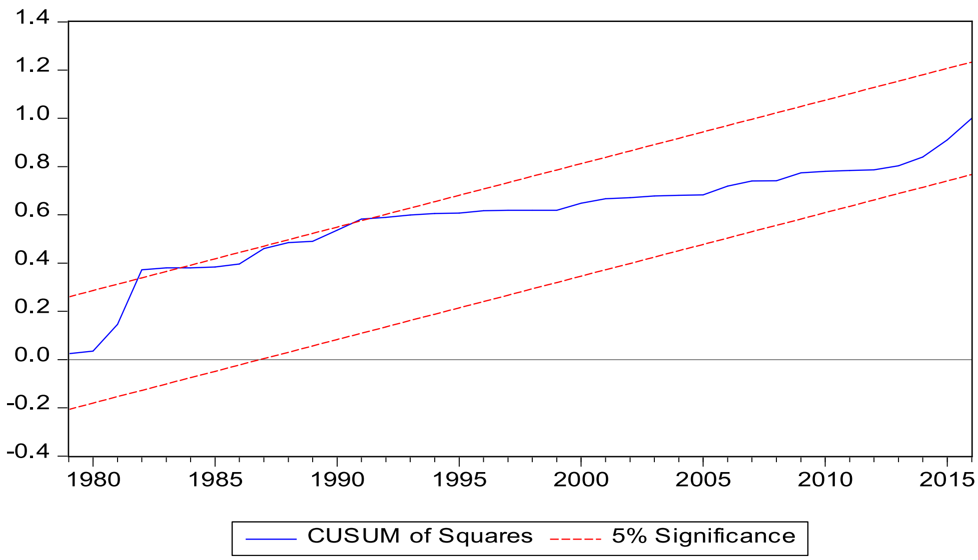


Table-1B: Chow Forecast Test

Test predictions for 1982-2016		
	Value	Probability
F-statistic	1.0296	0.5068
Likelihood ratio	77.6746	0.0000

The Imports Model

Figure 3B: CUSUM

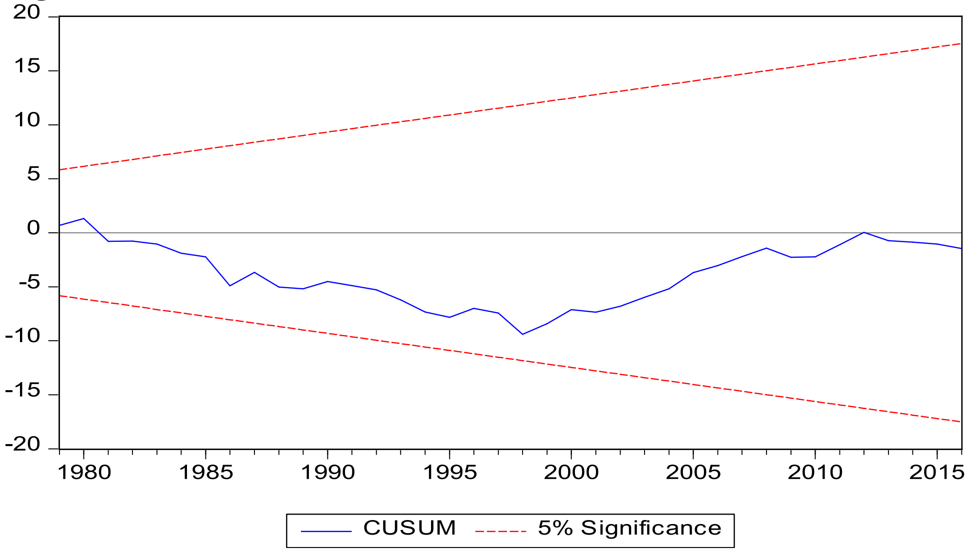
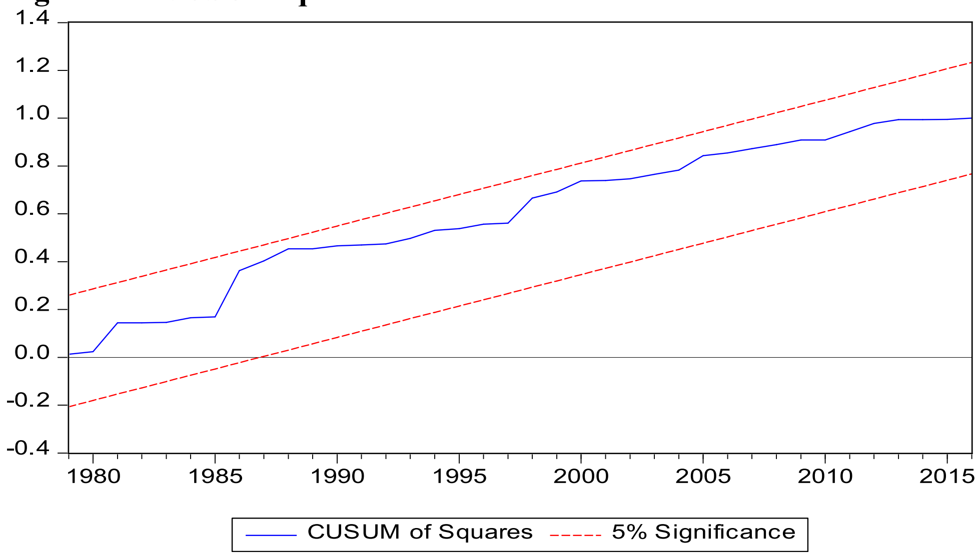


Figure 4B: CUSUMsq



The Trade Model

Figure 5B: CUSUM

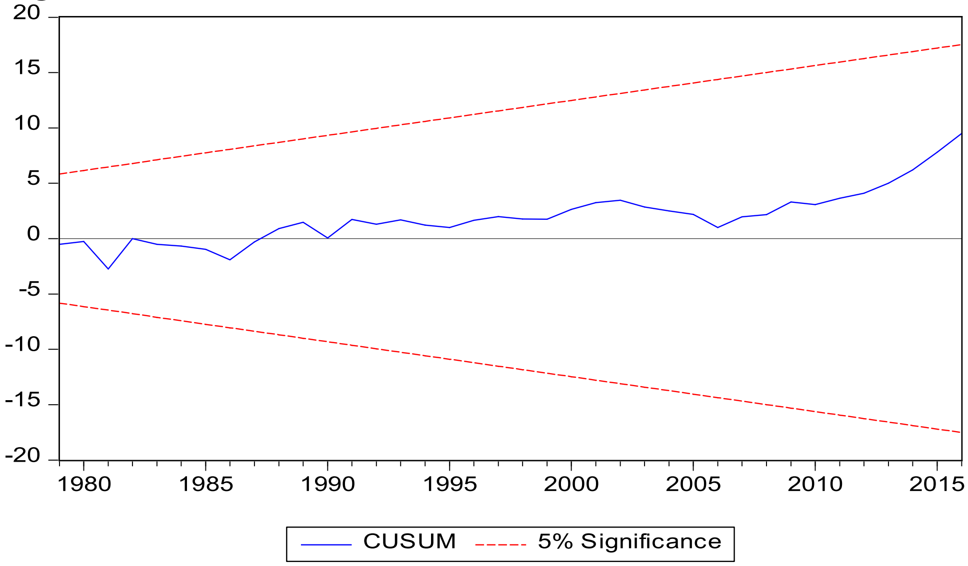


Figure 6B: CUSUMsq

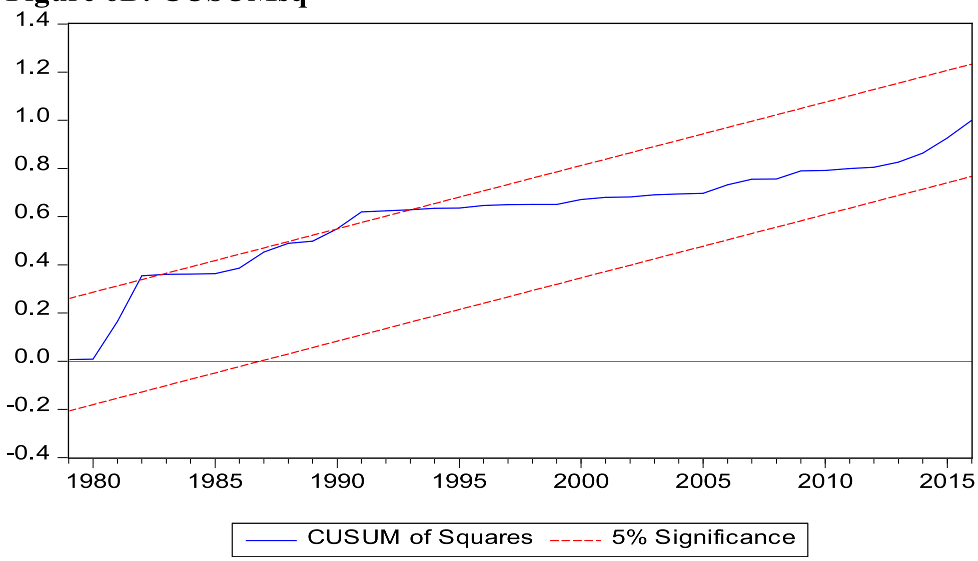


Table-2B: Chow Forecast Test

Test predictions for 1991-2016		
	Value	Probability
F-statistic	0.5394	0.9320
Likelihood ratio	28.6481	0.3273

II. Cubic Carbon Emissions Function

The Exports Model

Figure 7B: CUSUM

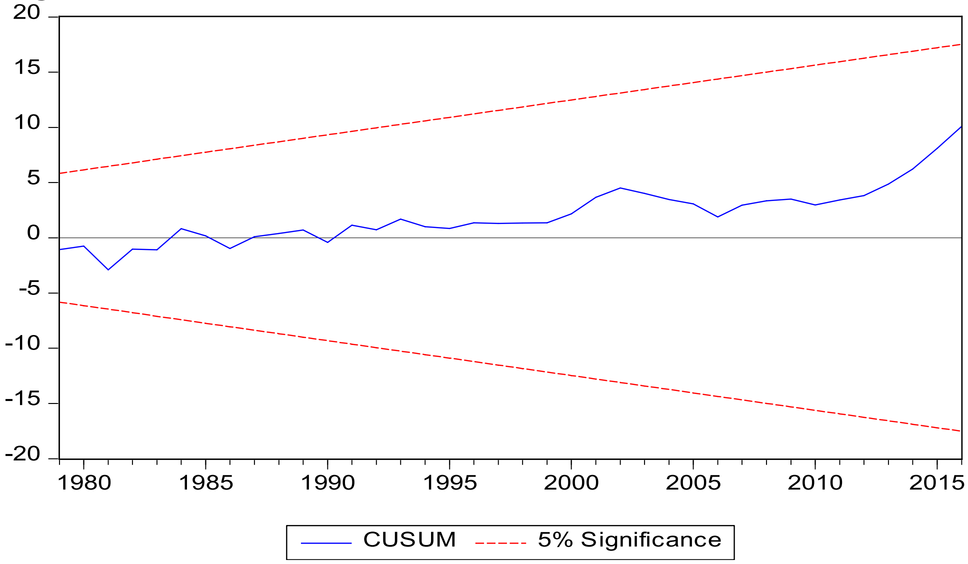
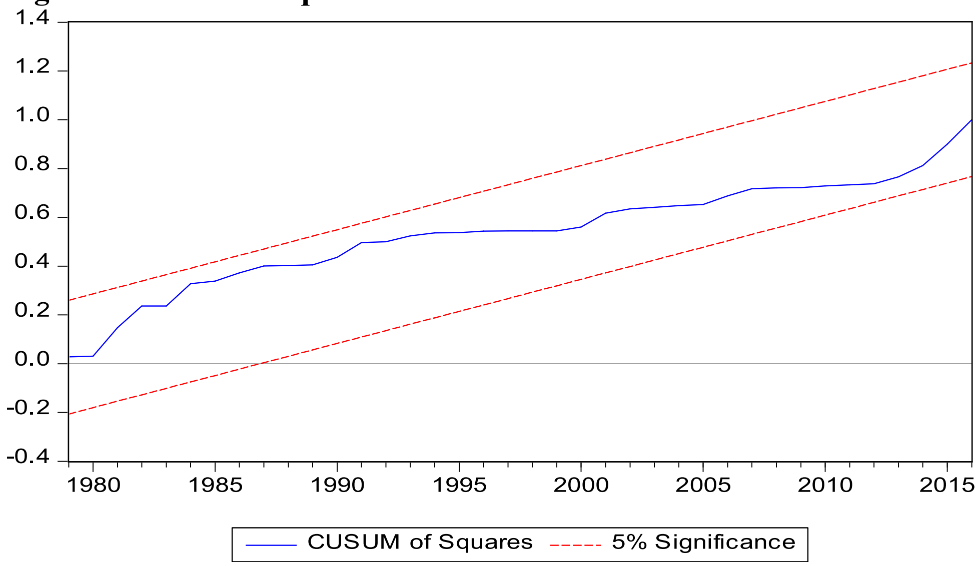


Figure-8B: CUSUMsq



The Imports Model

Figure 9B: CUSUM

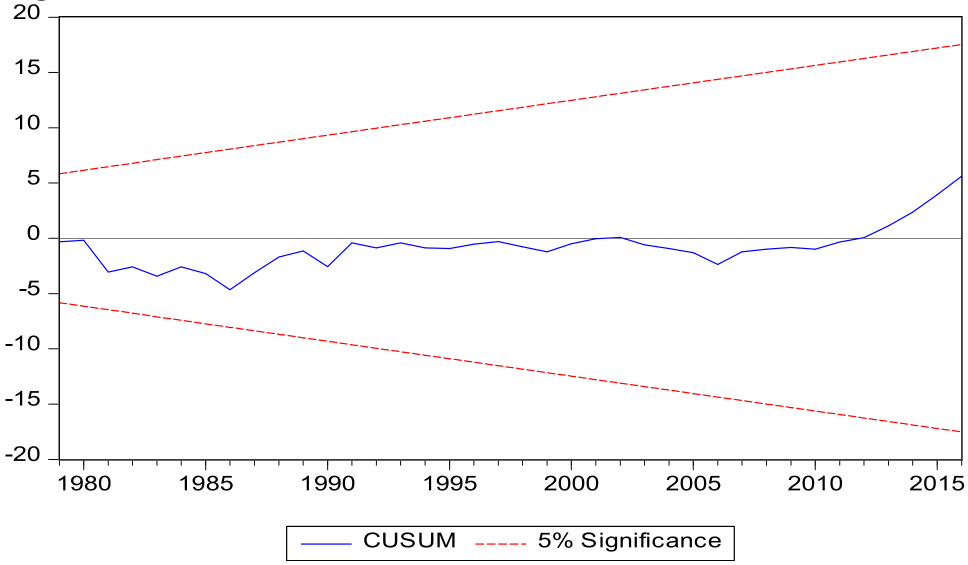


Figure 10B: CUSUMsq

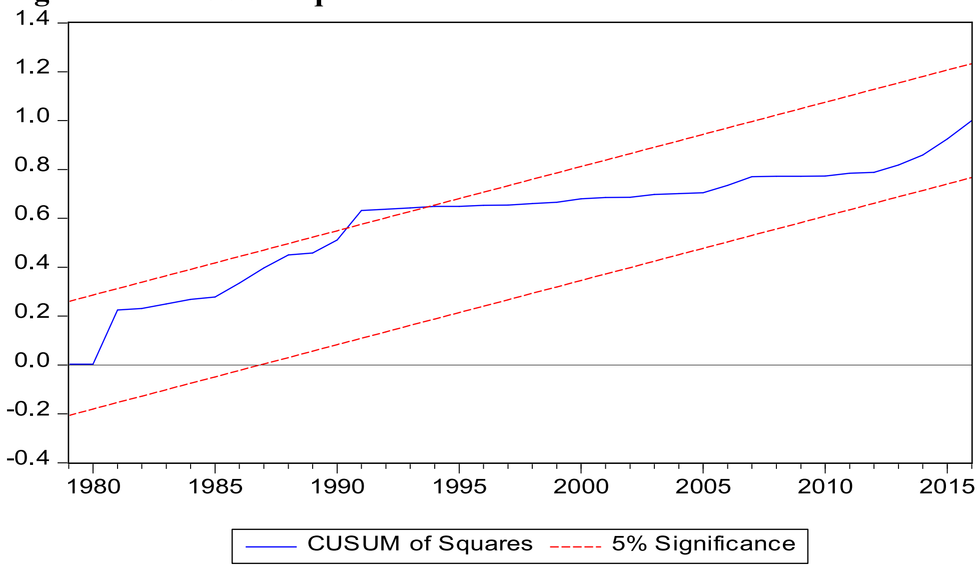


Table-3B: Chow Forecast Test

Test predictions for 1990-2016		
	Value	Probability
F-statistic	0.577825	0.9063
Likelihood ratio	33.56928	0.1789

The Trade Model

Figure 11B: CUSUM

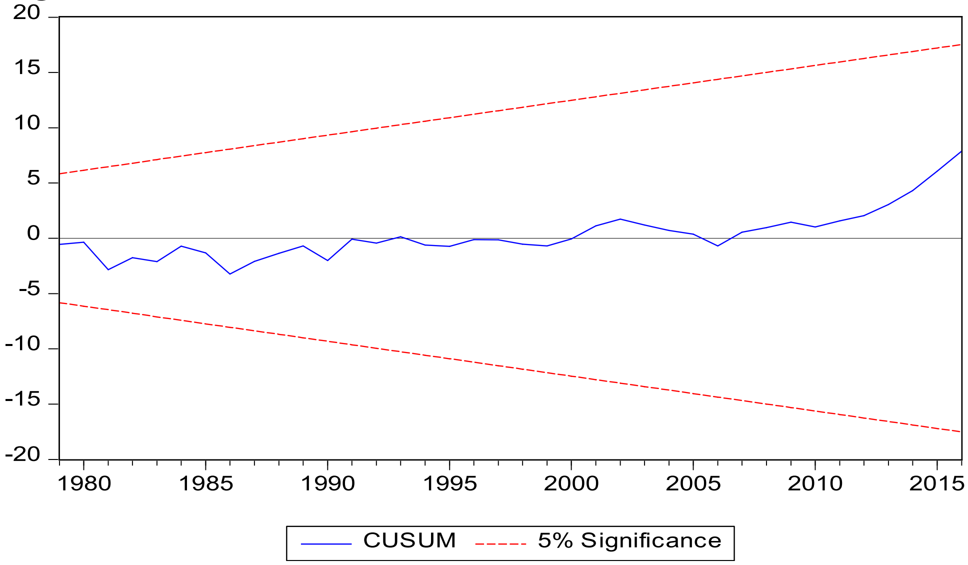
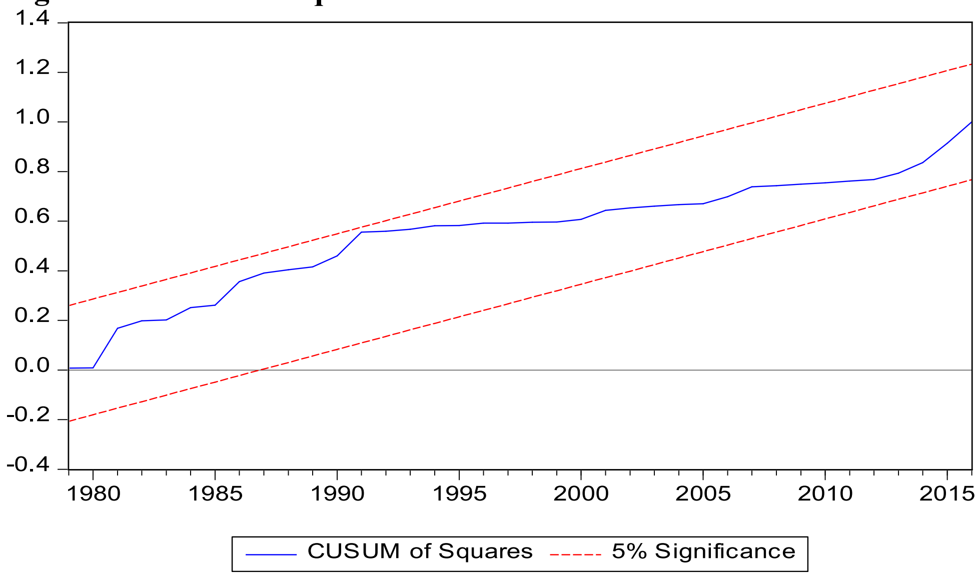


Figure 12B: CUSUMsq



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