ENERGY CONSUMPTION IN THE US RECONSIDERED. EVIDENCE ACROSS SOURCES AND ECONOMIC SECTORS.

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Abstract

This study analyzes the impact of GDP shocks in USA on primary energy consumption and the reverse impact in a comprehensive and novel framework, distinguishing by economic sectors (commercial, industrial, residential and transportation) and energy source, i.e., total fossil (coal, natural gas and petroleum), nuclear, and renewable (hydroelectric, geothermal and biomass) for the period 1973:1 to 2015:2. To this end, we apply Granger causality analysis through the Hatemi-J [1] and Toda and Yamamoto [2] approaches from a time series perspective to evaluate the existence of asymmetries on this bidirectional relationship. The empirical results suggest that the impact of GDP on primary energy consumption is heterogeneous and energy source-specific, and an asymmetric behavior appears among cycles. Moreover, it seems clear that the US economy is highly dependent on petroleum energy consumption. The renewable energy sources do not seem to show any relationshipsources seem to show no relationship with economic growth, and finally, our results suggest that energy consumption in the industrial sector is key to economic growth and is also very sensitive to negative economic shocks.

***Keywords*:** Energy consumption; growth; Granger causality, asymmetric causality.

1. Introduction

Meeting the essential energy needs economically and sustainably requires a balanced energy portfolio that is suited to the economic, social, and resource conditions of individual countries and regions [3]. Furthermore, the International Energy Agency [4] warns that current trends in energy supply and use are still economically, environmentally and socially unsustainable. In this context, renewable energy sources, such as wind, solar, hydro, geothermal, and bioenergy, have partially replaced the fossil fuels and nuclear power in four distinct markets: power generation, thermal applications, transport fuels energy and non-networked services in rural areas in developing countries. Overall, investment in renewable energy has grown exponentially in recent years - from 22,000 million dollars in 2004 to 211,000 million dollars in 2010 - while the involvement of countries in promoting the use of alternative energy sources has also been evident; 118 countries had some types of policies to support renewable energy, well above the 55 countries that had such policies in place in 2005 [5]. In 2012, the USA was responsible for 18% of the world's total primary energy consumption. In this country, petroleum is the main source of energy among the fossil fuels in the U.S. energy mix. Nevertheless, renewable energies have experienced a remarkable popularity in recent years, when the use of renewable energy increased from approximately 16.8 million metric tons of oil equivalent in 2001 to nearly 60 million metric tons of oil equivalent in 2013, whereas 13 percent of the nation's total electricity generation was derived from biomass, hydro and wind sources.

Comprehending the actual direction of causality between energy consumption and economic growth has substantial implications for policymakers as well as for the natural environment, at least with respect to reducing the consumption of non-renewable energies and consequently the impact on the environment through the reduction of carbon dioxide (CO_2) emissions [6]. A unidirectional causal relationship from energy consumption to growth reflects an unsustainable energy security situation even with high energy resources present in one country [7]. From an optimistic point of view, continuous technological advancements and the possibility of substitution of natural inputs with manmade capital sustains growth trends ([8] or [9]). However, in terms of empirical research, academics are far from establishing a clear consensus about the direction of causality.

Although many studies have investigated the relation between energy consumption and economic growth, few studies have paid attention to this relationship by breaking down the different energy sources and distinguishing by economic sectors. To shed more light on this relationship, in this paper, we analyze the impact of GDP shocks in the USA on primary energy consumption (and viceversa) applying a Granger causality approach. As a novel approach in terms of the previous literature, we investigate the possible existence of asymmetries on the bidirectional relationship, distinguishing by total fossil (coal, natural gas and petroleum), nuclear and renewable (hydroelectric, geothermal and biomass) energies and by economic sector, in a comprehensive study on the little-studied possible relationship between growth and energy consumption. In other words, our paper presents a novel study in the energy economics literature that not only explores the causal relationships by sector, but even more importantly, it also investigates how to vary these relationships for different economic cycles. To accomplish this, we analyze a sample of these energy sources for the USA during the period 1973:Q1 to 2015:Q2, using real GDP as the economic growth indicator. Our econometric strategy consists of a set of techniques developed by Hatemi-J [1] and Toda and Yamamoto [2] for a Granger causality analysis from a time series perspective. Our results support heterogeneous evidence on the impact of GDP on primary energy consumption and the appearance of an asymmetric behavior among cycles.

The remainder of this paper is organized according to the following scheme. Section 2 illustrates the theoretical and empirical background on energy consumption and growth. Section 3 provides the data and methods description used in the empirical analysis. Section 4 outlines the main results, and section 5 provides the main conclusions and some useful recommendations for policy makers.

2. The relationships between energy and GDP growth

Since the seminal work of Kraft and Kraft [10], in which the relationship between energy consumption and GDP growth was established for the USA with causality running from GDP to energy, much literature concerning this relationship has sought to determine the direction of causality. Nonetheless, a common alternative is to study this relationship from the supply side in a production function approach [see for instance [11] or [12]), and from a demand side perspective that investigates the relationship between energy consumption, economic growth and energy prices [see [13] or [14] among others]. However, as is well known, this emerging literature can be divided into three strands depending on the focus of research: 1) environmental pollutants and GDP growth, which tests the validity of the Environmental Kuznet's Curve (EKC) hypothesis; 2) the causality running from GDP to energy; and 3) a combined approach, which is perhaps the least studied [7].

Thus, many researchers have emerged who have put the focus on the supply or demand side, including a range of control variables, in order to establish a complete explanation of the relationship between GDP and energy consumption. The possibilities that can drive the production model will depend on the availability; for example, the different economies may have different sources in relation to costs and prices. For instance, renewable energy sources remain significantly more expensive than fossil fuel and represent only a small fraction (less than 5%) of the total primary US energy consumption. This small contribution may explain why there is no causality between renewable energy sources and economic growth. Camarero et al., [15] show a broad overview of the control variables used in the literature with the aim of measuring the relationship between energy consumption and economic growth. These variables include: employment, energy prices, government spending, gross fixed capital formation, real money supply, energy intensity, energy efficiency, business sector productivity and exports.

Furthermore, a common problem in a bivariate analysis is the possibility of omitted variable bias ([16] or [17]). Recognizing this omitted variable problem, several studies incorporate additional variables in their analysis. However, the inclusion of control variables is not without problems. First, the choice of these variables has been ad hoc, made according to the subjective economic rationale of the authors [15]. Additionally, a recent survey by Narayan and Smyth [18] about this literature warns of the trade-off that necessarily emerges using the bivariate model, which is susceptible to omitted variable bias, and using a multivariate approach has an associated risk of over-parameterization of the model, which contributes to estimation error [18]. Finally, the data about control variables are not as complete as those about the energy consumption and GDP variables, either in terms of high frequency data or time span. To avoid this problem, in our study, we propose a bivariate analysis to test the energy consumption-GDP nexus causality by sector and address asymmetries.

To establish a comprehensive framework on the energy consumption and growth relationship, following the main surveys in the literature, including the works of Kraft and Kraft [10], Özturk [19] and recently Omri [20], several hypotheses have been developed on this regard, summarizing the causal relationship in four ways. First, the *Growth hypothesis* suggests that energy consumption causes GDP growth; i.e., the availability of abundant cheap energy sources promotes economic growth. In that sense, although increases in energy consumption may contribute to further economic growth, reductions in energy consumption may have negative effects on growth. Second, the *Conservation hypothesis* recognizes the unidirectional causality from GDP growth to energy consumption and consequently any conservation policies concerning energy consumption will have little or no adverse effect on economic growth. Third, the *Feedback hypothesis* suggest bidirectional causality flows between GDP and energy consumption. Finally, the *Neutrality hypothesis* or no causality suggests no correlation between GDP and energy consumption and consequently energy scarcity and conservative policies in relation to energy use do not affect economic growth.

A great part of the existing research has been conducted on developed countries due the fact that high frequency data and time span are complete only in these countries. He shows in a review of 48 articles that regarding the energy consumption-growth connection, 29% of the articles support the growth hypothesis, 27% of the articles support the feedback hypothesis, 23% of the articles support the conservation hypothesis, and 21% of the articles support the neutrality hypothesis. Previously, Payne [17] provided similar results in his survey, concluding in an analysis including 101 studies over the period 1978 to 2008 that there was no clear consensus: 23.1% of the studies showed unidirectional causality from energy consumption to GDP growth, 19.5% of the studies found causality from GDP growth to energy consumption, 28.2% of the studies showed a bidirectional relationship, and 29.2% of the studies showed no relationship.

Although all of these hypotheses may be equally valid, it is only possible to discriminate between them empirically; unfortunately, the empirical findings do not provide conclusive results. There are various reasons for the lack of consensus in the literature. A great part of the existing research has been conducted for developed countries, due the fact that data, frequency and time span are complete only in these countries. Among the factors involved in this controversy over the link between growth and energy consumption, we can find in the literature some potential sources, such as the sample periods, model specifications, different consumption patterns, omitted variable bias, trade agreements among countries, structural frameworks and the policies followed by countries, the varying impacts from different sources of energy, their energy imports and exports profile, the different development stages and processes in each country or the cross-section dependence between countries, which is usually overseen and leads to biased results (see [17], [19], [20] or [21], for a surveys).[1] In that

[1] Kraft and Kraft [10] summarizes four primary econometric approaches to analyze the causal relationship: Granger–Sims causality testing, Engle–Granger/Johanssen–Juselius cointegration and error-correction modeling, Toda–

sense, Menegaki [7] argues that the long-run elasticity of GDP growth with respect to energy consumption is not independent of the method employed for cointegration, the data type and the inclusion of variables, such as the price level or capital, in the cointegration equation. Hence, he proposes that a 1% increase in capital increases the elasticity of GDP with respect to energy consumption by 0.85%. However, the recent meta-analysis by Kalimeris *et al*. [21] supports neither the existence of a fundamental "macro" direction nor the so-called neutrality hypothesis in the causal relationship between energy consumption and economic growth.

Nonetheless, another factor that arises in the mentioned empirical controversy is the type of energy included in the analysis that addresses the causality between energy consumption and growth. Although most studies have used electricity as a source of energy consumption, in recent years there has been a growing interest in knowing the relationship between the different sources of energy and economic growth, i.e., the fossil fuels, nuclear energy and renewable energy. According to the recent survey by Omri [20], we can observe empirical evidence supporting each type of hypothesis with several energy sources. Concerning the electricity consumption-growth connection, 40% of the studies in the survey supported the growth hypothesis, 33% of the studies supported the feedback hypothesis, and 27% of the studies supported the conservation hypothesis; regarding the nuclear consumption-growth nexus: 60% of the studies supported the neutrality hypothesis, and 40% of the studies supported the growth hypothesis; and concerning the renewable consumption-growth nexus: 40% of the studies supported the neutrality hypothesis, 40% of the studies the conservation hypothesis and 20% of the studies supported the growth hypothesis. Ohler and Fetters [22] contribute with empirical research concerning different energy sources across 20 OECD countries from 1990 to 2008, showing four sets of results from a commonly used panel error correction model. A bidirectional relationship between aggregate renewable generation and real GDP exists, whereas biomass, hydroelectricity, waste, and wind energy exhibit a positive long-run relationship with GDP. Conversely, hydroelectricity and waste generation exhibit a short-run positive bidirectional relationship with GDP

Yamamoto long-run causality testing, and panel cointegration error correction modeling. Belke *et al.* [23] summarize the main econometric approaches used in the literatura: the vector autoregression method (VAR), which assumes stationarity of the underlying variables; the Engle and Granger procedure, which also considers non-stationarity; Johansen's multivariate approach, which includes more variables in the cointegration relationship; and the panel estimation techniques.

growth, and finally biomass, hydroelectric, and waste electricity generation have the largest impact on real GDP in the long-run. Ohlen and Fetters also analyze the existence of structural breaks and cross-sectional dependence and find that in the short-run, increases in biomass and waste generation negatively affect GDP, whereas aggregate renewable and hydroelectricity increase GDP. Ohler and Fetters [22] also argue that biomass and waste generation are important drivers in the renewable energy–GDP relationship, but the environmental impacts between sources vary.[2]

Finally, to conduct a complete analysis concerning the causality between growth and energy consumption, we wonder if this relationship holds in different economic sectors. Gross [24] warn that bivariate models, which analyze the causality only at the macro level, are eventually misleading because the relationship between energy and growth seems to be neutral on the macro level; however, the Granger causality for a lower level of aggregation in some cases emerges (see [25]; [26]). In other words, he reminds us of 'Simpson's Paradox' [27], who argued that in statistical analyses it is not uncommon that evidence can be found for a lower level of aggregation while the results for the total population suggest the opposite.[3] Another reason is that the literature recognizes that the different energy demands that exist for each economic sector are supported by the EKC hypothesis. The shift in the composition of output in the economy could affect the energy consumption-output relationship because different industries may have different energy intensities, i.e., when the country passes to an economy based on the service sector, the energy demands decline [28]. Thus, to find an adequate response to this, it is necessary to include matters related to the capture of the GDP allocation by the three productive sectors because some of the divergence across sectors can be explained by the fundamental differences between goods and service producing industries [24].

The next subsection is devoted to an explanation of the relationship established

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[2] Omri et al. [29] provides an extensive summary of empirical studies on the causality between nuclear and renewable energy consumption and growth (see Table 1).

[3] Gross [24] warns that the potential linkages between the input of transport fuels and the related output would be distorted by all other economic activities. As an example, he proposes that total GDP is dominated by the commercial sector, which does not make extensive use of transport services compared to the industry sector. Taking GDP as the growth variable would then mainly account for production processes in which transport services are not required.

between growth and each specific source of energy, total fossil (coal, natural and petroleum), nuclear and renewable energies (hydroelectric, geothermal and bio-mass) and by economic sector (commercial, industrial, residential and transportation). To explore the mentioned puzzle regarding the causal relationship and the direction, we provide in Table 1 a summary of selected papers following the exhaustive survey of Omri [20], classified by author, country, period, energy source and its measure, data source, methodology, the main result and the confirmed hypothesis. In this survey, we observe that these mixed results are also supported in the recent literature.

Existing empirical evidence in the US

The novel study analyzing the causal relationship among energy consumption and growth in the USA was conducted by Kraft and Kraft [10], who found that GDP caused energy consumption. Later Stern [30] found support for thisor this result and revealed that the opposite causality also appeared. At the moment, the evidence is still mixed in the US. The causes of this lack of consensus can be found in the arguments above. Nevertheless, the majority of studies at a macro perspective for the U.S. find neutrality between energy and growth at the macro level [24]. However, among the results that emerge in literature, common analysis of the causal link between growth and energy consumption has not discriminated between power sources. Attention in recent years has perhaps mainly focused on the distinction between renewable and non-renewable energies. In fact, Sari et al. [31] analyzed the two-way causality between renewable energy consumption and industrial energy consumption in the USA over the period of 1969-2009 and found support for the conservation hypothesis.

To obtain a better understanding of the use of energy sources and their role in growth, the empirical evidence available in the case of the US has produced some interesting results. Kum et al. [32] found evidence of bidirectional Granger-causality between natural gas and growth. Payne [33] found evidence of unidirectional Granger-causality running from biomass energy consumption to real GDP and hence obtained support for the growth hypothesis. In another work, Payne [34] analyzed the case of coal consumption neglect the Granger-causality between coal consumption and real GDP; however, he found support for positive unidirectional Granger-causality running from real GDP to natural gas consumption and positive unidirectional Granger-causality running from petroleum consumption to real GDP.

Regarding the USA renewable energies evidence, the Conservation Hypothesis has been supported by Sari *et al.* [30] and Menyah and Wolde-Rufael [35], who found support for unidirectional causality from growth to renewable energy. Other contributions have appeared in favor of the Growth Hypothesis: for instance, [33] and [28]. Finally, there is also evidence in line of the Neutrality Hypothesis in the case of renewable energies in the work of Payne [36]. Particularly, biomass energy has been investigated in Payne [33] through the causal relationship between biomass energy consumption and real GDP, where the empirical findings revealed the growth hypothesis.

Another line of research has investigated the relationship of growth and energy consumption focusing on the economic sectors, and some interesting results emerge in the existing literature for the U.S. For instance, Bowden and Payne [25] found evidence that the relationship between energy consumption and real GDP is not uniform across sectors. Bowden and Payen also affirm that Granger-causality is absent between total and transportation primary energy consumption and real GDP, while bidirectional Granger-causality is present between commercial and residential primary energy consumption and real GDP, respectively. Finally, their results indicate that industrial primary energy consumption Granger-causes real GDP. In another study, Gross [24] finds evidence for unidirectional long-run Granger causality in the commercial sector from growth to energy. He also finds evidence for bidirectional Granger causality in the transport sector, whereas in the industrial sector, controlling for trade is important for identifying short-run Granger causality when growth is the dependent variable.

Table 1

Selected papers on the energy consumption and growth hypothesis after 2014

Study	Country or countries	Period	Energy source and measure*	Data source	Methodology	Main result: Confirmed hypothesis
[37]	80 countries	1990 - 2012	Renewable energy, real gross fixed capital and labor (L).	U.S. Energy Information Administration and World Bank Development Indicators (WDI)	Canning and Pedroni long-run causality test	$\leftrightarrows$ ***Feedback Hypothesis***
[6]	U.S.	1973q1-2012q1	Primary energy consumption	U.S. Energy Information Administration and the Bureau of Economic Analysis of the U.S. Department of Commerce	Granger causality tests	$\boldsymbol{EC \mapsto GDP - Growth\ Hypothesis}$.
[35]	15 developing countries: Belarus, Bulgaria, Czech Republic, Latvia, Lithuania, Russian Federation;, Ukraine Albania, Macedonia, Moldova, Poland, Romania, Serbia, Slovak Republic and Slovenia.	1975–2010	Electricity consumption per capita	WDI (2013)	Panel causality approach	$\boldsymbol{EC \mapsto GDP - Growth\ Hypothesis}$. (Belarus and Bulgaria); $\boldsymbol{EC \leftarrow\!\shortmid Growth - Conservationh\ hypothesis}$ (Czech Republic, Latvia, Lithuania and the Russian Federation); $\leftrightarrows$ ***Feedback Hypothesis.*** (Ukraine -no Granger causality Albania, Macedonia, Moldova, Poland, Romania, Serbia, Slovak Republic and Slovenia).
[38]	Bangladesh, Bangladesh Egypt, Indonesia, Iran, Korea Mexico, Pakistan, Philippines, Turkey (N-11 countries except for Nigeria and Vietnam)	1971-2007/10/11	Energy use per capita	WDI (2013)	[2] bootstrapped AR metric causality approach	$\nLeftrightarrow$ ***Neutrality hypothesis*** (all of the countries except for Turkey). $\boldsymbol{EC \mapsto GDP - Growth\ Hypothesis}$ (Turkey)
[22]	20 OECD countries: Australia, Austria, Belgium, Canada, Denmark, France, Germany, Iceland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, United	1990-2008	Gross electricity production. Coal (bit.) Coal, Biomass.	International Energy Agency's dataset on world renewable and waste energy statistics & OECD.	Several panel cointegration tests, panel error correction models and analysis for structural breaks and cross-sectional dependence	$\leftrightarrows$ ***Feedback Hypothesis***

Study	Country or countries	Period	Energy source and measure*	Data source	Methodology	Main result: Confirmed hypothesis
	Kingdom, and United States.					
[39]	Brazil, Russian, India, China, Turkey and South Africa	1980-2011	OEC (oil energy consumption), CEC (coal energy consumption), NGC (natural gas energy consumption)	BP Statistical Review of World Energy 2011, WDI and International Financial Statistics of the IMF (International Monetary Fund).	ARDL (autoregressive distributed lag bounds)	⇆**Feedback hypothesis: Bi-directional causality** OEC and Y for all countries (long-run causality for China and India). NGC and Y for Brazil, Russia and Turkey.
[40]	U.S.	January 1973–October 2011.	Natural Gas Consumption, Primary Energy Consumption Total, Coal Consumption, Total Electricity End Use, Total Renewable Energy Consumption and real GDP.	U.S. Energy Information Admin- istration (June 2012 Monthly Energy Review) and http://www.bea.doc.gov/.3	Asymmetric Granger-causality developed by Hatemi-J	**Asymmetric Granger-causality** (i.e., Coal Consumption (CC), Natural Gas Consumption (NG), Primary Energy Consumption (PE), and Total Renewable Energy Consumption (TRE)) and GDP (all measured in growth rates). *Positive shocks* - $\boldsymbol{EC \mapsto GDP - Growth\ Hypothesis. EC \leftarrow Growth - Conservationh\ hypothesis}$ (growth rate of Total Electricity End Use (EC) to GDP growth rate). $\leftrightarrows$ $\boldsymbol{Feedback\ Hypothesis}$ (NG and GDP, PE and GDP and TRE and GDP) . *Negative shocks* – growth rates in CC and TRE do **not Granger-cause GDP growth**.
[41]	China, Brazil and India	1971-2010	Renewable energy; CO2 while trade openness.	WDI	The ARDL bounds testing approach to cointegration and vector error correction model (VECM)	$\leftrightarrows$ $\boldsymbol{Feedback\ Hypothesis.}$ (BRICS countries)
[42]	25 EU countries: Austria, Belgium, Bulgaria, Cyprus, the Czech Republic, Denmark, Estonia, Finland, France, Hungary, Greece, Germany, Ireland, Italy, Latvia, Lithuania, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and the United Kingdom	1993–2011	Energy consumption. Real gross fixed capital formation per capita in constant 2005 U.S. dollars.	WDI, 2013	Bootstrap Granger panel causality approach proposed by Kònya (2006)	$\nLeftrightarrow$ $\boldsymbol{Neutrality}$

Study	Country or countries	Period	Energy source and measure*	Data source	Methodology	Main result: Confirmed hypothesis
[43]	EU 15	1990-2011	Non-renewable energy consumption -total petroleum products, natural gas and solid fuels-. Renewable energy -biomass, hydropower, geothermal energy, wind and solar energy-.	EUROSTAT and OECD	Pedroni Panel Cointegration test, the fully modified OLS (FMOLS) technique, panel vector error correction model (Pesaran et al., 1999) and VECM Granger Causality Test.	$\boldsymbol{EC \mapsto GDP - Growth\ Hypothesis.}$ $(\boldsymbol{Renewable + Non\ renewable-})$ $\boldsymbol{EC \leftarrow\!\shortmid Growth - Conservationh\ hypothesis.}$ (Non renewable)
[44]	51 Sub-Sahara African countries	1980–2009	Biomass consumption [used extraction of Biomass in kt].	Penn World Table, version 8.0 and Global Material Flow Database	Autoregressive (AR) and individual AR processes, considers panel common AR and individual AR cointegration analyses and employs panel Dynamic Ordinary Least Squares (DOLS)	$\boldsymbol{EC \mapsto GDP - Growth\ Hypothesis}$
[45]	G7 countries: Canada, France, Germany, Italy, Japan, the UK and the USA	1980–2010	(iv) biomass consumption [used extraction of Biomass].	Penn World Table and from Global Material Flow Database	Uçnit root analyses, panel cointegration analyses, conventional OLS and dynamic OLS analyses	$\boldsymbol{EC \mapsto GDP - Growth\ Hypothesis.E}$
[46]	China	1977 to 2013(supply-side) and 1965 to 2011 (demand-side)	*Supply-side analysis* - output, labor, capital, coal consumption, oil consumption, renewable energy consumption and combined energy consumption. *Demand-side analysis* -income, coal consumption, oil consumption, renewable energy, combined energy consumption, coal price, crude oil price, combined coal and oil price index and carbon emissions.	WDI of July 2013, LABORSTA Labor Statistics Database, Labor Organization (ILO) and Statistical Review of World Energy, 2014 published by British Petroleum (BP)	Autoregressive distributed lag (ARDL) and vector error correction modeling (VECM)	$\boldsymbol{EC \leftarrow\!\shortmid Growth - Conservationh\ hypothesis}$ $\boldsymbol{EC \mapsto GDP - Growth\ Hypothesis.}$ **(coal, oil and renewables consumption**,)

Study	Country or countries	Period	Energy source and measure*	Data source	Methodology	Main result: Confirmed hypothesis
[29]	Argentina, Belgium, Brazil, Bulgaria, Canada, Finland, France, Hungary, India, Japan, Netherlands, Pakistan, Spain, Swe- den, Switzerland, the United Kingdom, and the United States.	1990-2011	Nuclear energy consumption, renewable energy consumption, gross fixed capital,formation, total labor force, CO2 emissions, real oil Price, crude oil, and oil consumption.	British Petroleum Statistical Review of World Energy and the WDI	Two- stage least squares (2SLS), three stage least squares (3SLS), and the generalized method of moments (GMM)	$\not\Leftrightarrow$ ***Neutrality hypothesis.*** (Finland, Hungary, India, Japan, Switzerland, and the U. K.) $\leftrightarrows$ ***Feedback Hypothesis.*** (Argentina, Brazil, France, Pakistan, and the USA) $\boldsymbol{EC \mapsto GDP - Growth\ Hypothesis}$. (Belgium and Spain). $\boldsymbol{EC}$ $\boldsymbol{\leftarrow\!\shortmid\ Growth}$ $\boldsymbol{-\ Conservationh\ hypothesis}$ (Bulgaria, Canada, Netherlands, and Sweden)
[47]	Nigeria	1971–2011	Electricity power consumption per capita.	WDI, 2014	Phillips–Perron (PP) test, and the Dickey–Fuller generalised least squares (DF-GLS) test KSS test, and the Zivot–Andrews test.	$\boldsymbol{EC \mapsto GDP - Growth\ Hypothesis}$

* In all the papers summarized the real GDP is used as the measures of growth. $\not\Leftrightarrow$ *Neutrality hypothesis.* $\leftrightarrows$ *Feedback Hypothesis.* $EC \mapsto GDP - Growth\ Hypothesis.\ EC \leftarrow\!\shortmid\ Growth - Conservation\ hypothesis$

3. Data and Methodology

3.1 Data

In this paper, we analyze the nature of the relationship between the GDP and primary energy consumption by source and economic sector for the USA. The data used are quarterly observations from 1973:1 to 2015:2. The primary energy consumption, measured in quadrillion British Thermal Units (BTu), is disaggregated by source, total fossil fuels (coal, natural gas, petroleum), nuclear energy, and total renewable energies (hydroelectric, geothermal, and biomass), and the total is extracted from the US Energy Information Administration (EIA). We approach our econometric applications by economic sectors: commercial, industrial, residential and transportation. The GDP data are taken from the US Bureau of Economic Analysis (BEA) and measured in billions of chained 2009 dollars. Before conducting the empirical analysis, the data were seasonally adjusted and converted to natural logarithms. The time plots of the series are shown in Appendix 1.

3.2. Methodology

The aim of our empirical strategy is to determine the possible existence of Granger causality relationships between GDP and energy consumption, using a set of econometric techniques to obtain more robust and comparable results. We analyze the Granger causality tests by applying the method proposed by Toda and Yamamoto [2] and, secondly, the methodology proposed by Hatemi-J [1] as an extension of Toda and Yamamoto [2], which allows us to analyze the asymmetric causality energy consumption by source and does not require us to previously test the existence of unit root or cointegration; that is, the variables in the system do not need to be stationary and can be used in level form.

3.2.1. Granger causality: *Toda-Yamamoto test.*

In energy economics, and more specifically in energy topics, perhaps the most common technique of examining the causality effects between variables is to use the Granger causality method based on the estimation of VAR models. The methodology proposed by Toda and Yamamoto [2] tries to measure causality to solve the problems stemming from the cointegration relationship and non-stationarity of the data series.

Furthermore, an asymmetric structure in the study of causality suggested by Granger and Yoon [48] is considered and extended by Hatemi-J [1] to analyze the effects on causality relationships.

For a broad study of our proposed relationship, we propose the Toda-Yamamoto causality approach as a developed version of the Granger causality test based on augmented-VAR models in levels and extra lags, which is a more efficient and robust results than the standard VAR model because it can lead to biased results, particularly with finite samples; see [49], [50], [51], [52] and [53]. The main advantage of the Toda-Yamamoto test is that it can be applied irrespective of the order of integration or whether the time series are cointegrated [54]. In our exercise, a bivariate model including the GDP and energy consumption by the source variables under analysis, we can describe the benchmark model for this test as follows:

$$GDP_t = \alpha_1 + \sum_{i=1}^{p+d_{max}} \beta_{1i}\, GDP_{t-i} + \sum_{j=1}^{p+d_{max}} \gamma_{1j}\, Energy_{t-j} + \varepsilon_{1t} \quad [1]$$

$$Energy_t = \alpha_2 + \sum_{i=1}^{p+d_{max}} \beta_{2i}\, Energy_{t-i} + \sum_{j=1}^{p+d_{max}} \gamma_{2j}\, GDP_{t-j} + \varepsilon_{2t} \quad [2]$$

According to the Akaike Information Criterion (AIC), p is the optimal lag length structure for the VAR model, where d_{max} is an extra lagged explanatory variable, i.e., is the maximum order of integration for the variables considered in the model, and $\varepsilon_{1t}\ and\ \varepsilon_{2t}$ are residual terms that are Gaussian distributed and follow white noise processes. Hence, this test estimates a $VAR\ (k)$ model using a Modified Wald test (MWALD) whose statistic is asymptotically distributed as chi-squared with p degrees of freedom. Therefore, we only need to establish the maximum order of integration d_{max}, and construct a VAR in their levels with a total of p+d_{max} lags."

To test the Granger causality between these two variables, note, for the first equation, that $\sum_{j=1}^{p} \gamma_{1j} \neq 0$ implies that $Energy_t$ Granger causes GDP_t. Analogously, in the second equation, $\sum_{j=1}^{p} \gamma_{2j} \neq 0$ implies that GDP Granger causes $Energy_t$.

Consequently, rejecting both hypotheses implies that there exists bidirectional causality in the analyzed relationship.

3.2.2. Looking for asymmetric causality relationships.

Concerning the empirical works, in many cases, causality is rejected because no nonlinear relationships are contemplated. To address this issue, a nonlinear test developed by Hatemi-J [1] based on the initial ideas of Granger and Yoon [41] is applied in our exercise, allowing us to determine whether the cumulative positive and negative shocks can cause different impacts on the causal relationship between GDP and energy consumption by source. In other words, This test allows for asymmetry in causality and separates the potential causal impact of positive (negative) shocks from the positive (negative) ones. Following this strategy, we initially specify our two variables by means of a random walk model:

$$GDP_t = GDP_{t-1} + \varepsilon_{1t} = GDP_0 + \sum_{i=1}^{t} \varepsilon_{1i} \qquad [3]$$

and

$$Energy_t = Energy_{t-1} + \varepsilon_{2t} = Energy_0 + \sum_{i=1}^{t} \varepsilon_{2i} \qquad [4]$$

where $t = 1, 2, \ldots T$; the constants GDP_0 and $Energy_0$ are the initial constant values; and the variables ε_{1i} and ε_{2i} are white noise disturbance terms. The shocks, positive and negative, are denoted as follows: $\varepsilon_{1i}^{+} = \max\ (\varepsilon_{1i}, 0)$; $\varepsilon_{2i}^{+} = \max\ (\varepsilon_{2i}, 0)$; $\varepsilon_{1i}^{-} = \min\ (\varepsilon_{1i}, 0)$; $\varepsilon_{2i}^{-} = \min\ (\varepsilon_{2i}, 0), respectively$. Grouping these terms as $\varepsilon_{1i} = \varepsilon_{1i}^{+} + \varepsilon_{1i}^{-}$ and $\varepsilon_{2i} = \varepsilon_{2i}^{+} + \varepsilon_{2i}^{-}$, we can write out the following:

$$GDP_t = GDP_{t-1} + \varepsilon_{1t} = GDP_0 + \sum_{i=1}^{t} \varepsilon_{1i}^{+} + \sum_{\square=1}^{t} \varepsilon_{1i}^{-} \qquad [5]$$

$$GDP_t = GDP_{t-1} + \varepsilon_{1t} = GDP_0 + \sum_{i=1}^{t} \varepsilon_{1i}^{+} + \sum_{i=1}^{t} \varepsilon_{1i}^{-} \qquad [6]$$

Therefore, positive and negative shocks can be written as follows:

$$GDP_t^+ = \sum_{i=1}^{t} \varepsilon_{1i}^+ \,; \; GDP_t^- = \sum_{i=1}^{t} \varepsilon_{1i}^- \,; Energy_t^+ = \sum_{i=1}^{t} \varepsilon_{2i}^+ \,; Energy_t^- = \sum_{i=1}^{t} \varepsilon$$

Assuming that $y_t^+ = (GDP_t^+, Energy_t^+)$, $y_t^- = (GDP_t^-, Energy_t^-)$, $y_t^\pm = (GDP_t^+, Energy_{1t}^-)$, and $y_t^\mp = (GDP_t^-, Energy_{1t}^+)$, the causal relationship between the variables can be tested using a vector autoregressive model VAR of order p , for lag order $r = (1, \ldots, p)$. To run a Wald test, the VAR (p) model can be written in a compact form (e.g., for the first combination, y_t^+):

$Y = DZ + \delta$, where

$Y \coloneqq (y_1^+, \ldots, y_T^+)\ (n\ x\ T)\ matrix,$

$D \coloneqq \left(v, A_1 \ldots, A_p\right)\ (n\ x\ (1 + np))\ matrix,$

$$Z_t \coloneqq \begin{pmatrix} 1 \\ y_t^+ \\ y^+{}_{t-1} \\ \vdots \\ y_{t-p+1}^+ \end{pmatrix} ((1 + np)\ x\ 1)\ matrix, for\ t = 1, \ldots, T,$$

$Z \coloneqq (Z_0 \ldots, Z_{T-1})\ ((1 + np)\ x\ T)\ matrix, and$

$\delta \coloneqq (u_1^+, \ldots, u_T^+)\ (n\ x\ T)\ matrix$

The MWald statistic is $(C\beta)'\ \left[C((Z'Z)^{-1} \otimes S_U)C'\right]^{-1} (C\beta)$, where $\beta = vec(D)$, and *vec(·)* is the column-stacking operator; ⊗ is the Kronecker product; C is a $p\ x\ n(1 + np)$ indicator matrix with elements of one for restricted parameters and zeros for the rest of the parameters; and $S_U = \frac{\hat{\delta}'_U \hat{\delta}_U}{T-q}$, where q is the number of parameters in each equation of the VAR model. Under the assumption of normality, the Wald statistic follows an asymptotic χ^2 distribution with the same degrees of freedom as the number of restrictions to be tested (in our case, equal to p). The null hypothesis of non-Granger causality, $H_0: C\beta = 0$, is rejected at the α level of significance (1%, 5% or 10%) according to the bootstrap critical values generated by the GAUSS software.

4. Empirical Results: Granger causality findings

According to the econometric strategy previously described, in this section, we present the empirical findings on the Granger causality relationships established between the energy consumption by source and growth, allowing non-linear behavior between the variables using the methodology suggested by Toda and Yamamoto [2] and Hatemi-J [1]. In the next subsections, the results of these approaches are reported as distinguishing according to our goals: a) Table 2 presents the total primary energy; b) Table 3 includes the supply-side viewpoint for each energy source; c) Table 4 reports the demand-side viewpoint for each economic sector. It would make the reading more interesting and smooth because the causality results vary for different tests. In addition, to explore the issue in depth, we estimated asymmetric Granger-causality test statistics and tested their significance with 5.000 bootstrapped critical values. The estimation results are presented in Tables 2-4, while Table 5 summarizes the main results.

By looking at Table 2, we can see that linear and asymmetric non Granger-causality only from GDP is rejected at the 1% level of significance for total primary consumption. For all cases of the opposite causality, i.e., from energy consumption to GDP, we find that the null hypothesis that energy does not Granger-cause GDP is non-rejected.

Attending on the supply side, results are provided in table 3. These results also confirm the causality from GDP to energy except in the case of renewables energies. On the opposite, only in the case of petroleum and nuclear consumption we reject the null hypothesis that energy does not Granger caused GDP. In consequence, our findings also show evidence of the bidirectional Granger-causal relationship between energy consumption and economic growth in the petroleum and nuclear energy sources. Conversely, the results from asymmetric Granger-causality analysis reveal the importance to distinguish the direction of the causality. In the positive approach, it is important to distinguish the direction of the causality. Although the results are similar to the previous findings, in the case of a positive relationship from energy to GDP, we only reject the null hypothesis clearly in the petroleum case. Regarding the GDP to energy relationship, our results reveal that petroleum consumption is not Granger caused by GDP. When the Wald test statistic is used for negative shocks, the null hypothesis for non-Granger-causality from GDP to energy consumption is rejected only in three cases: total primary energy consumption, total fossil and coal. In the reverse case, from energy to GDP, petroleum and nuclear are the cases where we can reject the null hypothesis of causality.

Table 4, regarding the economic sectors, we find bidirectional causality in the commercial and industrial sector, whereas the transportation sector shows causality from GDP to energy consumption, and, finally, the reverse causality is achieved in the residential sector. For its par, the positive shocks in GDP cause positive shocks in energy consumption in the commercial and transport sector. Furthermore, focusing in the negative approach, the causality in the opposite direction appears only in the industrial sector. Finally, our results also confirm the causality from GDP to energy consumption in the industrial sector, whereas the transport sector shows the opposite behavior.

Table 2. Total energy consumption

	Test statistic	Bootstrap critical values			Test statistic	Bootstrap critical values		
		1%	5%	10%		1%	5%	10%
	$Energy \nRightarrow GDP$				$GDP \nRightarrow Energy$			
Total	4.013	11.472	7.498	6.160	29,980***	11.847	8.058	6.558
	$Energy^{+} \nRightarrow GDP^{+}$				$GDP^{+} \nRightarrow Energy^{+}$			
Total	2.010	9.977	6.036	4.707	11.218***	9.927	6.444	4.521
	$Energy^{-} \nRightarrow GDP^{-}$				$GDP^{-} \nRightarrow Energy^{-}$			
Total	1.717	10.075	6.196	4.480	11.528**	12.232	6.299	4.799

Notes: *, ** and *** indicate statistical significance at 10, 5 and 1% level respectively. Critical values are obtained from 5000 bootstrap replications.

Table 3. Energy sources, or supply side

	Test statistic	Bootstrap critical values			Test statistic	Bootstrap critical values		
		1%	5%	10%		1%	5%	10%
	$Energy \nRightarrow GDP$				$GDP \nRightarrow Energy$			
Total fossil	3.156	12.378	7.559	6.215	30.666***	11.847	8.203	6.364
Coal	0.619	10.152	6.111	4.512	17.269***	9.929	6.694	5.226
Natural Gas	1.796	11.553	7.826	6.400	10.660**	11.291	7.928	5.990
Petroleum	9.424***	9.240	6.079	4.749	10.220***	9.650	6.197	4.475
Nuclear	11.042**	16.639	10.964	9.029	16.304***	15.024	11.025	9.466
Renewable	0.788	8.503	5.912	4.554	0.071	9.491	5.708	4.272

Hydroelectric	0.857	8.181	5.623	4.398	0.188	9.219	6.113	4.567
Geothermal	0.739	10.290	6.483	4.882	3.447	9.206	6.157	4.138
Biomass	3.110	19.137	14.061	11.276	8.459	19.329	13.475	11.431
	$Energy^{+} \nRightarrow GDP^{+}$				$GDP^{+} \nRightarrow Energy^{+}$			
Total fossil	1.391	9.382	6.197	4.621	9.055*	9.648	6.530	4.612
Coal	1.758	9.305	5.895	4.709	12.335***	9.391	6.102	4.631
Natural Gas	1.290	10.206	6.309	4.734	7.501**	9.835	6.167	4.717
Petroleum	29.552***	23.172	17.258	13.826	13.010	21.262	16.171	13.416
Nuclear	10.864	18.513	13.337	10.975	22.789***	18.284	13.515	11.473
Renewable	0.268	8.928	6.231	4.687	0.000	9.787	5.931	4.853
Hydroelectric	2.307	8.887	6.065	4.604	0.198	9.681	6.179	4.873
Geothermal	2.473	10.781	6.487	4.488	14.724***	10.383	6.544	4.975
Biomass	4.438	11.581	6.132	4.824	1.270	11.065	6.275	4.821
	$Energy^{-} \nRightarrow GDP^{-}$				$GDP^{-} \nRightarrow Energy^{-}$			
Total fossil	1.523	9.653	6.308	4.799	15.806***	11.434	6.263	4.760
Coal	0.325	12.451	7.013	4.981	8.173**	11.759	6.351	4.759
Natural Gas	4.645	12.189	8.217	6.397	5.686	12.897	7.913	6.008
Petroleum	41.086***	16.614	10.190	8.060	1.227	14.414	10.289	8.389
Nuclear	27.243**	34.072	18.488	12.049	2.753	23.209	13.992	10.222
Renewable	1.576	13.077	6.514	4.599	2.130	11.992	6.771	4.777
Hydroelectric	3.882	13.356	6.643	4.787	0.007	10.862	6.220	4.786
Geothermal	1.585	14.033	6.999	4.805	1.901	14.263	7.814	4.681

Notes: *, ** and *** indicate statistical significance at 10, 5 and 1% level respectively. Critical values are obtained from 5000 bootstrap replications.

Table 4. Economic sectors, or Demand side

Global	Test statistic	Bootstrap critical values			Test statistic	Bootstrap critical values		
		1%	5%	10%		1%	5%	10%
	$Energy \nRightarrow GDP$				$GDP \nRightarrow Energy$			
Residential	7.384*	13.369	8.613	6.885	4.522	11.333	8.012	6.273
Commercial	10.535**	12.384	9.413	7.848	18.170***	14.328	10.252	8.214
Industrial	9.704**	10.657	6.454	5.030	33.535***	10.176	6.620	4.736
Transportation	0.347	9.424	6.074	4.820	18.818***	10.504	6.106	4.657
	$Energy^{+} \nRightarrow GDP^{+}$				$GDP^{+} \nRightarrow Energy^{+}$			
Residential	4.546	12.216	8.369	6.274	3.229	12.531	8.468	6.538
Commercial	2.300	9.011	5.950	4.723	8.635**	9.894	6.422	4.772
Industrial	11.386***	10.631	6.095	4.463	3.978	9.849	5.822	4.555
Transportation	0.384	9.861	6.513	5.053	7.917**	9.698	6.023	4.529
	$Energy^{-} \nRightarrow GDP^{-}$				$GDP^{-} \nRightarrow Energy^{-}$			
Residential	1.710	14.494	7.829	6.330	2.512	12.995	8.508	6.586
Commercial	6.332	18.049	11.418	9.113	1.982	16.161	10.553	7.901
Industrial	7.583	24.005	16.078	12.988	84.300***	22.803	16.859	13.762
Transportation	46.154***	28.162	14.596	11.107	5.878	15.853	11.630	9.859

Notes: *, ** and *** indicate statistical significance at 10, 5 and 1% level respectively. Critical values are obtained from 5000 bootstrap replications.

Finally, to better meet the set of found results, the results are synthesized in Table 5. Among the most relevant findings, according to the energy sources or supply side, we note that the conservation hypothesis is supported in the case of total fossils (including natural gas and coal), nuclear and total primary energy sources. Additionally, the relationship established by the feedback hypothesis is supported in the case of petroleum and nuclear energies, whereas the neutrality hypothesis is confirmed only for renewables. When the asymmetries are observed, we confirmed that the growth hypothesis is an interesting result because only the petroleum energy source has an important role in the positive shocks of GDP. Thus, we can see that negative shocks in the GDP occur when there are falls in the consumption of oil and nuclear energy. Moreover, it seems clear that the conservation hypothesis is very clear with respect to primary energy consumption, total fossil and coal, independent of the direction of the shocks in the economy. In this sense, the conservation hypothesis is supported for positive shocks in natural gas and nuclear energy; however, we do not find evidence for negative shocks. For renewable energies, the results reveal again the neutrality hypothesis.

The approximation made for the economic sectors, i.e. from demand side, provide different results. The industrial sector seems to be the determinant of economic growth. In this sense, the growth hypothesis is confirmed in the linear approximation and the positive effects. By contrast, in response to the negative effects, the conservation hypothesis is shown in the industrial sector. The commercial and transportation sectors also confirm the hypothesis of conservation in positive effects.

Table 5. Summary of Results

Objective	H_0: Energy $\nRightarrow$ GDP Growth	H_0: GDP $\nRightarrow$ Energy Conservation	Bidirectionality Feedback	No causality Neutrality
Total		✓ ***Linear*** ✓ ***Positive*** ✓ ***Negative***		
Supply side				
	✓ ***Positive***: Petroleum ✓ ***Negative***: Petroleum and Nuclear	✓ ***Linear***: Total fossil, coal, natural gas ✓ ***Positive***: Total fossil, coal, natural gas, nuclear and	✓ ***Linear***: Petroleum and nuclear	

		geothermal. ✓ ***Negative***: Total fossil and coal	
Demand side	✓ ***Linear:*** Residential ✓ ***Positive:*** Industrial. ✓ ***Negative:*** Transportation	✓ ***Linear:*** Transportation ✓ ***Positive:*** Comercial and transportation. ***Negative:*** Industrial	✓ ***Linear:*** Comercial and industrial

5. Conclusions

Determination of the causal link between growth and energy consumption has captured the interest of researchers, academics and politicians because of its implications for economic development, the environment, and the appropriate use of energy resources. Unfortunately, although a large number of articles have been devoted to trying to explain this relationship, there is a surprising lack of consensus in the literature on the directions of causality. This study has analyzed the impact of GDP shocks in the USA on primary energy consumption and the reverse impact, distinguishing by total fossil (coal, natural gas and petroleum), nuclear, and renewable (hydroelectric, geothermal and biomass) and distinguishing by economic sectors for the period 1973:1 to 2015:2. To this end, we applied the Toda and Yamamoto [2] and Hatemi-J. [1] approaches for a Granger causality analysis from a time series perspective to evaluate the existence of asymmetries in this bidirectional relationship.

Our empirical results suggest that GDP causes energy consumption, i.e., the conservation hypothesis is confirmed independently of the linear or asymmetric perspective. When causality is observed on the side of supply, energy sources confirm different assumptions and fundamentally distinguish between renewable and non-renewable energy. On the one hand, we have nonrenewable energy in a causal relationship with GDP, confirming the neutral hypothesis. However, the behaviour within the non-renewable energy is mixed. Although the conservation hypothesis is confirmed for most sources, nuclear energy and oil either have different patterns or asymmetrical linear function analyses. Consequently, our work guarantees that oil appears as the source that is most determinant for growth energy; it is the only energy source that confirms the hypothesis of growth. On the demand side, there is a bidirectional causality between sectors and energy consumption. In addition, positive shocks in the industrial sector would generate positive shocks in GDP.

In summary, due to the observation of different patterns by energy sources and sectors, and most importantly, the effect of economic shocks, it would be advisable for policy makers to consider the time when policy measures are taken and to establish a suitable framework for a balance between renewable and nonrenewable energy sources."

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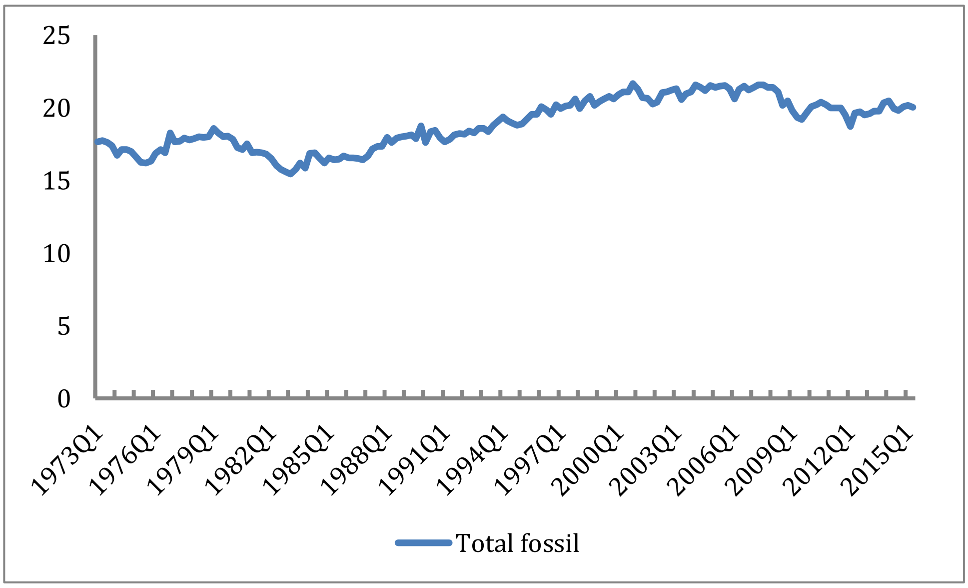
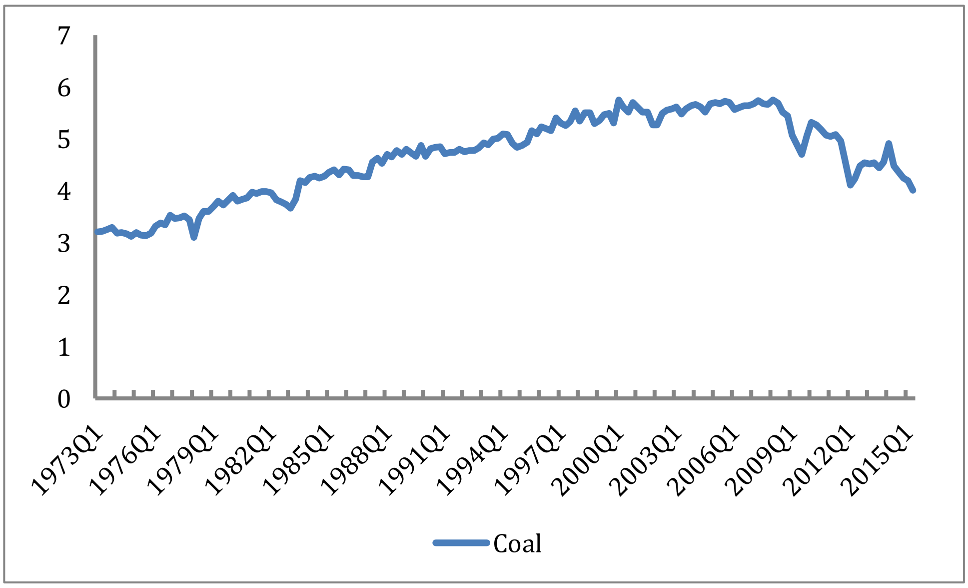
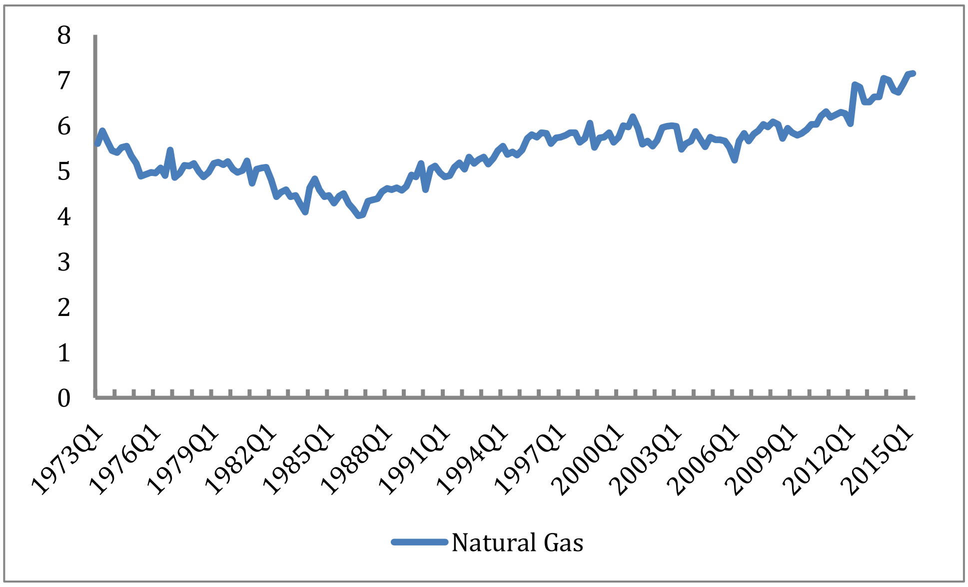
APPENDIX

***A1. Time plots of the variables** (All the variables included in this append are expressed in logs).*

A.1.1 Energy consumption by source and sectors *(measured in quadrillion British Thermal Units (BTu)).*



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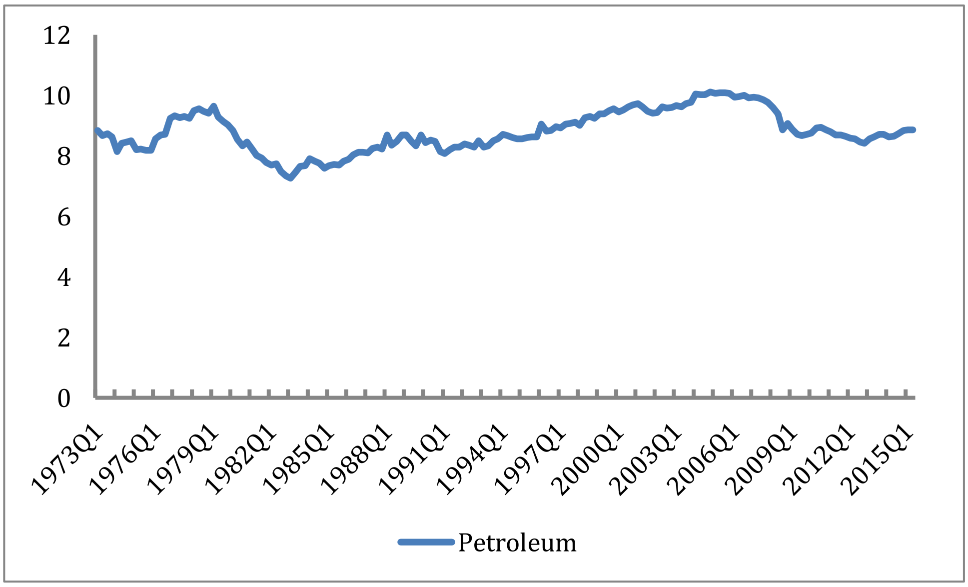
Natural Gas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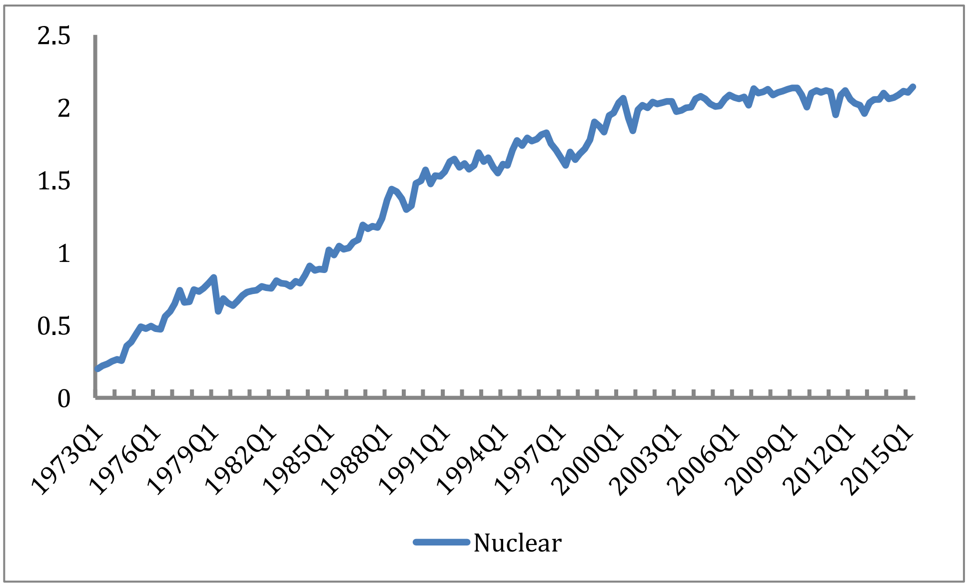
Petroleum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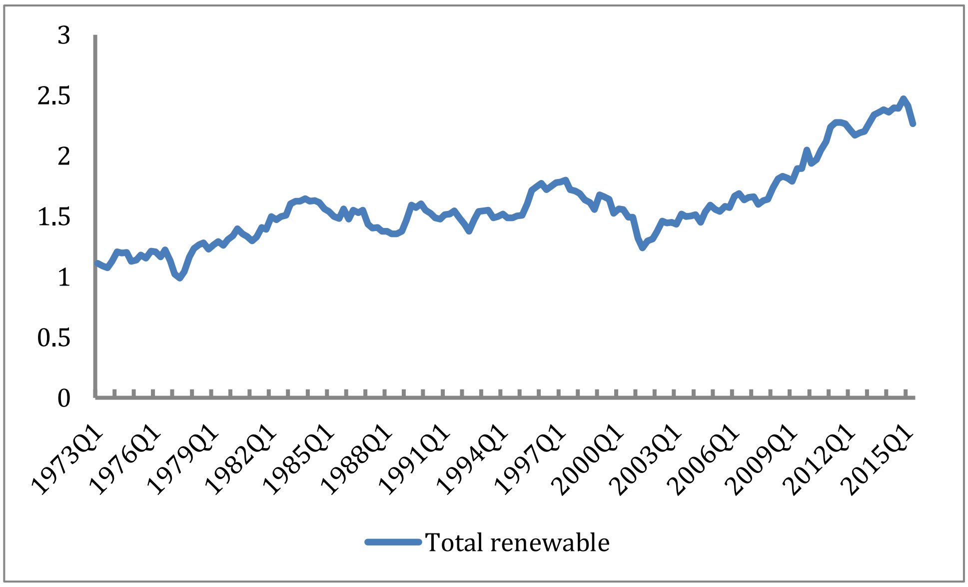
Nuclear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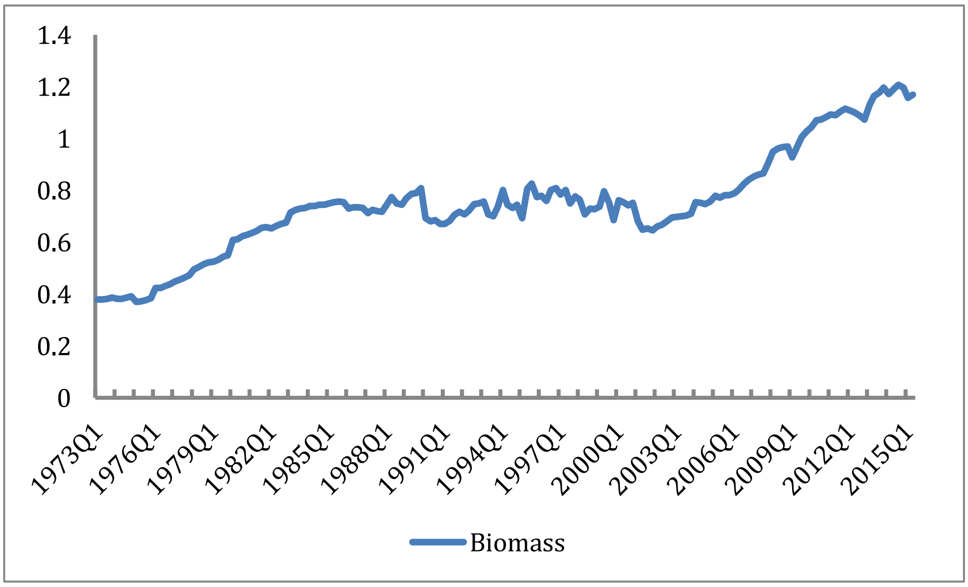
Total renewable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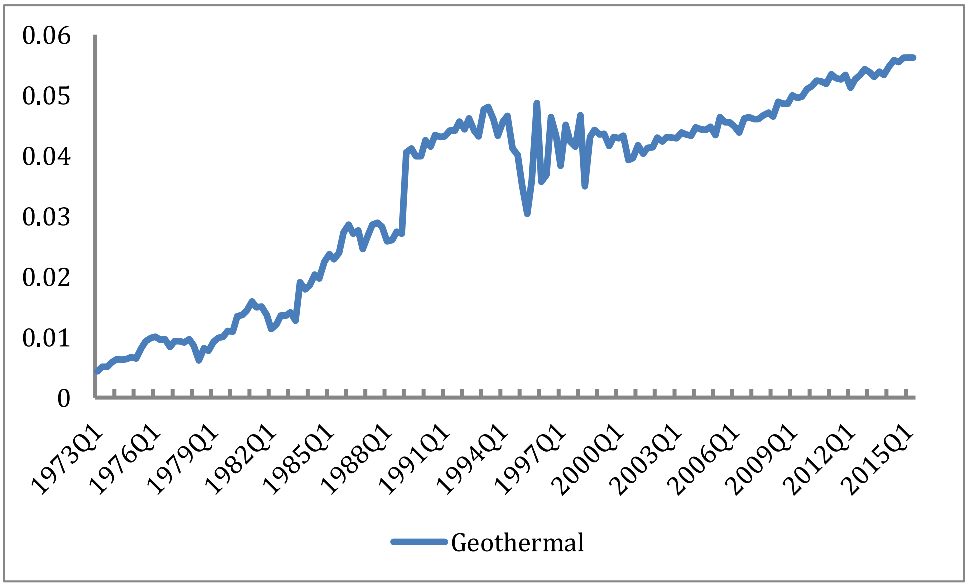
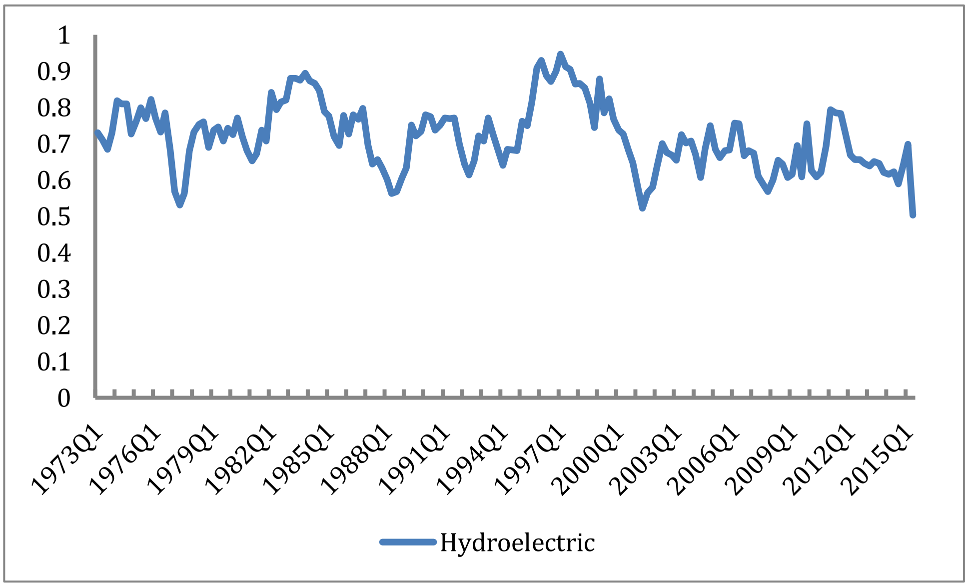
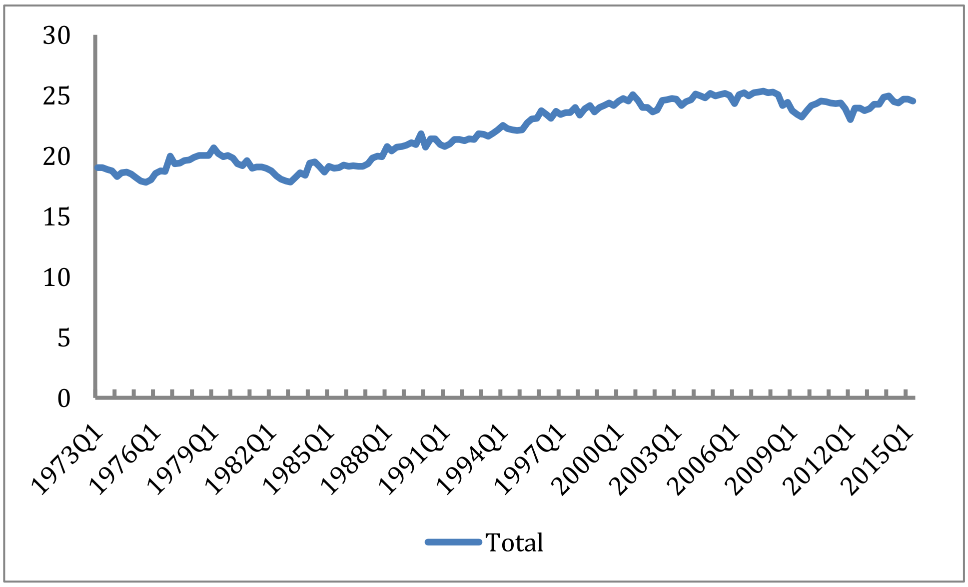
2003Q1
2006Q1
2009Q1
2012Q1
2015Q1
Biomass


0.06
0.05
0.04
0.03
0.02
0.01
0
1973Q1
1976Q1
1979Q1
1982Q1
1985Q1
1988Q1
1991Q1
1994Q1
1997Q1
2000Q1
2003Q1
2006Q1
2009Q1
2012Q1
2015Q1
Geothermal


1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1973Q1
1976Q1
1979Q1
1982Q1
1985Q1
1988Q1
1991Q1
1994Q1
1997Q1
2000Q1
2003Q1
2006Q1
2009Q1
2012Q1
2015Q1
Hydroelectric


30
25
20
15
10
5
0
1973Q1
1976Q1
1979Q1
1982Q1
1985Q1
1988Q1
1991Q1
1994Q1
1997Q1
2000Q1
2003Q1
2006Q1
2009Q1
2012Q1
2015Q1
Total

A.1.2 Gross domestic product is expressed in billions of chained 2009 dollars (*Quarterly data, seasonally adjusted annual rates*)