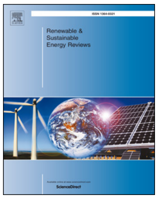
Renewable and Sustainable Energy Reviews 107 (2019) 1–19

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



A revisited renewable consumption-growth nexus: A continuous wavelet approach through disaggregated data

Faik Bilgili[a,*], Sevda Kuşkaya[b], Nurhan Toğuç[c], Erhan Muğaloğlu[d], Emrah Koçak[a], Ümit Bulut[e], H. Hilal Bağlıtaş[a]

[a] *Erciyes University, Faculty of Economics and Administrative Sciences, Department of Economics, 38039 Melikgazi, Kayseri, Turkey*
[b] *Erciyes University, Social Sciences Institution, 38039 Melikgazi, Kayseri, Turkey*
[c] *İstanbul Esenyurt University, The School of Applied Disciplines, 34510 İstanbul, Turkey*
[d] *Abdullah Gül University, Faculty of Business Administration, Department of Economics, 38170 Melikgazi, Kayseri, Turkey*
[e] *Ahi Evran University, Faculty of Economics and Administrative Sciences, Department of Economics, 40100 Kırsehir, Turkey*

ARTICLE INFO

Keywords:
Wavelet analyses
Continuous wavelet coherence
The US economy
Geothermal
Wind
Solar
Biofuels
Wood
Waste

ABSTRACT

In this research, we aim at exploring the influence of renewables on industrial production (Ip) in the US by following continuous wavelet coherence and partial continuous wavelet coherence analyses. To this end, we observed the co-movements between, biofuels and Ip, solar and Ip, wind and Ip, geothermal and Ip, wood and Ip, and, waste and Ip in the US for the monthly period from January 1989 to November 2016.

The primary motivations behind this research are twofold. Firstly, it attempts to reach the co-movements, if exists, between renewables' consumption and industrial production by following time domain and frequency domain analyses. Secondly, it aims at observing the potential co-movements between renewable energy sources (geothermal, solar, wind, biofuels, wood, and, waste) and Ip by adding some control variables (fossil fuels, total biomass etc.) into the wavelet models to understand clearly the responses of the industrial production to the impulses in renewables in both short term and long term periods.

The paper hence eventually reveals significant effects of geothermal, wind, solar, biofuels, wood, and, waste on US industrial production in short term cycles and long term cycles. Thereby, following this paper's results of continuous wavelet analyses which depict the impact of renewables on US economy at 1–3-year frequency and 3–8-year frequency for the time period from January 1989 to November 2016, one might provide policy makers with relevant current and future efficient renewables' energy policy for the US and other countries which have similar structures with the US.

1. Introduction

United States of America is one of the most energy-producing and consuming countries in the world.

Currently, the shares of United States in global energy supply, energy demand, oil import, and natural gas import are 15%, 20%, 23%, and 10%, respectively [1]. This energy structure of the United States contributes most likely to several prominent issues, such as global warming, local and global air pollution, and energy insecurity. Increasing concerns of public raise the importance of energy policies. Actually, United States, United Kingdom, Germany and several other developed countries have increased their research programs for energy and have developed their renewable energy sources and technologies since the 1970s. They aimed to use energy obtained from sun, wind, ocean systems, geothermal, biomass and wastes in residential and commercial buildings, electricity production, heat and steam production, and in the production of solid, liquid, and gas fuels. Commercialization of national and renewable sources have many advantages, namely (1) decreasing the usage of fossil fuels, (2) stimulating regional development and employment, (3) removing the effects of climate change stemming from the usage of fossil sources, (4) providing national energy security, and (5) improving trade balances of countries that import fossil sources. Substitution of fossil sources with renewable sources were low in many countries including the US from 1970s to early 2000s [2], however, energy sector of United States has experienced a great transformation, and many policies have been implemented in states and at federal level to support and encourage the use of renewable energy over the past decade [3]. One must note that

---

[*] Corresponding author.
E-mail address: fbilgili@erciyes.edu.tr (F. Bilgili).

https://doi.org/10.1016/j.rser.2019.02.017
Received 5 June 2018; Received in revised form 17 February 2019; Accepted 18 February 2019

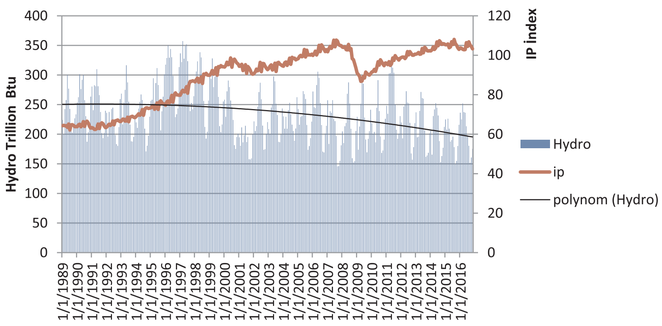


Fig. 1. The US hydro power energy consumption for the period 1989:1–2016:11 in Btu (blue bar charts) and its polynomial representation (solid black line) and industrial production index (red line).
Data Sources: EIA [90], Federal Reserve Economic Data [91].

state governments dominate and lead the development of renewable energy policies in the United States in spite of the national importance of renewable energy [4,5]. For instance, one of the most prevalent and innovator policy instruments is renewable portfolio standard (RPS). RPS is a program that legally forces states to produce a certain rate of electricity production from renewable energy sources. While only three states adopted the RPS program in 1998, nine states implemented this program by 2001, and 29 states have accepted it at the present time. The scope of this program has gone on increasing nowadays [5,6].

Then, one question becomes considerable for the US economy: do these incentives and supports affect renewable energy production? It is with no doubt that the answer of this question is positive. Figs. 1–4 and 6–10 depict increases in renewable energy production/consumption in the last years by observing both aggregated and disaggregated data from January 1989 to November 2016. The wood consumption, on the other hand, shows a slight decrease during the same period (Fig. 11), although it has greater value than the consumption values of geothermal, solar, wind, waste, and biofuels (Fig. 12). Many papers in the energy economics literature reveal the positive effect of incentives and supports for renewable energy. For instance, Menz and Vachon [7] examine the effects of some government policies on the development of wind energy in 39 states over the period 1998–2013 through ordinary least squares (OLS) method. They yield that there is a positive relationship between renewable energy incentives and wind energy. Delmas et al. [8] who investigate the effects of Mandatory Information Disclosure on the shares of clean and fossil energy for 145 large electricity companies by employing panel fixed effects model and instrumental variable model, find that this program decreases the share of fossil energy while it increases the share of renewable energy. Yin and Powers [9] consider the relationship between the RPS program and renewable electricity generation in 50 states using data spanning the period from 1993 to 2006 through panel fixed effects model. They

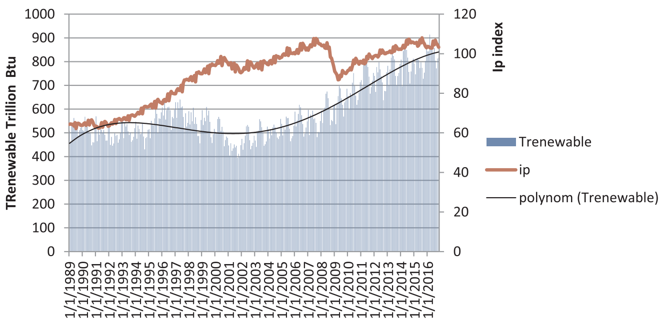


Fig. 2. The US total renewables energy consumption for the period 1989:1–2016:11 in Btu (blue bar charts) and its polynomial representation (solid black line) and industrial production index (red line).
Data Sources: EIA [90] Federal Reserve Economic Data [91].

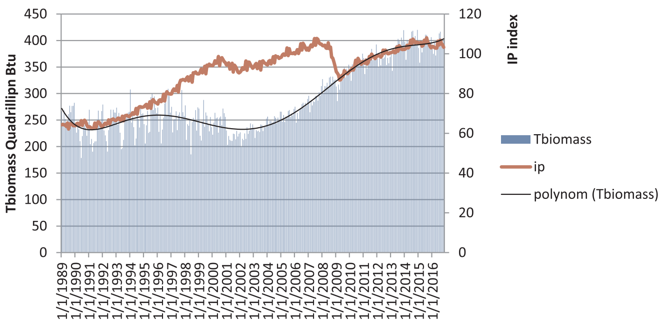


Fig. 3. The US total biomass energy consumption for the period 1989:1–2016:11 in Btu (blue bar charts) and its polynomial representation (solid black line) and industrial production index (red line).
Sources: EIA [90], Federal Reserve Economic Data [91].

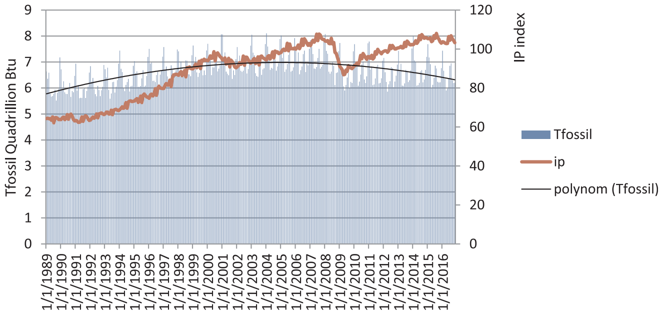


Fig. 4. The US total fossil energy consumption for the period 1989:1–2016:11 in Btu (blue bar charts) and its polynomial representation (solid black line) and industrial production index (red line).
Data Sources: EIA [90], Federal Reserve Economic Data [91].

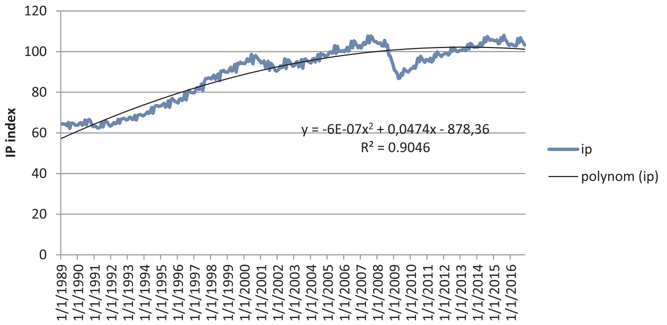


Fig. 5. The US industrial production index (as a proxy for GDP) for the period 1989:1–2016:11 and its polynomial representation (solid black line).
Data Source: Federal Reserve Economic Data [91].

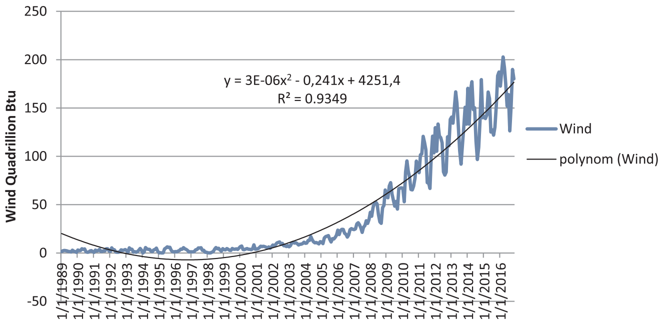


Fig. 6. The US wind energy consumption for the period 1989:1–2016:11 in Btu and its polynomial representation (solid black line);.
Data Source: EIA [90].

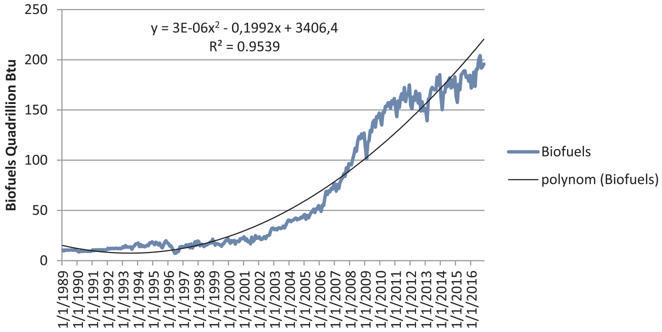


Fig. 7. The US biofuels energy consumption for the period 1989:1–2016:11 in Btu and its polynomial representation (solid black line).
Data Source: EIA [90].

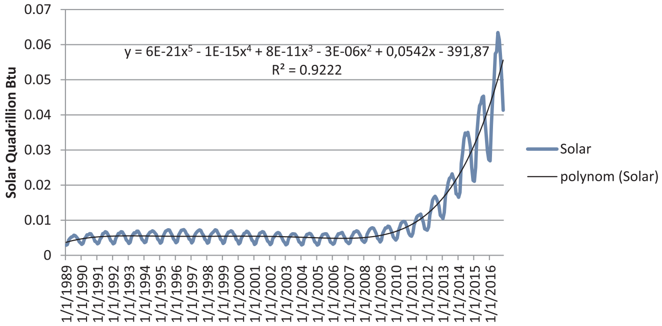


Fig. 8. The US solar energy consumption for the period 1989:1–2016:11 in Btu and its polynomial representation (solid black line).
Data Source: EIA [90].

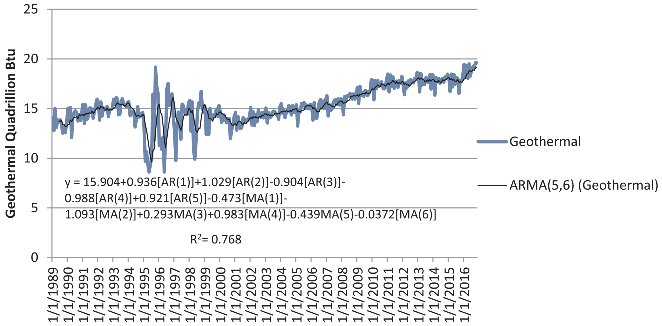


Fig. 9. The US geothermal energy consumption for the period 1989:1–2016:11 in Btu and its ARMA representation (solid black line).
Data Source: EIA [90].

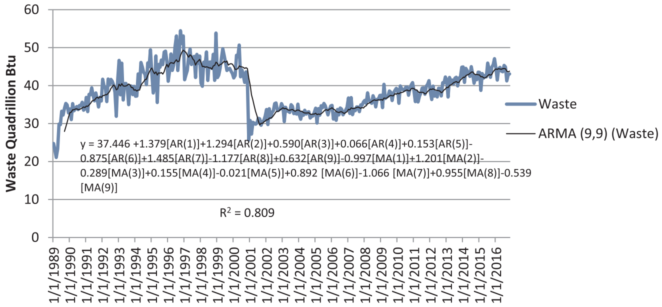


Fig. 10. The US waste energy consumption for the period 1989:1–2016:11 in Btu and its ARMA representation (solid black line).
Data Source: EIA [90].

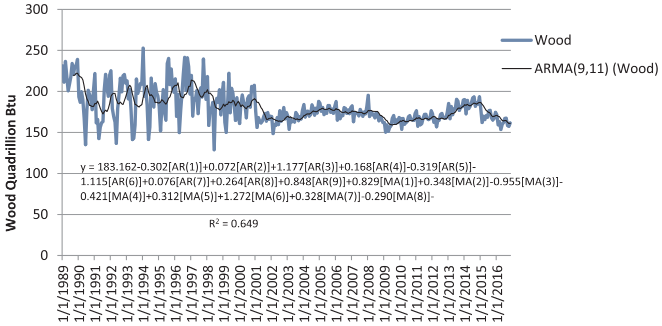


Fig. 11. The US wood energy consumption for the period 1989:1–2016:11 in Btu and its ARMA representation (solid black line).
Data Source: EIA [90].

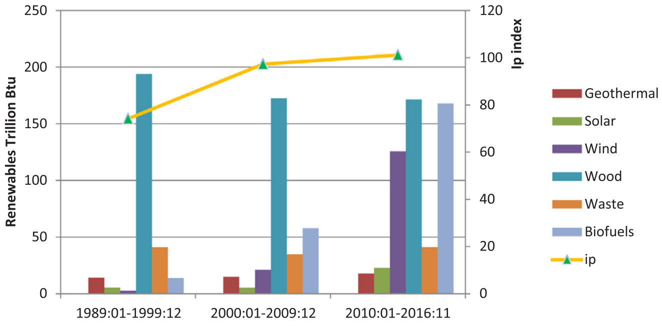


Fig. 12. The mean values of disaggregated renewables data (Trillion Btu) and Ip data (2012 = 100): 1989:01–2016:11.
Data Sources: EIA [90], Federal Reserve Economic Data [91].

explore that renewable electricity generation is positively related to the RPS program. Shrimali et al. [10] research the effects of national and state-level policies promoting the distribution of wind energy in 50 states by performing panel OLS technique. They use data over the period 1990–2011 and find that national and state-level production tax credit encourages the distribution of wind energy. They explore the diversity in renewable energy sources have positive effects on confidence towards wind policies as well. Stokes and Breetz [3] examine the effects of Production Tax Credit (PTC), RPS, Net Energy Metering (NEM), federal investment tax credit (ITC), and California's zero emission vehicle (ZEV) mandate implementations on wind, solar, and biomass energy through case studies. They find out that (i) the potential of these policies and renewable energy technologies is underestimated and misunderstood at the beginning, (ii) policies towards the implementation of these technologies are gradually revised and extended, and (iii) these policies become crucial.

When all these cases and empirical research are evaluated, it is seen that renewable energy incentives and subsidies applied at both the state and national level in the USA cause significant increases in renewable energy production/consumption. Moreover, there has been a significant transformation in the energy structure in recent years in the United States. What are the economic consequences of this change in energy structure in the United States or of the developments in renewable energy? The question is also an important research topic. The aim of this study is to explore the movements of industrial production of the USA together with disaggregated renewables consumption of the USA through time series and frequency analyses. Hence, we might be able to (1) depict if solar, wind, geothermal, biofuels, wood, and waste consumptions, separately, lead to an expansion (a contraction) in GDP of the USA and/or (2) exhibit if GDP of the USA lead to an increase (a decrease) in the consumptions of renewables. The analysis covers monthly data of the period between January 1989 and November 2016 in the USA. If energy economists are willing to give reliable and approved results for effective policy implications in the context of energy-

Table 1
Empirical literature on energy consumption-economic growth nexus.

Author(s)	Country	Period	Type of energy	Methodology	Conclusion
Kraft and Kraft [13]	USA	1947–1974	Aggregated energy	Causality	Conservation
Akarca and Long [26]	USA	1950–1970	Aggregated energy	Causality	Neutrality
Yu and Hwang [27]	USA	1947–1979	Aggregated energy	Causality	Neutrality
Abosedra and Baghestani [28]	USA	1947–1987	Aggregated energy	Cointegration and causality	Growth
Yu and Jin [29]	USA	1974–1990	Aggregated energy	Cointegration and causality	Neutrality
Stern [30]	USA	1947–1990	Aggregated energy	Causality	Growth
Cheng [31]	USA	1947–1990	Aggregated energy	Cointegration and causality	Neutrality
Cheng and Lai [32]	Taiwan	1955–1993	Aggregated energy	Causality	Conservation
Stern [33]	USA	1948–1994	Aggregated energy	Cointegration and causality	Growth
Hondroyiannis et al. [34]	Greece	1960–1996	Aggregated energy	Cointegration and causality	Feedback
Altinay and Karagol [35]	Turkey	1950–2000	Aggregated energy	Causality	Neutrality
Oh and Lee [36]	S. Korea	1981–2004	Aggregated energy	Cointegration and causality	Conservation
Shiu and Lam [37]	China	1971–2000	Aggregated energy	Cointegration and causality	Growth
Yoo [38]	S. Korea	1970–2002	Aggregated energy	Cointegration and causality	Feedback
Yoo [16]	S. Korea	1968–2002	Disaggregated energy (oil)	Cointegration and causality	Feedback
Mehrara [39]	11 oil exporting countries	1971–2002	Aggregated energy	Cointegration and causality	Conservation
Akinlo [40]	11 Sub-Sahara African countries	1980–2003	Aggregated energy	Cointegration and causality	Neutrality (Congo, Kenya, Nigeria, Togo, Cameroon, and Cote D'Ivoire) Feedback (Gambia, Ghana, and Senegal) Conservation (Sudan and Zimbabwe)
Erdal et al. [41]	Turkey	1970–2006	Aggregated energy	Cointegration and causality	Feedback
Lee and Chang [42]	16 Asian countries	1971–2012	Aggregated energy	Cointegration and causality	Growth
Abosedra et al. [43]	Lebanon	1995–2005	Aggregated energy	Cointegration and causality	Growth
Odhiambo [44]	Tanzania	1971–2006	Aggregated energy	Cointegration and causality	Growth
Apergis and Payne [17]	OECD countries	1980–2005	Disaggregated energy (coal)	Cointegration and causality	Feedback
Bartleet and Gounder [45]	New Zealand	1960–2004	Aggregated energy	Cointegration and causality	Conservation
Wolde-Rufael [18]	6 Major coal consuming countries	1965–2005	Disaggregated energy (coal)	Causality	Growth (India and Japan) Conservation (China and S. Korea) Feedback (S. Africa and USA)
Ozturk et al. [46]	51 Low and middle income countries	1971–2005	Aggregated energy	Cointegration and causality	Conservation (Low-income countries) Feedback (Middle-income countries)
Belke et al. [47]	25 OECD countries	1981–2007	Aggregated energy	Cointegration and causality	Feedback
Eggoh et al. [48]	21 African countries	1970–2006	Aggregated energy	Cointegration and causality	Feedback
Chu and Chang [19]	G − 6 countries	1971–2010	Disaggregated energy (nuclear and oil)	Causality	(a) For nuclear Neutrality (Canada, France, and Germany) Feedback (USA) Growth (Japan and UK) (b) For oil Neutrality (Canada, France, and UK) Growth (Japan and Germany) Conservation (USA)
Kum et al. [20]	G − 7 countries	1970–2008	Disaggregated energy (natural gas)	Causality	Neutrality (Canada and Japan) Feedback (France, Germany, and USA) Conservation (UK) Growth (Italy)
Behmiri and Manso [21]	33 Sub-Saharan African countries	1985–2011	Disaggregated energy (oil)	Cointegration and causality	Feedback
Shahbaz et al. [22]	Pakistan	1972–2010	Disaggregated energy (natural gas)	Cointegration	Growth
Hamdi et al. [49]	Bahrain	1980–2010	Aggregated energy	Cointegration and causality	Feedback
Yildirim et al. [50]	9 Emerging market economies	1971–2010	Aggregated energy	Causality	Neutrality (Bangladesh, Egypt, Indonesia, Iran, Korea, Mexico, Pakistan, and Philippines) Growth (Turkey)
Ozturk and Al-Mulali [23]	Gulf Cooperation Council countries	1980–2012	Disaggregated energy (natural gas)	Cointegration and causality	Feedback

(*continued on next page*)

Table 1 (*continued*)

Author(s)	Country	Period	Type of energy	Methodology	Conclusion
Iyke [51]	Nigeria	1971–2011	Aggregated energy	Cointegration and causality	Growth
Arora and Shi [24]	USA	1973–2014 (monthly)	Aggregated and disaggregated energy (oil, natural gas and coal)	Causality (time varying)	(a) Aggregated energy Feedback (1990s) Conservation (2000s) (b) Disaggregated energy Feedback (oil) Neutrality (natural gas) Growth (coal/1990s) Conservation (Coal/2006–2012)
Bilgili et al. [25]	USA	2008–2013 (monthly)	Disaggregated energy (shale gas)	Cointegration	Growth
Tang et al. [52]	Vietnam	1971–2011	Aggregated energy	Cointegration and causality	Growth
Saidi et al. [53]	53 (Global) countries	1990–2014	Aggregated energy	Cointegration and causality	Feedback (African and Middle East countries) Growth (European countries) Conservation (American countries and Global)
Khobai et al. [54]	BRICS countries	1990–2013	Aggregated energy	Cointegration and causality	Conservation
Kourtzidis et al. [55]	USA (sectoral level)	1991–2016 (monthly)	Aggregated energy	Cointegration and causality	Neutrality (all sectors)

growth relation, they are encouraged including new economic variables into analysis and applying new estimation techniques, rather than employing classic methods for different countries and changing time periods [11,12]. Therefore continuous wavelet transformation, wavelet coherency, partial wavelet coherency, and, phase difference analyses are applied to disaggregated renewable energy and industrial production data to examine the relationship between variables.

The merits of this study are three-fold. First, it is the first study in the literature that searches for a causal relation between disaggregated renewable energy resources and economic growth in the USA by using wavelet methodology. Wavelet decomposition provides researchers with analyses for both short- and long-run co-movements. Furthermore, it employs partial wavelet analysis, by which the consequences of other economic variables into observed variables can be factored out; hence, the results will arise more obvious and clear and the policy implications will be more reliable and consistent. This paper, therefore, aims to fill an important gap in the literature. Second, most of the works in renewable energy-growth literature – 76% – (see Table 2) considers aggregated renewable energy consumption. This study examines the relationship between aggregated and disaggregated renewable energy consumption and industrial production. Disaggregated renewable energy data may lead to more effective and comprehensive results within the context of renewable energy-growth relationship. Third, this study indirectly reveals the economic impact of renewable energy incentive policies implemented at both national and state levels in the United States.

The rest of the paper is as follows: Section 2 reviews the literature. Section 3 describes the data set and methodology. Section 4 reveals the wavelet-time and frequency domain-estimation output. Section 5 assesses and discusses the empirical, statistical facts underpinning the wavelet estimations. Section 6 provides conclusions.

2. Literature review

The relationship between energy consumption and economic growth has become a field of interest for researchers since the seminal paper of Kraft and Kraft [13], because energy cannot be substituted with other factors of production. Today, economic development of a country is directly related to energy. According to IEA [14] data, the share of non-renewable energy sources, such as oil, coal, and natural gas, in world energy demand is about 82%. Based on this great share of fossil sources, many global problems, namely energy dependency, energy security, and environmental problems, arise. For this reason, researches that focus on energy-growth-environment nexus are considerable for designing energy policies. In the energy economics literature, the relationships between energy consumption and economic growth are examined within the scope of four hypotheses. These hypotheses are as follows:

(1) Neutrality hypothesis is valid when there is not a causal relationship between energy consumption and economic growth. In such a case, a decrease in energy consumption has no effects on economic growth.
(2) Growth hypothesis prevails if there is a causal relationship running from energy consumption to economic growth. This hypothesis indicates that energy has great effects on economic growth as a subsidiary factor of production. When this hypothesis is valid, energy saving policies and/or energy shocks negatively affect economic growth.
(3) When there is a causal relationship running from economic growth to energy consumption, then the conservation hypothesis dominates. This hypothesis posits that economic growth supports energy consumption and that energy saving implementations and/or energy shocks do not affect economic growth.
(4) Feedback hypothesis prevails when there is bidirectional causality between energy consumption and economic growth. This

Table 2
Empirical literature on renewable energy consumption-economic growth nexus.

Author(s)	Country	Period	Type of energy	Methodology	Conclusion
Payne [58]	USA	1949–2006	Aggregated renewable energy	Causality	Neutrality
Sadorsky [59]	18 emerging countries	1994–2003	Aggregated renewable energy	Cointegration and causality	Conservation
Tugcu et al. [60]	G7 countries	1980–2009	Aggregated renewable energy	Cointegration and causality	(1) Feedback for classical production function (for All G7) (2) Mix results for augmented production function (a) Neutrality (France, Italy, Canada, and USA) (b) Feedback (England and Japan) (c) Growth (Germany)
Menyah and Wolde-Rufael [61]	USA	1960–2007	Aggregated renewable energy	Cointegration and causality	Conservation
Apergis and Payne [62]	20 OECD countries	1985–2005	Aggregated renewable energy	Cointegration and causality	Feedback
Apergis and Payne [63]	13 Eurasian countries	1992–2007	Aggregated renewable energy	Cointegration and causality	Feedback
Menegaki [64]	27 European countries	1997–2007	Aggregated renewable energy	OLS	Neutrality
Apergis and Payne [65]	6 Central American countries (Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, and Panama)	1980–2006	Aggregated renewable energy	Cointegration and causality	Feedback
Apergis and Payne [66]	25 developed 55 developing countries	1990–2007	Aggregated renewable energy	Cointegration and causality	Feedback
Tiwari [67]	India	1960–2009	Aggregated renewable energy	Cointegration and a structural VAR	Growth
Yildirim et al. [68]	USA	1949–2010	Aggregated and disaggregated renewable energy (biomass, hydro, biomass wood, geothermal, and biomass waste)	Causality	(1) Neutrality (aggregated renewable, biomass, hydro, biomass wood, and geothermal) (2) Growth (biomass waste)
Apergis and Payne [69]	80 countries	1990–2007	Aggregated renewable energy	Cointegration and causality	Feedback
Shahbaz et al. [70]	Pakistan	1972–2011	Aggregated renewable energy	Cointegration and causality	Feedback
Salim and Rafiq [71]	6 Countries (Brazil, China, India, Indonesia, Philippines, and Turkey)	1980–2006	Aggregated renewable energy	Cointegration and causality	Growth (long-run)
Ocal and Aslan [72]	Turkey	1990–2010	Aggregated renewable energy	Cointegration and causality	Neutrality
Pao and Fu [73]	Brazil	1980–2010	Aggregated renewable energy	Cointegration and causality	Feedback
Bildirici [74]	10 developing and emerging countries	1980–2009	Disaggregated renewable energy (biomass)	Cointegration and causality	(1) Growth (Argentina, Bolivia, Cuba, Costa Rica, Jamaica, Nicaragua, Panama, and Peru) (2) Neutrality (Paraguay) (3) Feedback (El Salvador)
Lin and Moubarak [75]	China	1977–2011	Aggregated renewable energy	Cointegration and causality	Feedback
Al-mulali et al. [76]	18 Latin American countries	1980–2010	Aggregated renewable energy	Cointegration and causality	Feedback
Salim et al. [77]	29 OECD countries	1980–2011	Aggregated renewable energy	Cointegration and causality	Feedback
Ohler and Fetters [78]	20 OECD countries	1990–2008	Aggregated and disaggregated renewable energy (biomass, geothermal, hydro, solar, wind, and waste)	Cointegration and causality	Feedback (aggregated renewable energy, biomass, geothermal, hydro, solar, wind, and waste)
Pao et al. [79]	MIST Countries	1990–2010	Aggregated renewable energy	Cointegration and causality	Feedback
Bilgili [57]	USA	1981–2013 (monthly)	Aggregated renewable energy	wavelet coherence	Growth
Ozturk and Bilgili [80]	51 Sub-Sahara African countries	1980–2009	Disaggregated renewable energy (biomass)	Cointegration and causality	Growth
Bilgili and Ozturk [81]	G7 countries	1980–2009	Disaggregated renewable energy (biomass)	Cointegration and causality	Growth
Solarin and Ozturk [82]	8 Latin America countries	1970–2012	Disaggregated renewable energy (hydro)	Cointegration and causality	Growth (Brazil, Chile, Colombia, Ecuador, and Peru) Feedback (Argentina, Chile and Venezuela)
Hamit-Haggar [83]	11 Sub-Saharan African countries	1971–2007	Aggregated renewable energy	Cointegration and causality	Growth
Dogan [84]	Turkey	1988–2012	Aggregated renewable energy	Cointegration and causality	Feedback
Bilgili et al. [85]	USA	1982–2011	Disaggregated renewable energy (biomass)	Causality	Growth

(*continued on next page*)

Table 2 (*continued*)

Author(s)	Country	Period	Type of energy	Methodology	Conclusion
Koçak and Sarkgunesi [86]	9 Black Sea and Balkan countries	1990–2012	Aggregated renewable energy	Cointegration and causality	Feedback
Armeanu et al. [87]	28 European Union countries	2003–2014	Aggregated and disaggregated renewable energy (biomass, hydropower, geothermal, wind, and solar)	Cointegration and causality	Conservation
Rafindadi and Ozturk [88]	Germany	1971–2013	Aggregated renewable energy	Cointegration and causality	Feedback
Saad and Taleb [89]	12 European Union countries	1990–2014	Aggregated renewable energy	Cointegration and causality	Feedback

hypothesis postulates that energy saving policies and/or energy shocks negatively affect economic growth. Besides, a contraction in GDP has negative effects on energy consumption.

This paper classifies the findings of the empirical literature under two groups: (a) the relationship between energy consumption and economic growth and (b) the relationship between renewable energy consumption and economic growth.

2.1. The relationship between energy consumption and economic growth

This study in this section considers the available papers in the literature examining the effects of total energy, fossil energy, electricity, nuclear energy, oil, natural gas, coal, and shale gas consumption on economic growth.

We selected papers available in the literature as described in (a), (b), (c), (i) and (ii) as follows; (a) papers examining the nexus between energy consumption and economic growth through country specific data, (b) papers investigating the relationship between energy consumption and economic growth through multi -country data, (c) papers considering developing and developed countries through individual country and/or multi -country data. Hence, we also classified the articles in terms of (i) articles examining the nexus between energy consumption and economic growth through time series methodology (launching country specific data), and, (ii) articles investigating the relationship between energy consumption and economic growth through group or panel data methodology (following panel data or multi-country data).

We basically classified the literature in Table 1 in chronological order, which examines the causal relationship between energy consumption and economic growth. In particular, we observed the consumption of non-renewable energy types such as fossil energy sources, nuclear energy and non-conventional gas (shale gas). The regarding empirical literature basically dates back to the article of Kraft and Kraft [13] published in 1978.

Kraft and Kraft [13] investigated the relationship between total energy consumption and economic growth for the US for the period 1947–1974 through Granger causality analyses. Their findings support the conservation hypothesis for the US. Following the seminal article of Kraft and Kraft [13] in the related field, there has been a significant increase in the number of outstanding studies which deal with the nexus between energy consumption and economic growth, and, which consider the nexus between energy consumption and sustainability.

An important part of the relevant literature carried out the analyses mostly by employing country-specific data [13,16,22,24–38,41,43–45,49,52,55]. Findings on country-specific researches were expected to contribute to the design of national energy and growth policies. Other part of the literature has followed multi-country analyses to explore the possible causality between energy and growth [17–21,23,39,40,42,46–48,50,53,54]. The multi-country studies aimed at providing current and future regional energy policies

The findings of the country-specific studies differ from each other in terms of observed time periods and the development levels of individual country/countries. For example, the works employing the data for the US support the hypotheses of neutrality and conservation [13,26,27,29,31,32,55]. Some other works support the growth and feedback hypotheses in developing countries such as China, Lebanon, Nigeria, Turkey, Tanzania, Pakistan, Vietnam and Bahrain [22,37,41,43,44,49,51,52]. The results in general indicate that there exists a significant connection between the level of development and energy consumption.

Launching multi-country data, Mehrara [39], Akinlo [40], Ozturk et al. [46], Yildirim [50] and Khobai et al. [55] verify the neutrality and conservation hypotheses in developing countries, while Ozturk and Al-mulali [23], Lee and Chang [42] and Eggoh et al. [48] confirm feedback and growth hypotheses. Following the multi-country analyses for developed countries, Apergis and Payne [17], Kum et al. [20] and Belke et al. [47] reach the outcome verifying the feedback and growth hypotheses, whereas, for instance, Chu and Chang [19] obtain mix results from G-6 countries.

Other prominent assessments for energy consumption-growth nexus can be summarized as follows: (i) the works employed either time series techniques for a specific country or panel data methods for country groups or regions. They performed mostly cointegration and causality tests to examine the energy-growth nexus. (ii) While a significant portion of the studies focused on the relationship between total energy / aggregated energy and economic growth (see Table 1), few studies examined the relationship between dis-aggregated energy and economic growth [16–23,25]. Disaggregated energy-growth nexus has especially drawn great attention in the last years. (iii) The empirical works did not exhibit clear-cut evidence.

One might observe from Table 1 that each hypothesis has been confirmed by the relevant works given in the table. The different outcomes of the works might stem from different countries/country groups, different periods, differences in different energy types, and empirical techniques [12,15].

2.2. The relationship between renewable energy consumption and economic growth

While there is an immense empirical literature on the relationship between total energy consumption and economic growth, the number of papers focusing on renewable energy-growth nexus is restricted [56]. Increasing concerns about global warming have raised the importance of renewable energy sources recently. Thereby, due to more accessibility of data for renewable energy sources and new developments in econometric techniques increased the number of works in this field.

Table 2 summarizes the papers which investigate the relationship between renewable energy consumption and economic growth.

In reviewing and classifying the literature on renewable energy consumption-economic growth, we observed the articles in terms of (a) hypothesis (growth, feedback, neutrality, and conservation), (b) energy type (disaggregated and/or aggregated renewable energy consumption), (c) empirical methods, and (d) chronological order. The relevant works eventually, in general, highlighted sustainable energy and environmental policies for policy authorities. In addition, these studies provided policy makers with considerable outputs revealing the feasibility of possible replacement between renewable resources and fossil resources in the economic development process.

Table 2 exhibits that numerous studies examined the relationship between aggregated renewable energy consumption and economic growth while few works investigated the relationship between disaggregated renewable energy (hydro, geothermal, solar, wind, wood, wastes and biofuels) consumption and economic growth [68,74,78,80–82,85,87]. The latter works employ mostly the bioenergy, geothermal, solar, wind, and bio-waste. The empirical models employing disaggregated renewables rather than total renewables to depict the causal effects of different types of renewable energy on economic growth can produce more specific energy policies.

Table 2 explores as well that the majority of observed literature follows panel data for multi-country analyses as given, e.g., in Sadorsky [59], Tugcu et al. [60], Apergis and Payne [62], Apergis and Payne [63], Menegaki [64], Salim and Rafiq [71], Bildirici [74], Armeanu et al. [87], and, Saad and Taleb [89]. Some other papers consider time series data for country-specific analyses as depicted in Bilgili [57], Payne [58], Tiwari [67], Yildirim [68], Shahbaz et al. [70], Ocal and Aslan [72], Pao and Fu [73], Lin and Moubarak [75] and Rafindai and Ozturk [88]

Results of researches focusing on developed countries can be divided into two groups. The first group supports the hypothesis of neutrality and conservatism [58,61,64,68,87] whereas the second group reaches the findings verifying growth and feedback hypotheses [57,62,66,77,78,81,85,88,89]. The results achieved in developing countries mostly indicate that renewable energy has a significant impact on economic growth [63,65,67,70,71,73–76,79,80,82–84,86]. According to regarding outcomes, renewable energy can be considered an important ‘growth dynamic’ in developing countries. On the other hand, it can be also stated that there are other important growth dynamics along with renewable energy in developing and developed countries such as population, urbanization, ruralisation, access to electricity, and dynamics of energy markets.

Finally, when the literature is classified in terms of methodology, it is seen that the works employ either time series methods (for a country) or panel data techniques (for country groups or regions). All paper, except Bilgili [57], utilize cointegration and causality tests to examine the relevant relationship. The current literature has followed mainly the cointegration and Granger causality methods to examine the responses of economic growth to the impulses in energy consumption. The Granger test reveals whether a time series (Yt) can be forecast by lagged values of another times series (Xt). If past values of Xt can predict the current value of Yt, then, Xt Granger causes Yt (or, Yt is said to be Granger-caused by Xt). The cointegration analysis is implemented to observe if Xt and Yt have a long-run relationship. In time series methodology, the parameter estimations of Cointegration and Granger causality analyses are fixed for the entire time period of the sample data except some cointegration analyses in which estimations might change from one regime to another regime. In panel data estimations, the intercept term, or, group means of estimated model might change across individual countries. However, two or more structural breaks or shocks might occur due to technological shock(s), and/or political-financial-economic shocks, and/or demographical changes within a certain time period in a country or in a group of countries. The changes, for instance, in economic leading indicators, which are called business cycles, might affect the relationships between economic variables differently in different sub-time periods of the estimated entire time period. This might be a considerable constraint for Granger causality and cointegration analyses. Wavelet analysis, on the other hand, estimates the relationships between variables taking into account possible different frequencies and different sub-time periods. Following high frequency (i.e. 1-year, or 2-year frequency), or, low frequency (i.e., 2-year or 4-year frequency), wavelet analysis can capture all possible co-movements between variables at different time points/intervals. Therefore, we follow a different analysis method from the literature. The effort to fill this gap in the literature is our main motivation. We also aim at providing more robust outputs on the energy-growth relationship for policy authorities and potential readers.

3. Data and methodology

3.1. The data

Within the literature of nexus between energy (and/or renewable energy) and economic growth, as explained in Section 2, the seminal articles mainly observe annual or quarterly data for energy (and/or renewable energy) and Gross Domestic Product (GDP) or percentage growth in GDP.

This research considers the nexus between components of renewables and economic growth through wavelet analyses that will be explained latter. The wavelet analyses yield better results with the employment of possible highest frequency data available in the data sources. To this end, we followed monthly data for renewables’ consumption and industrial production index (Ip) instead of quarterly or annual data for relevant variables. The Ip is a monthly economic indicator measuring real output in the manufacturing, mining, electric and gas industries, relative to a base year. The Ip is a common proxy for monthly real output of a national economy and can be used as a proxy for GDP.

Thereby, this research employs monthly disaggregated renewables

Table 3
Descriptive statistics of main energy consumption (Trillion Btu) and Industrial production index (2012 = 100) data: 1989:01–2016:11.
Data Sources: EIA [90], Federal Reserve Economic Data [91].

	Hydro	Tbiomass	Trenewable	Tfossil	Ip
Mean	234,030	287,067	585,892	6656	89.083
Median	230,354	265,619	548,684	6640	94.173
Maximum	357,387	420,089	914,061	8104	108.038
Minimum	145,715	178,544	395,828	5518	62.101
Std. Dev.	46,099	62,026	117,920	560	14.174
Observations	335	335	335	335	335

data and industrial production index of the US for the period 1989:01–2016:11. Before conducting wavelet analyses, in this section, we aim at presenting preliminary findings through descriptive statistics for (i) the data of main energy sources [90] and Ip [91] (Table 3), (ii) disaggregated renewables data and Ip (Table 4). Beside descriptive statistics, we aim at, as well, observing (iii) the trend curves of aggregated main energy sources and Ip (Figs. 1–5), and, (iv) the trend curves of disaggregated renewable energy sources (Figs. 6–11). The tables and figures, hence, are expected to provide one with some preliminary statistical/visual inspection. The advanced mathematical/statistical analyses through wavelet analyses, the estimations on potential co-movements between renewables and economic growth will be launched later.

3.1.1. *Main energy consumption and industrial production data*

The total renewables include hydro, geothermal, wind, solar, wood, waste and biofuels. Hydro power and total biomass (geothermal, wind, solar, wood, waste and biofuels) are considerable renewable energy sources to produce electricity. Table 3 reveals the descriptive statistics of total renewables consumption (Trenewable), total fossil energy consumption (Tfossil), the main components of Trenewable which are hydro energy power consumption (Hydro) and total biomass energy consumption (Tbiomass) and industrial production (Ip), respectively. All energy source variables are measured in (trillion) British thermal unit (Btu) while Ip is an index in which 2012 = 100. The first implication of Table 3 is that the mean and median values of Tfossil are greater than those of Trenewable and Ip. The mean and median values of Tbiomass are greater than those of Hydro. With 335 observations, the dispersion of Tfossil's observations from the mean of Tfossil seems to be higher (560) in comparison with the dispersion of Trenewable (117,920). The standard deviations of Tbiomass and Hydro are 62,026 and 46,099, respectively.

Below figures (from 1 to 11) reveal the slope of the energy sources and Ip. The purpose of plotting curve or line (slope) is to illustrate the function which has the best fit to a series of data points. There exist several functions to draw a curve or line trend such as linear function, exponential function, polynomial function, AR (Autoregressive), MA (Moving average), or ARMA (Autoregressive, Moving average). We tested (i.e. in terms of R-squared criteria) each function for each variable and plotted the trend from the function that gives the best fit. From Fig. 1 to Fig. 8, we followed polynomial trend to depict the slope of univariate estimation of the relevant variable (Hydro, Tbiomass, Trenewable, Tfossil, Wind, Biofuels, Solar and Ip). From Fig. 9 to Fig. 11, we considered ARMA trend to observe more clearly the trend of the geothermal, waste and wood.

Exponential or ARMA or ARIMA models are implemented to forecast a time series (Y_t) provided that time series (Y_t) is stationary. ARMA stands for 'Autoregressive-Moving average' and ARIMA stands for 'Autoregressive, Integrated of order (d), and Moving average'. They are identical if relevant time series (Y_t) is stationary. If Y_t is not stationary (if it has unit root), the researcher takes its first difference, or 2nd difference, or d^{th} difference until Y_t becomes stationary.

The Figs. 1, 2, 3, and 4 indicate polynomial representations of the US hydropower energy consumption, the US total renewables energy consumption, the US total biomass energy consumption, and the US total fossil energy consumption respectively, for the period 1989:1–2016:11 in Btu.

The Fig. 1 depicts the US hydro power energy consumption (blue bar charts) and its polynomial trend representation (solid black line). It reveals that hydro energy consumption tends to decline slightly from 1989:01 to 2016:11. The values of hydro power energy during the first and second halves of the sample period were 248,92 trillion Btu and 219,02 trillion Btu, respectively. During the same period, one may observe from Fig. 1 that Ip tends to increase. The index values of Ip during the first and second halves of the sample period were 78.57 and 99.87, respectively.

Fig. 2 presents the US Trenewables energy consumption (blue bar charts) and the polynomial trend representation of Trenewable (solid black line). The trend fluctuates with two peak points occurring in the beginning of 1990s, and, at the end year of sample period, and, one trough point of the beginning period of 2000s. Overall, both total renewables consumption and industrial production tend to increase for the period 1989:01–2016:11. Fig. 3 yields the US Tbiomass energy consumption (blue bar charts) and the polynomial trend representation of Tbiomass (solid black line). Fig. 2 and Fig. 3 have identical co-movements in terms of the trends of total renewables and total biomass consumption for the period 1997–2016. After 1997, they both decline till 2002, and, later, they both increase till the end of sample.

Fig. 4 explores The US total fossil energy consumption for the period 1989:1–2016:11 in Btu (blue bar charts) and its polynomial representation (solid black line) and industrial production index (red line).

The trend of fossil energy consumption, first, until 2000, is positively sloped, later, the slope of consumption diminishes considerable, almost becomes horizontal to time axes till 2008. The polynomial trend implies, hence, the fossil energy consumption of USA did not change mostly during the 2000s. After 2008, the fossil consumption seems to have negative slope, indicating relatively decline in demand for fossil energy sources in the USA, while, as depicted before, industrial production of USA, throughout some peaks and troughs, seems to have upward trend.

One might claim through, Figs. 1–4 that especially after 2000s, during the years of 2010s, as the demand for hydro energy power and fossil energy power tend to reduce, the renewables and biomass, as a considerable part of renewables, tend to grow. The renewables and

Table 4
Descriptive statistics of disaggregated renewables consumption (Trillion Btu) and Industrial production index (2012 = 100) data: 1989:01–2016:11.
Data Source: EIA [90].

	Geothermal	Solar	Wind	Wood	Waste	Biofuels	Ip
Mean	15,354	9666	39,772	180,623	38,775	67,668	89.083
Median	15,174	6095	9062	174,970	38,599	30,723	94.173
Maximum	19,625	63,461	202,790	252,903	54,461	204,280	108.038
Minimum	8603	2881	0000	128,700	21,067	7258	62.101
Std. Dev.	2017	10,797	54,299	21,054	5704	65,222	14.174
Observations	335	335	335	335	335	335	335

biomass consumption seem to have more common cycles (co-movements) with industrial production than hydro energy power and fossil energy power do.

3.1.2. Disaggregated renewables energy consumption and industrial production data

This part displays some preliminary observations about disaggregated data of total renewables. In terms of January 1989, for instance, total biomass energy consumption is 266,572 Trillion Btu. This value corresponds to the horizontal summation of Wood (231,17 trillion Btu), Waste (24,753 trillion Btu) and Biofuels (10,649 trillion Btu) energy consumption values in the USA. Again in terms of January 1989, the total renewables energy consumption level of 509,146 trillion Btu is equal to sum of Hydro (224,04 trillion Btu), Geothermal (14,134 trillion Btu), Solar (0,002881 trillion Btu), Wind (1,521 trillion Btu) and total biomass (266,572 trillion Btu).

Table 4 gives the descriptive statistics of geothermal energy consumption (Geo), solar energy consumption (Solar), wind energy consumption (Wind), wood energy consumption (Wood), waste energy consumption (Waste), biofuels energy consumption (Biofuels) and industrial production (Ip), respectively. All energy source variables are depicted in Trillion Btu whereas Ip is an index in which 2012 = 100. Table 4 exhibits that the greatest differences between mean and median occur in Wind and Biofuels data. The mean value of Wood is the greatest among other variables' mean values. Biofuels, Wind and Waste have the second, third and fourth greatest mean values, respectively. The standard deviations of Biofuels (65,222) and Wind (54,2999) appear to be higher than those of Wood, Solar, Waste and Geo.

Figs. 5–8 show polynomial representations of the US industrial production index, the US wind energy consumption, the US biofuels energy consumption and the US solar energy consumption, respectively, for the period 1989:1–2016:11 in Btu.

Figs. 9–11 depict the ARMA representations of the US geothermal energy consumption, the US waste energy consumption, the US wood energy consumption for the period 1989:1–2016:11 in Btu. All polynomial representations indicate that the relevant models (equations) fitted the data well with high R squared values ranging from 0.904 to 0.953. The ARMA models yield also acceptable R squared values ranging from 0.649 to 0.809. We observed geothermal, waste and wood data through the models of polynomial, exponential, linear, logistic, and, logarithmic as well as ARMA. The ARMA has revealed the best R squares among all models. The ARMA trend analyses of geothermal, waste and wood energy consumptions revealed relatively lower R squared values in comparison with polynomial trend analyses, because of higher volatilities of geothermal, waste and wood of the series for the period 1989:01–2016:11. The higher the volatility is, the less the explained sum of squares will be. The highest volatility appears in the data of wood energy consumption.

The models of industrial production, the US wind energy consumption, the US biofuels energy consumption and the US solar energy consumption follow upward slopes whereas the models of the US geothermal energy consumption, the US waste energy consumption, the US wood energy consumption experience both upward and downward slopes.

Taking into consideration the values of Fig. 12, a slight decrease in consumption of wood energy consumption is observed during the period of 1989:01–2016:11. Throughout this 28-year-period, significant increases in consumptions of solar, wind and biofuels are observed, while the rise in geothermal energy consumption remained at reasonable levels. Meanwhile, waste energy consumption first drops after period 1989–1999, and, later increases during time interval of 2000:01–2016:11. Industrial production Index increases at increasing rate during the first half of the sample, continuous to increase at decreasing rate during the second half of the data period.

3.2. Methodology: wavelet analyses

Spectral analysis decomposes signals into frequency and time domains by which their major business cycles and seasonal characteristics might be exposed evidently. Fourier and wavelet transformations are the main spectral decomposition techniques of financial and economic time series. While Fourier transformation determines predominant frequency intervals of a signal, it is incapable of presenting that these frequencies when to appear in time horizon.[1]

However, wavelet transformation provides simultaneous information over a signal both in time and frequency domain. This helps researchers evaluate how cycles, seasonality and trends of a signal change over time and transition between different frequencies occur among periods [92,93]. In contrast to frequency transformation wavelet transformation is more appropriate for non-stationary, strongly trended and complex signals as most of the economic and financial time-series is categorized, since it has the ability to capture the properties of time-series localized in time [94,95]. Thus wavelet techniques have become more common particularly in economics and financial economics literature including those of Gençay et al. [94], Crowley [96], Kim and In [98], Aguiar- Conraria et al. [95], Vacha and Barunik [99], and Bilgili et al. [1] and Reboredo et al. [100].

A wavelet is defined as a function of a specific mother wavelet as follows;

$$\eta_{(d,l)}(t) = \frac{1}{\sqrt{d}}\eta\left(\frac{t-l}{d}\right), \qquad l\in\mathbb{R} and d \in \mathbb{R}^{+}. \tag{1}$$

A wavelet daughter $\eta_{(d,l)}(t)$ which is a square differentiable function of time,[2] $\eta(.)\in L^2(\mathbb{R})$, and its mother wavelet $\eta(.)$ consists of two parameters d and l. Location or translation parameter ,l, determines the wavelet's center or location in time. Scale parameter, d, and compresses or enlarges wavelet to find cycles or trends in different frequencies. Furthermore, when the scale s increases (decreases), it generates long (short) wavelets, which specify long-run relations (short-run dynamics) and low (high) frequency properties of time series. Thus this indicates an inverse relation between scale and frequency.

When the time series of $z(t) \in L^2(\mathbb{R})$ is given, the continuous wavelet transformation (CWT) of $z(t)$ with respect to wavelet $\eta_{(d,l)}(t)$ can be obtained as follows:

$$W_z(d,l) = \int_{-\infty}^{\infty} z\left(t\right)\frac{1}{\sqrt{d}}\eta\left(\frac{\bar{t}-l}{d}\right)dt \quad , \qquad l\in\mathbb{R} and d>0 \quad , \tag{2}$$

where the bar over the mother wavelet function and $W_z(d, l)$ represent complex conjugation and CWT, respectively.[3] Besides square differentiability, time series $z(t)$ should be obtained again from its wavelet transformation, which requires admissibility condition for its mother wavelet. The admissibility condition is defined as follows,

$$G_\eta = \int_0^{\infty} \frac{|\mathrm{H}(f)|^2}{f} d\kappa < \infty \quad , \tag{3}$$

where G_η is the admissibility constant and $\mathrm{H}(f)$ is the FT of wavelet $\eta(t)$. Wavelet is expected to have no zero frequency element, $\mathrm{H}(0) = \int_{-\infty}^{\infty} \eta(t)dt = 0$, which implies that wavelet should have zero

---

[1] Fourier Transformation (FT) can decompose any periodic and some non-periodic signals into a sine/cosine function. FT of an arbitrary signal z(t) can be written as $\mathrm{Z(f)} = \int_{-\infty}^{\infty} \mathrm{z(t)exp\,(-i2\pi ft)dt} = \int_{-\infty}^{\infty} \mathrm{z(t)[cos(2\pi ft) - isin\,(2\pi ft)]dt}$, where Z(f) is a function of frequency f and $\mathrm{i} = \sqrt{-1}$ is the complex or imaginary number. Alternatively this equation can be written with radian frequencies as $\mathrm{Z(w)} = \int_{-\infty}^{\infty} \mathrm{z(t)e^{-iwt}dt} = \int_{-\infty}^{\infty} \mathrm{z(t)[cos(wt) - isin\,(wt)]dt}$, where $\mathrm{w} = 2\pi\mathrm{f}$ denotes radian frequency.

[2] If a wavelet is square integrable $\eta(t)\in L^2(\mathbb{R})$, then it must satisfy $\int_{-\infty}^{\infty} \eta(t)^2 dt < \infty$.

[3] The conjugate of a complex number, $b + hi$, is simply $b - hi$. If it has only real value rather than complex, its conjugate will be itself.

mean, namely negative and positive cycles disappear each other. When wavelet is normalized to have unit energy, $\int_{-\infty}^{\infty} |\eta(t)|^2 dt = 1$, this enables to make a comparison between different time-series' wavelet transformations at each scale d [101].

Haar, Mexican hat, Daubechies, Cauchy, Coiflets and Morlet wavelets are the well-known examples for mother wavelet functions. Since each wavelet mother function has different features, it becomes crucial to set most appropriate mother wavelet which fits best with the oscillatory features of the time series data. Because of the fact that complex transformation is supplemented with information over both amplitude and phase characteristics of time series data, it allows researchers to analyze the location of cycles of different time series. Therefore Aguiar-Conraria et al. [95] recommend complex wavelet transformation especially for empirical applications in economics time series.

This paper employs complex Morlet wavelet transformation in its analysis part. Morlet wavelet function had been first introduced by Grossman and Morlet [102] and the complex Morlet wavelet function can be defined as:

$$\eta_\gamma(t) = \frac{1}{\pi^{1/4}}\left(\exp(i\gamma t) - \exp\left(\frac{-\gamma^2}{2}\right)\right)\exp\left(\frac{-t^2}{2}\right), \tag{4}$$

where complex Morlet wavelet $\eta_\gamma(t)$ has a central frequency parameter γ. In Eq. (4), if the location parameter is $\gamma > 5$, the value of $\exp(-\gamma^2/2)$ might be neglected, which simplifies Eq. (4) into Eq. (5) as;

$$\eta_\gamma(t) = \frac{1}{\pi^{1/4}} \quad \exp(i\gamma t) \quad \exp\left(\frac{-t^2}{2}\right) \tag{5}$$

If the central frequency parameter is set to six, $\gamma = 6$ (as it is preferred often in economic and financial applications), a conversion between scale and frequency parameters can be realized hereby complex Morlet wavelet might be defined and treated as a function of frequency as well. Aguiar-Conraria et al. [95], Madaleno and Pinho [103], Rua and Nunes [104], Crowley [97], and Percival and Walden [105] discuss further practice of complex Morlet wavelets in economic applications.

Admissibility is a sufficient condition which guarantees to obtain $W_z(d, l)$ CWT from time series $z(t)$, and convert its wavelet transformation into itself $z(t)$ thus $z(t)$ can be defined as a new function of CWT as:

$$z(t) = \frac{1}{G_\eta}\int_0^\infty \left[\int_{-\infty}^{\infty} W_z(d, l)\eta_{(d,l)}(t)dl\right]\frac{dd}{d^2}, \qquad l\in\mathbb{R} and d>0. \tag{6}$$

Besides the preserved energy of $z(t)$ by applying unit energy property of wavelet transformation, $\|m\|^2$ can be defined as:

$$\|z\|^2 = \frac{1}{G_z}\int_0^\infty \left[\int_{-\infty}^{\infty} |W_z(d, l)|^2 dl\right]\frac{dd}{d^2}, \qquad l\in\mathbb{R} and d>0, \tag{7}$$

where $|W_z(d, l)|^2$ denotes the wavelet power, which is the distribution energy, of single time series z(t) in both frequency and time domain. Wavelet analysis can be also employed for investigating the relationship between two different time series with cross wavelet power (CWP), wavelet coherency, partial wavelet coherency and phase differences. CWP depicts the local covariance between two time series in each time-frequency domain. Hudgins et al. [106] first presented CWP formula for separate time series z(t) and n(t) as below:

$$\mathrm{W_{zn}(d, l) = W_z(d, l)W_n(\bar{d}, l)}, \tag{8}$$

While $W_{zn}(d, l)$ represents the CWP of time series $z(t)$ and (t) , $W_z(d, l)$ and $W_n(d, l)$ are CWT of time series $z(t)$ and $n(t)$, respectively. Analogously how d and l do appear in CWT formula in Eq. (2), they are scale and location parameters respectively in CWP formula in Eq. (8). While high power shared wavelet areas of two time-series depicted by CWP, wavelet coherency shows the significant regions of co-movement between two time-series but does not necessarily high-powered regions in frequency-time domain. Aguiar-Conraria et al. [95,107] expresses wavelet coherency between $z(t)$ and $n(t)$ as;

$$\mathrm{R_{zn}(d, l)} = \frac{\mathrm{|S(W_{zn}(d, l))|}}{\sqrt{\mathrm{S(W_z(d, l))S(W_n(d, l))}}}, \tag{9}$$

where $\mathrm{R_{zn}}$ measures the magnitude of wavelet coherency between two time-series, which is intuitively similar to traditional coefficient of correlation parameter, varying from zero (no coherency) to 1 (high coherency) in time-frequency domain. Smoothing is required for the calculations of cross and individual wavelet power of time-series otherwise wavelet coherency would be spuriously high for all scales and periods [108].

The lead-lag relation and the direction of co-movement between two time-series can be captured by phase difference analysis. Then $\theta_{z,k}$ denotes the phase difference of complex cross wavelet transformation of time-series $z(t)$ and $n(t)$ as:

$$\theta_{z,n} = tan^{-1}\left(\frac{\Im(W_{zn}(d, l))}{\Re(W_{zn}(d, l))}\right) \quad \text{,with}\theta_{z,n} \in [-\pi, \pi]. \tag{10}$$

where $\Im(\mathrm{W_{zn}})$ and $\Re(\mathrm{W_{zn}})$ denote imaginary and real parts of a given complex cross wavelet transformation, respectively. An exact phase difference of π or $-\pi$ indicates an anti-phase relationship, which is a negative correlation. If $\theta_{z,n} \in (-\pi, \quad -\pi/2 \quad)$, then, the series are negatively correlated, where z(t) lags and if $\theta_{z,n} \in (\pi/2 \quad , \pi)$ then the series are again negatively correlated but z(t) leads. An exact phase difference of zero implies that both time-series move together at a certain frequency. If $\theta_{z,n} \in (0, \quad \pi/2 \quad)$, then, the series are positively correlated where $n(t)$ leads z(t). If $\theta_{z,n} \in (\quad -\pi/2 \quad , 0)$, then, the series are again positively related, on the contrary, now z(t) leads $n(t)$.

4. Wavelet-time and frequency domain-estimation output

Following continuous wavelet approach, in this section, we explore the movements of industrial production of the USA together with disaggregated renewables consumption of the USA through time series and frequency analyses. Hence, we might be able to (i) depict if solar, wind, geothermal, biofuels, wood, and waste consumptions, separately, lead to an expansion (a contraction) in GDP of the USA and/or (ii) exhibit if GDP of the USA lead to an increase (a decrease) in the consumptions of renewables.

Figs. 13–18 reveal the wavelet coherency between the pairs of geothermal (Geo) and industrial production (Ip), solar and Ip, wind and Ip, biofuels (Bio) and Ip, wood and Ip, and waste and Ip, respectively. All figures observe the movements of relevant pairs of variables by considering the relevant control variables.

In each figure, the black curve (contour) denotes the 5% significance level of the estimation through an ARMA (1, 1) representation. AR (1) and MA (1) terms of the ARMA model depict the autoregressive with one lag and moving average with one lag, respectively. The color code bars next to the figures indicate the range from weak coherency (blue) to strong coherency (red) between the variables. The color code, hence, exhibits the possible weakest coherence (dark blue) and strongest coherence (dark red). The dark blue and dark red, thereby, correspond to low energy of association and high energy of association between the variables, respectively. Then, one may consider the energy of association the power of correlation ranging from 0.05 to 0.95.

From Fig. 13 to Fig. 18, figure (.) a's, and, figure (.) b's represent the wavelet coherency analyses without control variables, and, wavelet coherency analyses with control variables, respectively. The figure (.) b1's and figure (.) b2's are produced from wavelet analyses considering relevant pair of variables together with controlled variables and exhibit the resulting phase difference (1–3 year frequency band), and, phase difference (3–8 year frequency band), respectively.

Fig. 13a reveals the wavelet coherency estimations following

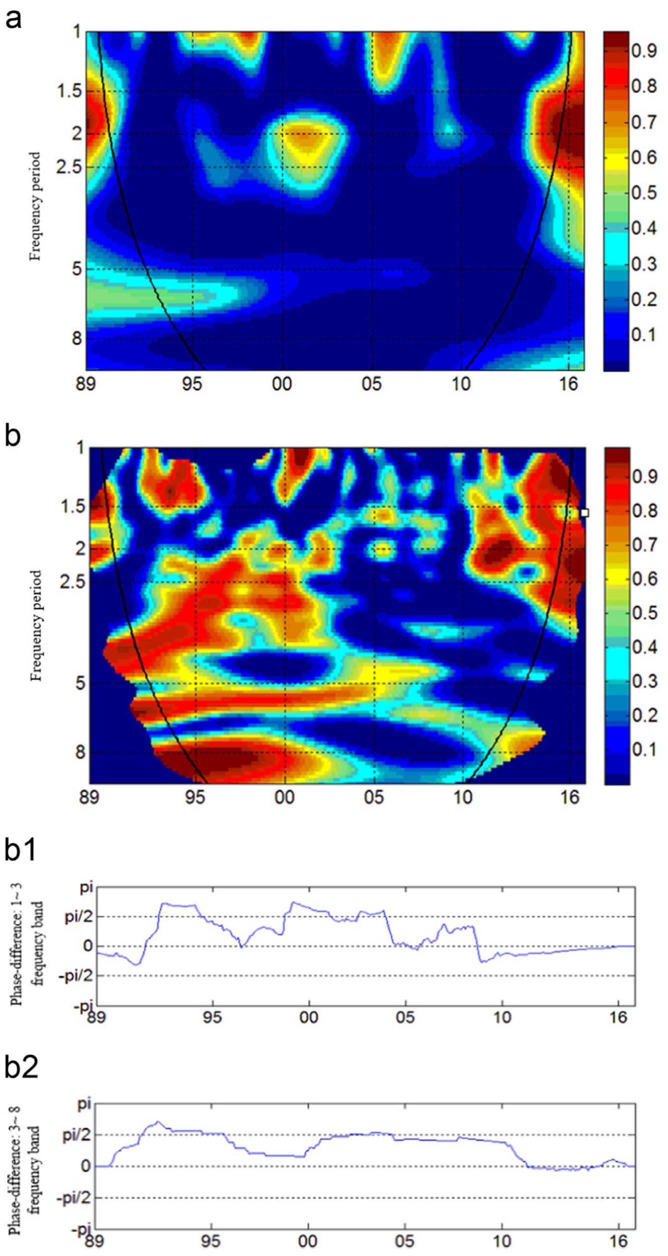


Fig. 13. a. Wavelet coherency (Geo, Ip), 1989:1–2016:11. b. Wavelet coherency (Geo, Ip|| Hydro, Wind, Tbiomass, Tfossil), 1989:1–2016:11.b1. 1–3 frequency band, 1989:1–2016:11. b2. 3–8 frequency band, 1989:1–2016:11.

simultaneously (i) the time series observations for the period 1989:1–2016:11, and, (ii) high and low frequencies that range from 1 year to 8 years. Fig. 13a exhibits, then, some significant coherencies between geothermal energy consumption (Geo) and industrial production (Ip) at high frequency periods (1–1.5 year frequency in 1995–1999 and 2005–2007 and 1.5–2.5 year frequency within 2013–2016). The phase difference analyses (which are not presented here to save place) indicate that the Geo leads Ip to increase for the period 1995–1999 and Ip causes Geo to increase for the time intervals of 2005–2007 and 2013–2016. The Fig. 13a exposes, on the other hand, that there does not exist significant co-movements between Geo and Ip at low frequencies (3–8 year frequency band).

When the controlled variables of energy consumptions of hydroelectricity (Hydro), Wind, total biomass (Tbiomass) and total fossil fuel (Tfossil) are added into the wavelet model, the wavelet coherencies between Geo and Ip becomes more explicit as shown in Fig. 13b. The total biomass comprises the consumptions of wood, waste and biofuels, and total fossils include the consumptions of coal, oil, natural gas and petroleum.

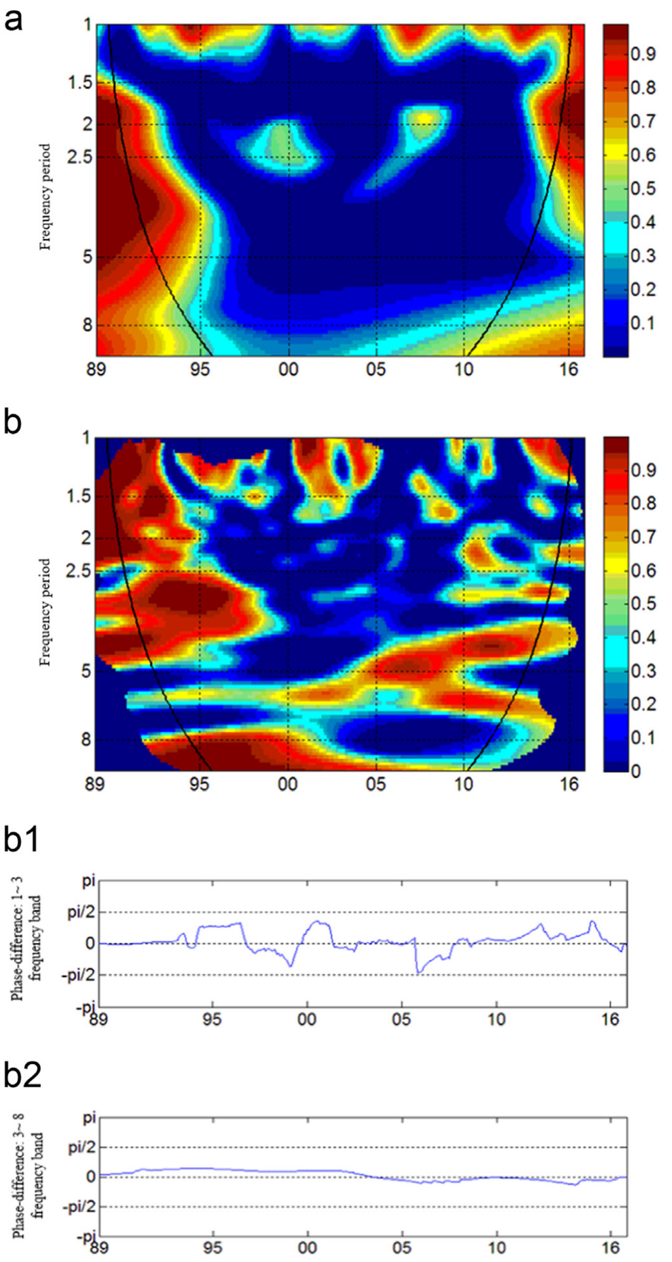


Fig. 14. a Wavelet coherency (Solar, Ip), 1989:1–2016:11. b Partial Wavelet coherency (Solar, Ip|| Hydro, Geo, Tbiomass, Tfossil), 1989:1–2016:11. 14b1 1–3 frequency band, 1989:1–2016:11. 14b2. 3–8 frequency band, 1989:1–2016:11. Figure 14b1 reveals that: (a) Solar power consumption causes Ip to increase during years 1993; 1995–1996; 2000–2001 and 2014–2016, (b) Ip and Solar move together positively during the 1989–1992; 2003–2005 periods, and (c) Ip leads to an increase in Solar during the years 1997–1999, 2000 and 2002. Figure 14b2 shows the evidence of (a) positive correlation between Solar and Ip, as Solar leads, during 1991–2003, (b) positive correlation between Solar and Ip, as Ip leads, during the 2004–2009 and 2014–2015 periods, and, (c) positive correlation between Solar and Ip as they move together for the period 2010–2013.

According to Fig. 13b, there exist strong co-movements between Geo and Ip at shorter cycles during 1990–2002; 2010–2016 (high frequency) and longer cycles 1990–2004 (low frequency). Following the 1–3 year cycle phase difference (Fig. 13b1), one may notice that Geo decreases as Ip is leading within 1–1.5 cycle (frequency band) for the

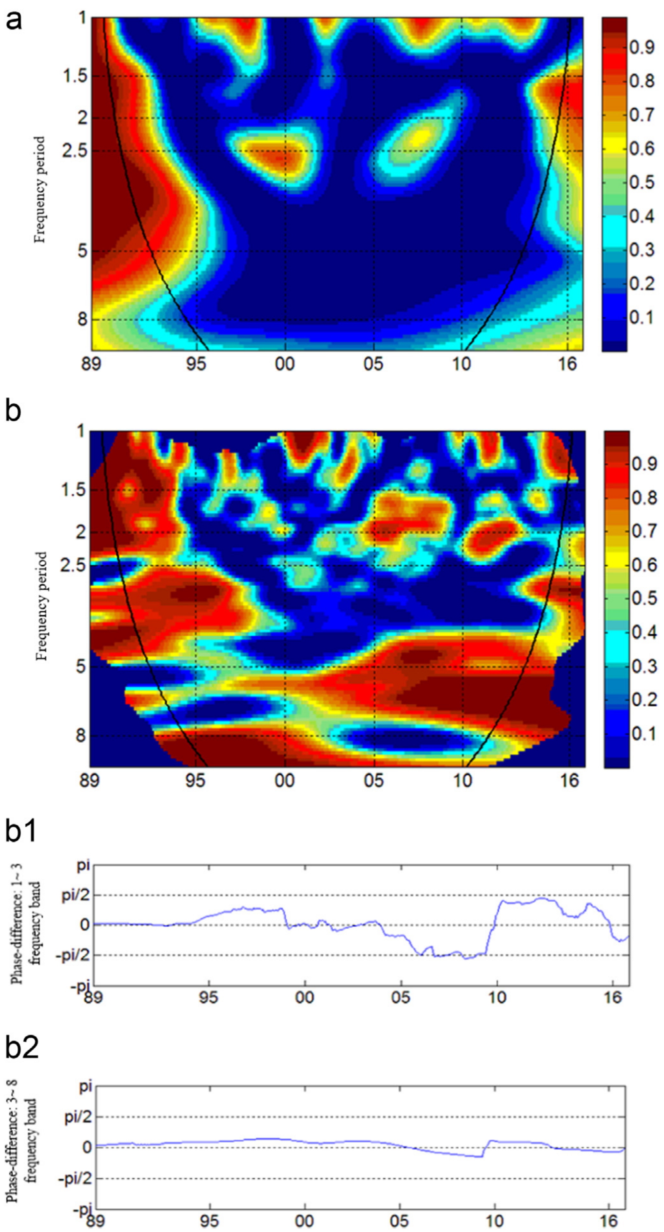


Fig. 15. a. Wavelet coherency (Wind, Ip), 1989:1–2016:11.b Partial Wavelet coherency (Wind, Ip || Hydro, Geo, Tbiomass, Tfossil), 1989:1–2016:11. b1. 1~3 frequency band, 1989:1–2016:11. b2. 3–8 frequency band, 1989:1–2016:11. Figure 15b1, showing phase difference analysis for 1–3 year frequency band, reveals that: (a) Wind energy consumption advances industrial production in the US during the years 1994–1998; 2001; 2003; 2010–2016), (b) Ip and Wind power use move together positively (1989–1993; 2000), and, (c) Ip boosts Wind (2002; 2004–2007, 2009), Figure 15b2, yielding phase differences for 3–8 year frequency band, demonstrates that: (a) Wind enlarges Ip (1989–2005; 2010–2013), and, (b) Ip expands Wind power use (2006–2009; 2014–2016).

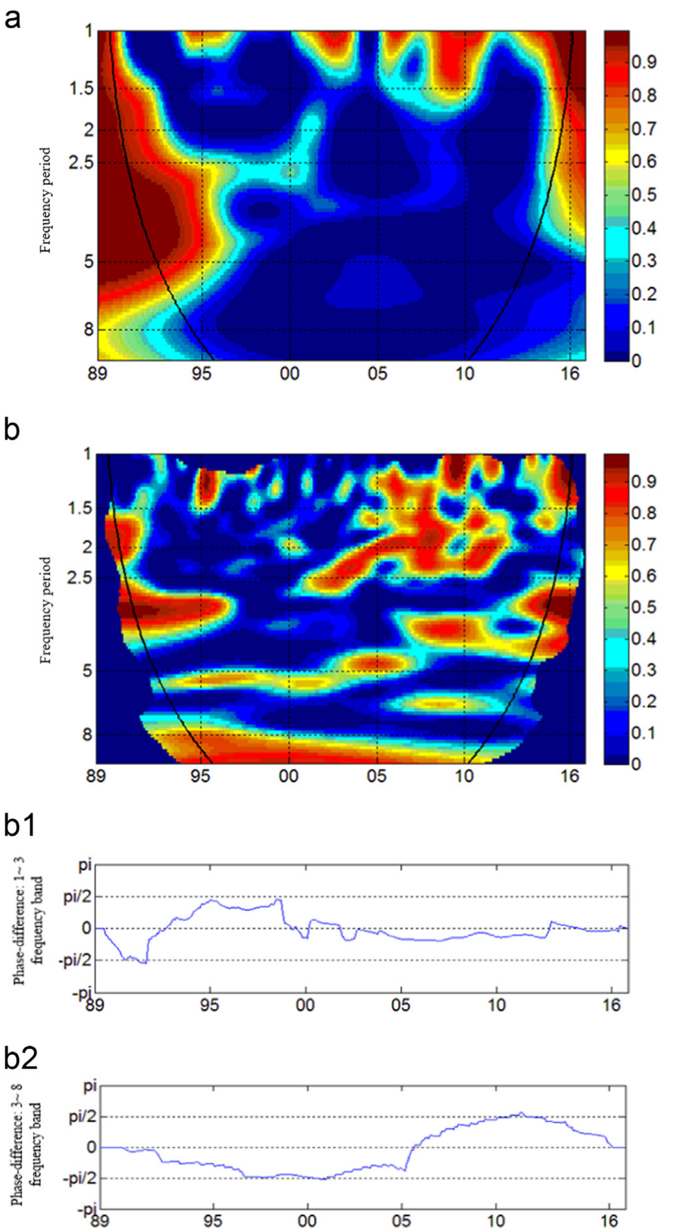


Fig. 16. a. Wavelet coherency (Biofuels, Ip), 1989:1–2016:11. b. Partial Wavelet coherency (Biofuels, Ip || Hydro, Geo, Wind, Tfossil), 1989:1–2016:11. Fig. 16b1. 1–3 frequency band, 1989:1–2016:11. Fig. 16b2. 3–8 frequency band, 1989:1–2016:11. Figure 16b1 exhibits that: a. Biofuel increases Ip (1993–1999, 2001; 2014), and, b. Ip leads Biofuel to increase (1989–1990, 1992, 2000, 2002–2013, 2015–2016). Figure 16b2 reveals that: a. Biofuel expands Ip during 2006–2012, and 2014–2016. One should underline here that Biofuel and Ip experience weak coherence in 2014. b. Ip raises Biofuel in 1989–2005. One needs also consider 1999–2004 period weak coherence cycle at 5-year frequency whereas they have strong co-movements at 8-year cycle for the period 1994–2010.

period 1992–1995; 1999–2001, and, that Ip increases Geo for the period 2012–2016. On the other hand, Geo increases national production level during 1991; 1994–1999; 2002.

The Fig. 13b2 exhibits that, in the long term cycle, Ip diminishes Geo in the years 1992–1993 and Geo increases Ip during years 1996–2001 and 2004. On the other hand, one may observe that Ip and Geo move together positively in 1994–1995 and 2002–2003.

Fig. 14a exhibits the wavelet coherency analyses between Solar and Ip for the period 1989:1–2016:11. Considering short term cycles (1–3 year frequency band), the co-movements (the possible pro cyclical and/or counter cyclical trends) of the variables seem to be significant for the periods 1990–1997 and 2015–2016. The long term cycle (3–8 year frequency band) coherencies, on the other, hand appear during 1991–1995.

Fig. 14b depicts partial wavelet coherency between Solar and Ip after adding control variables Hydro, Geo, Tbiomass and Tfossil into the wavelet model for the period. 1989:1–2016:11. Fig. 14b indicates stronger coherencies between Solar and Ip than Fig. 14a does. Considering both short term and long term cycles, the co-movements of Fig. 14b seem to be more powerful than those of Fig. 14a. In the high frequencies (1–3 year frequency band), the wavelet coherencies

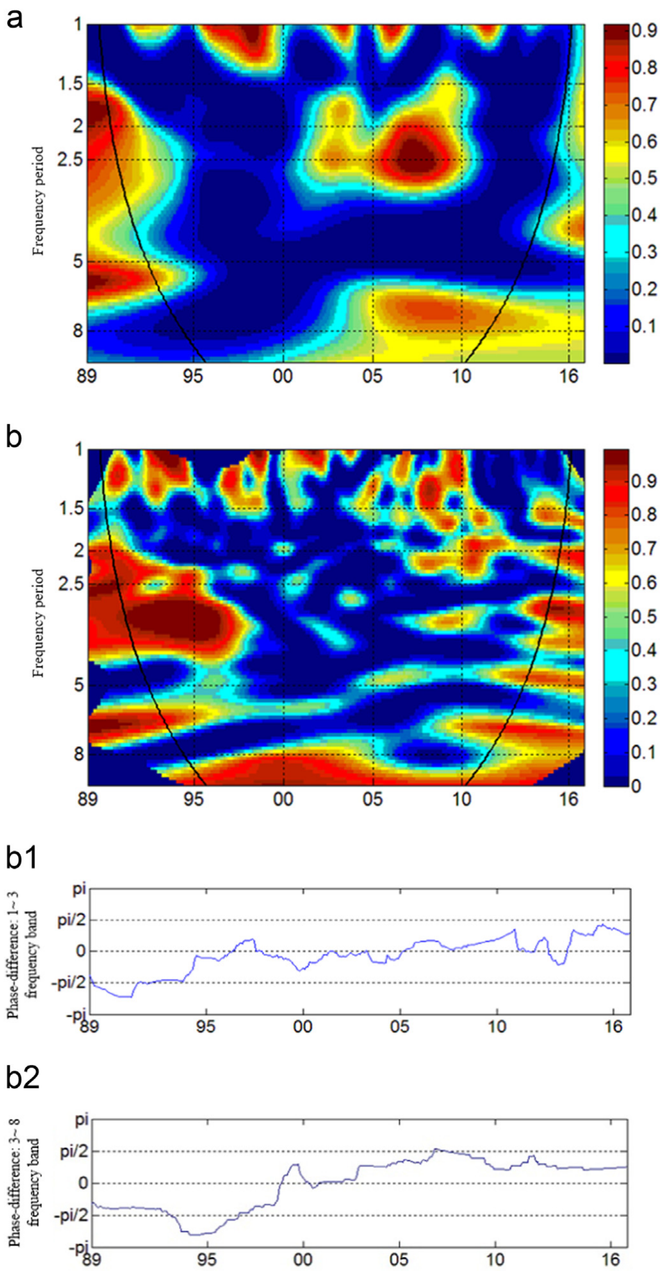


Fig. 17. a Wavelet coherency (Wood, Ip), 1989:1–2016:11. 17b. Wavelet coherency (Wood, Ip || Hydro, Geo, Wind, Tfossil), 1989:1–2016:11. 17b1. 1–3 frequency band, 1989:1–2016:11. 17b2. 3–8 frequency band, 1989:1–2016:11. The figure 17b1 indicates that: a. Wood advances Ip (1997, 2007–2012, 2014–2016).b. Ip boosts Wood (1993–1996, 1999, 2001–2003, 2004, 2013).c. Wood diminishes Ip (1990–1992). Figure 17b2 demonstrates that: a. Wood enhances Ip (2001–2015).b. Ip develops Wood (1997–1999).c. Wood lowers Ip (1994–1996).

between Solar and Ip have strong associations during the years 1990–1999; 2001–2005; 2013–2016. In the low frequencies (3–8 year frequency band), the wavelet coherencies between variables have powerful correlations for the period 1991–2015.

Now, we need to follow, as we did follow previously the phase differences, to observe which variable affects which variable, as leading variable, during strong coherencies.

Fig. 15a yields wavelet coherency for Wind and Ip during the 1989:1–2016:11period. Following 1–3 frequency, the energy of association (the power of correlation) tends to range from 0.8 to 0.95 for the periods 1990–1994, 1995–2000, 2002–2003, 2006–2009; 2013–2014.

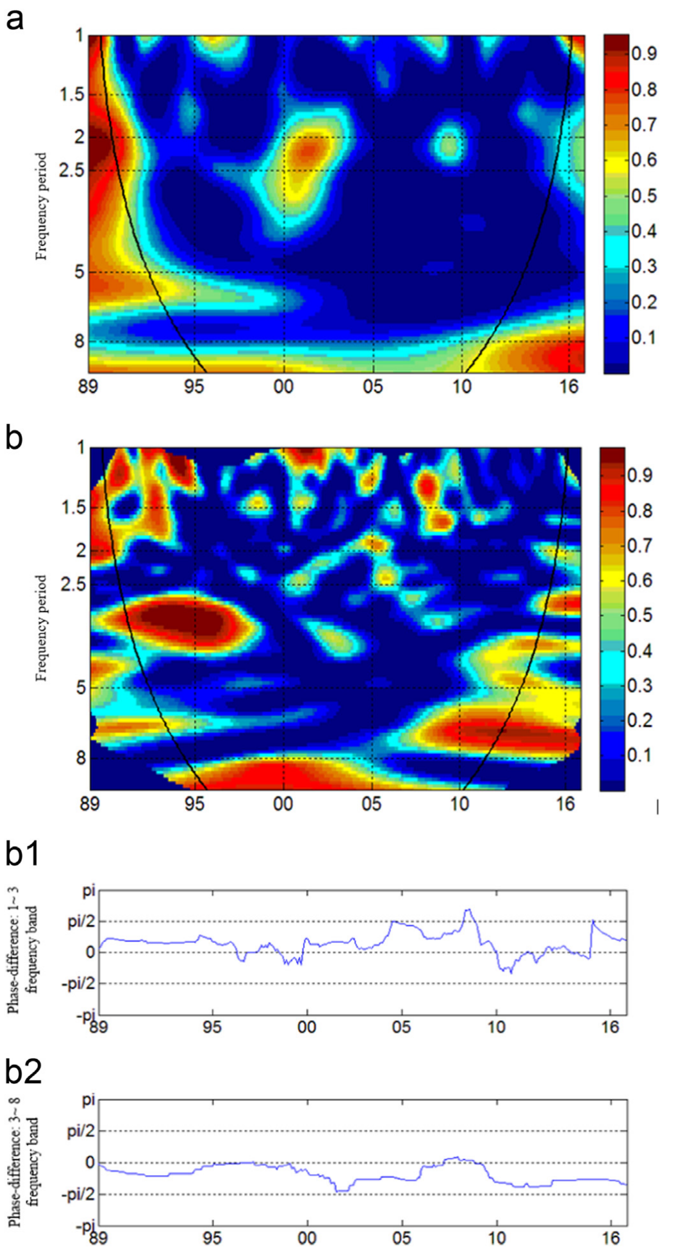


Fig. 18. a. Wavelet coherency (Waste, Ip), 1989:1–2016:11. 18b. Wavelet coherency (Waste, Ip || Hydro, Geo, Wood, Tfossil), 1989:1–2016:11. 18b1. 1–3 frequency band, 1989:1–2016:11. 18b2. 3–8 frequency band, 1989:1–2016:11.

Fig. 15b exhibits partial wavelet coherence analysis between Wind and Ip. Wind and Ip have significant long term continued significant association (cointegration) with the control variables of Hydro, Geo, Tbiomass, and Tfossil for the period 1991–2015. In comparison with partial wavelet coherence analyses for Geo-Ip (Fig. 13b) and Solar-Ip (Fig. 14b), Fig. 15b indicates that the correlation power of Wind-Ip appears to be stronger than those of Geo-Ip and Solar-Ip in the US.

Fig. 16a and Fig. 16b display wavelet coherency and partial wavelet coherency analyses, respectively, for Biofuels and Ip. One may observe from Fig. 16a that, in short and medium cycle terms (1–3 year frequency band), there exist meaningful energy associations between the relevant variables for the period 1990–1996; 2000–2003; 2006–2007; 2008–2012; and, 2013–2016. One also examines from Fig. 16a that, in the long term, Biofuels and Ip follow strong correlation for a limited time period (1991–1996).

Throughout examinations the reciprocity between Biofuels and Ip, before and after employing the control variables of Hydro, Geo, Tbiomass, and, Tfossil into the model, one might claim that Fig. 16b becomes more explicit than the Fig. 16a.

Fig. 16b presents the significant 1–3 year business cycle interconnection between variables during 1990–1996, 2001–2013, and 2015–2016 and produces significant 3–8 year business cycle interrelationship among the related variables for the periods 1991–2011; and 2014–2015.

Fig. 17a and Fig. 17b depict wavelet coherence and partial wavelet coherence, respectively, between Wood and Ip. As Fig. 17a is not adequate to verify strong movements between Wood and Ip, the Fig. 7b shows more explicit interconnection among Ip and Wood for the periods 1990–1999, 2001–2003, 2004, 2007–2015 (1–3 year cycles), and 1991–2014 (3–8 year cycle).

Following waste and Ip variables, Figs. 8a and 18b display weak co-movements and relatively stronger co-movements, respectively. According to the Fig. 18b, in short term cycles (1–3 year frequency band), one might monitor significant coherences during 1990–1998, 2000–2002, and, 2008–2009. Considerable long term (low frequency) coherence occurs among Waste and Ip for the period 1991–1998, 2000–2005, and 2008–2013.

By following Fig. 18b, Fig. 18b1 presents that Waste increases Ip (1990–1996, 1998, 2000–2002, 2008–2009). Considering Fig. 18b, the Fig. 18b2 reveals that Waste increases Ip (2008) and that Ip increases Waste for the periods 1991–1998, and, 2009–2013.

5. The empirical, statistical facts underpinning the wavelet estimations

This paper followed the mathematical/statistical analyses of wavelet coherence and partial wavelet coherence to depict, if exist, significant co-movements between industrial production index (Ip) and renewables' energy consumption (geothermal, solar, wind, biofuels, wood, and, waste) in the US.

In Section 4, the outcome from wavelet analysis is, in general, that renewables' energy consumption leads to economic growth. The geothermal, solar, wind and biofuels lead Ip to increase mostly during the 1990s, in the beginning of 2000s and mid of 2010s. The renewable wood is efficient on Ip rather within the second half of 2000s and 1st half of 2010s, as waste is forceful on Ip more often during 1990s and 2000s.

In addition to the results of the wavelet analysis, one might wonder in reality whether there has been a renewable energy-driven growth in the US economy for the period 1990s, 2000s and/or, 2010s. Or one might wish to observe some governmental or institutional announcements verifying wavelet analyses of this research pointing to the finding of renewable energy-induced growth in the US. To this end, in Section 5, we aimed at exploring some statistical facts underpinning the outcome of Section 4.

For instance, Union of Concerned Scientists [109] and EIA [110] point out considerable development/growth of renewables in the US. According to U.S. Energy and Employment Report [111–113], Solar Jobs Census [114], and Clean Technica [116] confirm the fact that renewables' sector induced employment (new jobs) and economic growth in the US.

Table 5 presents the increasing considerable role of renewables in electricity generation sector in the US for the period 1990–2017. In order for plants to be able to produce more electricity, with the employment of renewables, need to expand their demand for labor following their production functions, $Q_{sr} = f(K, L)$, where, Q_{sr}, K and L depict quantity of renewables supplied, amount of capital and amount of labor respectively. The increasing role of renewables in electricity markets should be accompanied with an increment of L employment and K employment. Expansion in demand for L and K in a market will eventually bring about expansion in local and national economy through direct and indirect effects of additional usages of the inputs of K and L.

Table 5
Percentage growth in electricity generation.
Data Source: EIA [110].

	1990–2000	2000–2010	2010–2017
Coal	23.35	− 6.05	− 34.61
Petroleum	− 12.05	− 66.68	− 43.09
Natural Gas	61.24	64.33	28.87
Other Gases	34.40	− 18.93	25.16
Nuclear	30.69	7.04	− 0.25
Hydro	− 6.68	− 5.68	15.25
Wood	15.60	− 1.12	16.44
Waste	74.44	− 18.22	9.81
Geothermal	− 8.69	7.99	4.97
Solar	34.40	145.69	4268.80
Wind	100.58	1592.26	168.62

Renewable energy development outperforms fossil fuels in two important ways when it comes to driving job growth: 1) Renewable energy production is relatively labor intensive, hence, electricity production, for instance, from renewables, might lead growth of employment to increase relatively more than that of fossil fuel resources, and, 2) Investment in renewable energy plants and grids employs primarily regional employees, therefore, investment dollars are kept in regional communities [109]. Union of Concerned Scientists [109] suggests that federal, regional, and state authorities invest in new transmission capacity for renewable energy, and, that administrators, policy makers follow some incentive policies, such as subsidies and/or tax advantages, to boost renewable energy production/consumption. Table 5 depicts that coal and petroleum used in electricity generation have dropped by 34.61%, and, 43.09%, respectively, from 2010 to 2017, and, that solar and wind employed in electricity power generation have increased dramatically by 4268.80% and 168%, respectively, for the same period. Other renewables; hydro, wood, waste, and geothermal have developed by 15.25%, 16.44%, 9.81% and, 4.97%, respectively.

Table 6 indicates that as employment in fossil-electric power generation grows by 11%, the growths in the employment of solar, wind, bioenergy/CHP, and, hydro in the same sector are 24.52%, 31.98%, 33.00%, and, 6.67%, respectively. Following Table 6, we can rank the first 5 growth rates of labor employment by electricity generation technology, from 1st one to 5th one, in the following way; 1st is bioenergy/CHP (33.00%), 2nd is wind (31.98%), 3rd is solar (24.52%), 4rth is nuclear (21.34%), and, 5th is fossil (11.11%), respectively.

In terms of last quarter of 2016, in the United States, there exist (a) 4.24 million employees in traditional energy sector, and (b) there available 1.9 million workers in fuel production and energy power generation sectors. The electric power generation sector has created totally 732, 478 job opportunities. Within this total amount, the labor employment shares of the fossil fuels, nuclear, and renewables are 25.54% (187,117 jobs), 9.30% (68,176 jobs), and 65.14% (477,185 jobs), respectively. The renewables' total amount of 477,185 jobs in electricity power generation consists of employments in wind energy sector (101,738 jobs), solar energy sector (260,077 jobs), hydro energy sector (65,554 jobs), geothermal energy sector (5,768 jobs), and, biomass energy sector (26,014 jobs) as indicated in U.S. Energy and Employment Report [113].

From 2012:1–2016:4, the growth rate of employment in solar sector and wind sector are 119% and 36%, respectively [113]. From January 2006-September 2016, the electricity generation growth from coal, natural gas, and, solar are −53%, 33%, and, 5000%, respectively. Regarding the only period September 2015-September 2016, the usage of solar in electricity generation has enhanced by 52% in the US [111]. Due to considerable construction of solar generation plants, solar energy equipment's, and solar energy capacity, the share of solar employment in total electricity generation in 2017 has been 43% which corresponds to 374,000 jobs [112].

According to Solar Jobs Census [114], in terms of installation,

Table 6
Employment by electricity generation technology, 2015: Q2–2016: Q1.
Data Source: U.S. Energy and Employment Report [111,112].

	2015	2016	Percentage Growth 2015–2016	Percentage Share in 2015	Percentage Share in 2016
Solar	300,192	373,807	24.52	42.05	43.42
Wind	77,088	101,738	31.98	10.80	11.82
Geothermal	7645	5768	−24.55	1.07	0.67
Bioenergy/CHP	19,559	26,014	33.00	2.74	3.02
Hydro	61,453	65,554	6.67	8.61	7.61
Nuclear	56,185	68,176	21.34	7.87	7.92
Fossil	135,898	151,001	11.11	19.04	17.54
Advanced Gas	35,98	36,117	0.38	5.04	4.20
Other	19,936	32,695	64.00	2.79	3.80
Total Jobs (Thousand)	713,936	860,87			

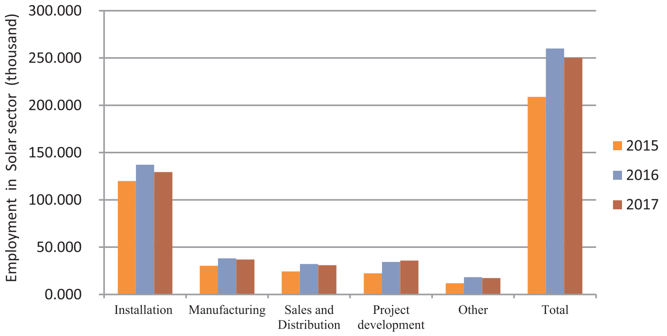


Fig. 19. Employment in solar sector in the US for the period 2015–2017.
Data Source: Solar Jobs Census [114].

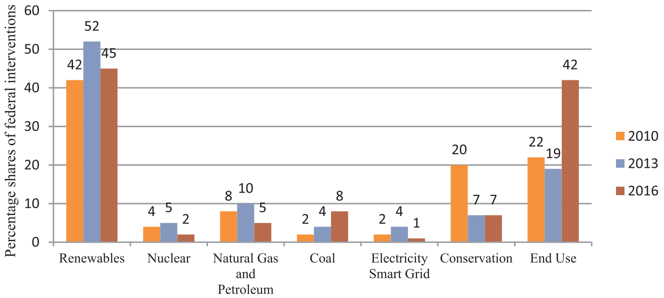


Fig. 20. Percentage shares of federal direct financial interventions in U.S. energy sectors by subsidy-support type.
Data Source: EIA [122].

manufacturing, sales and distribution, project development, and other, the number of people employed in solar sector in the US in 2015, 2016 and 2017 were 208,859; 260,077 and 250,271, respectively as shown in Fig. 19.

With 101,138 jobs in 2016, the wind sector is also a leading sector in the US energy market. Employment in wind sector has the growth rate of 31.98% from 2015 to 2016 as depicted in Table 6. The available jobs in wind sector were 51,000 at the end of 2013 [115]. From 2013 to 2016, the growth rate in employment of wind sector is 98.11%. According to the US Bureau of Labor Statistics, the jobs in wind sector will grow by 108% over the next decade [116]. According to Clean & Technica [117], U.S. Department of Energy forecasts that the US will construct additional 100,000 wind turbines that will demand for more than 500,000 employees by 2030. Therefore, wind energy sector induces powerful domestic supply chain in the US. Total 600,000 jobs in wind sector together with jobs current (100,000) and in the future expected (500,000) the sector will have a considerable role in manufacturing, installation, maintenance, and supporting services by 2050 in the US [118]. The US Energy Department [118] states that wind energy is more affordable than natural gas and coal since contracts of wind energy generating sector consists of fixed energy prices for 20 years and indicates that less vulnerability of the US to changes in prices and supply disruptions through long term contracts, the wind energy sector is expected to save households $280 billion by 2050. The wind sector has already an annual economic impact of about $20 billion on the U.S. economy [118].

Biomass and geothermal usages have also considerable contributions to the US economy. The biomass has approximately 100 billion US dollar direct and indirect contribution to the United States [119]. US Department of Energy [119] claims that biomass sector has employed half million people in the US, and, will triple the employment level of the sector in the next two decades. Besides, the developments in biomass, biofuels technologies are expected to produce a stable domestic energy which in return will cause US oil import to decline. Geothermal sources have supported the US economy by 20 billion US dollars in terms of 2015 [120] and are anticipated to create new potentials in US economy by 85 billion US dollars within next three decades [121].

Due to significant potentials and advantages of renewables in terms of employment, GDP, quality environment and hence health, and productivity, there exist renewable related several state and local programs and/or federal programs to subsidy the renewables production in the US. Fig. 20 presents the percentage shares of federal direct financial interventions in U.S. energy sectors by subsidy-support type. The subsidy-support types are divided into four groups; (1) Direct expenditures, (2) Tax expenditures, (3) Research and development, and, (4) DOE Loan Guarantee Program [122]. According to EIA [122] sources, the shares of renewables within federal direct total financial interventions and subsidies in 2010, 2013 and 2016 are 42%, 52% and 45%, respectively. On the other hand, the shares of nuclear, natural gas and petroleum, coal within total federal financial interventions and subsidies in 2016 appear to be 2%, 5% and 8%, respectively.

Overall one can argue that renewables have great positive influences on the US economy in terms of employment, investments, research and development, energy independency and energy security, and, environmental quality. Therefore, one should consider direct and indirect contributions simultaneously of the renewables to the household's life style, industrial production, and, new capital formations. The renewables have considerable direct and indirect impacts on the US economy. Direct effects include the labor employment (drilling, assembling, and manufacturing) and capital employment through initial realized renewables investments; the indirect impacts consist of relevant additional employment and economic activities through supply chain processes, research and developments, clean environment and public health.

The latter topic of decomposition of renewables' impulses in a national economy as direct and indirect impulses might be followed by potential possible future research paper(s) in detail to give more insight into the understanding the economic, social and environmental role of renewables.

6. Conclusion and recommendation

This research aims at exploring the influence of renewables on industrial production (Ip) in the US by following continuous wavelet coherence and partial continuous wavelet coherence analyses. To this end, we observe the co-movements between, biofuels-Ip, solar-Ip, wind-Ip, geothermal-Ip, wood-Ip, and, waste-Ip pairs in the US for the monthly period from January 1989 to November 2016.

Throughout wavelet analyses, this research presents firstly the evidence in the short term cycles (in high frequency band), and, explores findings of long term cycles (in low frequency band) as given in 1 and 2.

1- In short term cycles, geothermal, solar, wind, biofuels, wood and waste have significant positive effect on industrial production (Ip) in the US.

The geothermal, solar, wind and biofuels seem to lead Ip to increase mostly during 1990s, in the beginning of 2000s and mid of 2010s. The renewable wood is efficient on Ip rather within the second half of 2000s and 1st half of the 2010s, as waste is forceful on Ip more often during 1990s and 2000s.

2- In long term cycles, geothermal, solar, wind, biofuels and wood have significant positive impact on Ip in the US.

Wind and solar are seen to be effective on Ip during 1990s and 1st half of 2000s. Besides, wind power has significant influence on Ip for the 1st half of 2010s. The geothermal energy source shows its impact on Ip in the second half of the 1990s and first half of 2000s. Biofuels has significant impulses on Ip in the second half of 2000s and first half of the 2010s. The Ip is affected by wood during 2000s and first half of the 2010s. Renewable source waste appears to have an impact on Ip only in 2008, in low frequency band, in the US.

This paper eventually can claim that renewable energy sources can influence positively the US industrial production. Through time series, or, panel or wavelet analyses, a future work might explore the correlation between renewables consumption and welfare. This future work further might reveal the impact of renewables sector on national employment, investments, research and developments, energy independency and energy security, and, environmental quality through direct and indirect contributions of the renewables to the household's life style, industrial production, and, new capital formations.

References

[1] Bilgili F, Öztürk İ, Koçak E, Bulut Ü, Pamuk Y, Muğaloğlu E, Bağlıtaş HH. The influence of biomass energy consumption on CO_2 emissions: a wavelet coherence approach. Environ Sci Pollut Res 2016;23(19):19043–61.

[2] Klass DL. A critical assessment of renewable energy usage in the USA. Energy Policy 2003;31(4):353–67.

[3] Stokes LC, Breetz HL. Politics in the US energy transition: case studies of solar, wind, biofuels and electric vehicles policy. Energy Policy 2018;113:76–86.

[4] Delmas MA, Montes-Sancho MJ. US state policies for renewable energy: context and effectiveness. Energy Policy 2011;39(5):2273–88.

[5] Carley S, Browne TR. Innovative US energy policy: a review of states' policy experiences. Wiley Interdiscip Rev: Energy Environ 2013;2(5):488–506.

[6] Carley S. State renewable energy electricity policies: an empirical evaluation of effectiveness. Energy Policy 2009;37(8):3071–81.

[7] Menz FC, Vachon S. The effectiveness of different policy regimes for promoting wind power: experiences from the states. Energy Policy 2006;34(14):1786–96.

[8] Delmas M, Montes Sancho MJ, Shimshack JP. Information disclosure policies: Evidence from the electricity industry. Econ Inq 2010;48(2):483–98.

[9] Yin H, Powers N. Do state renewable portfolio standards promote in-state renewable generation?. Energy Policy 2010;38(2):1140–9.

[10] Shrimali G, Lynes M, Indvik J. Wind energy deployment in the US: an empirical analysis of the role of federal and state policies. Renew Sustain Energy Rev 2015;43:796–806.

[11] Karanfil F. How many times again will we examine the energy-income nexus using a limited range of traditional econometric tools? Energy Policy 2009;37(4):1191–4.

[12] Ozturk I. A literature survey on energy–growth nexus. Energy Policy 2010;38(1):340–9.

[13] Kraft J, Kraft A. On the relationship between energy and GNP. J Energy Dev 1978;3:401–3.

[14] International Energy Agency (IEA). World energy outlook. Paris: OECD/IEA; 2015.

[15] Omri A. An international literature survey on energy-economic growth nexus: evidence from country-specific studies. Renew Sustain Energy Rev 2014;38:951–9.

[16] Yoo SH. Oil consumption and economic growth: evidence from Korea. Energy Sources 2006;1(3):235–43.

[17] Apergis N, Payne JE. Coal consumption and economic growth: evidence from a panel of OECD countries. Energy Policy 2010;38(3):1353–9.

[18] Wolde-Rufael Y. Coal consumption and economic growth revisited. Appl Energy 2010;87(1):160–7.

[19] Chu HP, Chang T. Nuclear energy consumption, oil consumption and economic growth in G-6 countries: bootstrap panel causality test. Energy Policy 2012;48:762–9.

[20] Kum H, Ocal O, Aslan A. The relationship among natural gas energy consumption, capital and economic growth: bootstrap-corrected causality tests from G-7 countries. Renew Sustain Energy Rev 2012;16(5):2361–5.

[21] Behmiri NB, Manso JRP. How crude oil consumption impacts on economic growth of Sub-Saharan Africa? Energy 2013;54:74–83.

[22] Shahbaz M, Lean HH, Farooq A. Natural gas consumption and economic growth in Pakistan. Renew Sustain Energy Rev 2013;18:87–94.

[23] Ozturk I, Al-Mulali U. Natural gas consumption and economic growth nexus: panel data analysis for GCC countries. Renew Sustain Energy Rev 2015;51:998–1003.

[24] Arora V, Shi S. Energy consumption and economic growth in the United States. Appl Econom 2016;48(39):3763–73.

[25] Bilgili F, Koçak E, Bulut Ü, Sualp MN. How did the US economy react to shale gas production revolution? An advanced time series approach. Energy 2016;116:963–77.

[26] Akarca AT, Long TV. On the relationship between energy and GNP: a reexamination. J Energy Dev 1980;5:326–31.

[27] Yu SHE, Hwang BK. The relationship between energy and GNP: further results. Energy Econ 1984;6(3):186–90.

[28] Abosedra S, Baghestani H. New evidence on the causal relationship between United States energy consumption and gross national product. J Energy Dev 1989;14:285–92.

[29] Yu SHE, Jin JC. Cointegration tests of energy consumption, income, and employment. Resour Energy 1992;14(3):259–66.

[30] Stern DI. Energy and economic growth in the USA: a multivariate approach. Energy Econ 1993;15(2):137–50.

[31] Cheng BS. An investigation of cointegration and causality between energy consumption and economic growth. J Energy Dev 1995;21(1):73–84.

[32] Cheng BS, Lai TW. An investigation of co-integration and causality between energy consumption and economic activity in Taiwan. Energy Econ 1997;19(4):435–44.

[33] Stern DI. A multivariate cointegration analysis of the role of energy in the US macroeconomy. Energy Econ 2000;22(2):267–83.

[34] Hondroyiannis G, Lolos S, Papapetrou E. Energy consumption and economic growth: assessing the evidence from Greece. Energy Econ 2002;24(4):319–36.

[35] Altinay G, Karagol E. Structural break, unit root, and the causality between energy consumption and GDP in Turkey. Energy Econ 2004;26(6):985–94.

[36] Oh W, Lee K. Energy consumption and economic growth in Korea: testing the causality relation. J Policy Model 2004;26(8–9):973–81.

[37] Shiu A, Lam PL. Electricity consumption and economic growth in China. Energy Policy 2004;32(1):47–54.

[38] Yoo SH. Electricity consumption and economic growth: evidence from Korea. Energy Policy 2005;33(12):1627–32.

[39] Mehrara M. Energy consumption and economic growth: the case of oil exporting countries. Energy Policy 2007;35(5):2939–45.

[40] Akinlo AE. Energy consumption and economic growth: evidence from 11 Sub-Sahara African countries. Energy Econ 2008;30(5):2391–400.

[41] Erdal G, Erdal H, Esengün K. The causality between energy consumption and economic growth in Turkey. Energy Policy 2008;36(10):3838–42.

[42] Lee CC, Chang CP. Energy consumption and economic growth in Asian economies: a more comprehensive analysis using panel data. Resour Energy Econ 2008;30(1):50–65.

[43] Abosedra S, Dah A, Ghosh S. Electricity consumption and economic growth, the case of Lebanon. Appl Energy 2009;86(4):429–32.

[44] Odhiambo NM. Energy consumption and economic growth nexus in Tanzania: an ARDL bounds testing approach. Energy Policy 2009;37(2):617–22.

[45] Bartleet M, Gounder R. Energy consumption and economic growth in New Zealand: results of trivariate and multivariate models. Energy Policy 2010;38(7):3508–17.

[46] Ozturk I, Aslan A, Kalyoncu H. Energy consumption and economic growth relationship: evidence from panel data for low and middle income countries. Energy Policy 2010;38(8):4422–8.

[47] Belke A, Dobnik F, Dreger C. Energy consumption and economic growth: new insights into the cointegration relationship. Energy Econ 2011;33(5):782–9.

[48] Eggoh JC, Bangaké C, Rault C. Energy consumption and economic growth revisited in African countries. Energy Policy 2011;39(11):7408–21.

[49] Hamdi H, Sbia R, Shahbaz M. The nexus between electricity consumption and economic growth in Bahrain. Econ Model 2014;38:227–37.

[50] Yildirim E, Sukruoglu D, Aslan A. Energy consumption and economic growth in the next 11 countries: the bootstrapped autoregressive metric causality approach. Energy Econ 2014;44:14–21.

[51] Iyke BN. Electricity consumption and economic growth in Nigeria: a revisit of the energy-growth debate. Energy Econ 2015;51:166–76.

[52] Tang CF, Tan BW, Ozturk I. Energy consumption and economic growth in Vietnam. Renew Sustain Energy Rev 2016;54:1506–14.

[53] Saidi K, Rahman MM, Amamri M. The causal nexus between economic growth and

energy consumption: new evidence from global panel of 53 countries. Sustain Cities Soc 2017;33:45–56.

[54] Khobai H, Abel S, Le Roux P. A Review of the Nexus Between Energy consumption and Economic growth in the Brics countries. MPRA paper no: 82462; 2017. ⟨https://mpra.ub.uni-muenchen.de/82462/1/MPRA_paper_82462.pdf⟩ [Accessed 12 March 2018].

[55] Kourtzidis SA, Tzeremes P, Tzeremes NG. Re-evaluating the energy consumption-economic growth nexus for the United States: an asymmetric threshold cointegration analysis. Energy 2018;148:537–45.

[56] Bhattacharya M, Paramati SR, Ozturk I, Bhattacharya S. The effect of renewable energy consumption on economic growth: evidence from top 38 countries. Appl Energy 2016;162:733–41.

[57] Bilgili F. Business cycle co-movements between renewables consumption and industrial production: a continuous wavelet coherence approach. Renew Sustain Energy Rev 2015;52:325–32.

[58] Payne JE. On the dynamics of energy consumption and output in the US. Appl Energy 2009;86(4):575–7.

[59] Sadorsky P. Renewable energy consumption and income in emerging economies. Energy Policy 2009;37(10):4021–8.

[60] Tugcu CT, Ozturk I, Aslan A. Renewable and non-renewable energy consumption and economic growth relationship revisited: evidence from G7 countries. Energy Econ 2012;34(6):1942–50.

[61] Menyah K, Wolde-Rufael Y. CO_2 emissions, nuclear energy, renewable energy and economic growth in the US. Energy Policy 2010;38(6):2911–5.

[62] Apergis N, Payne JE. Renewable energy consumption and economic growth: evidence from a panel of OECD countries. Energy Policy 2010;38(1):656–60.

[63] Apergis N, Payne JE. Renewable energy consumption and growth in Eurasia. Energy Econ 2010;32(6):1392–7.

[64] Menegaki AN. Growth and renewable energy in Europe: a random effect model with evidence for neutrality hypothesis. Energy Econ 2011;33(2):257–63.

[65] Apergis N, Payne JE. The renewable energy consumption–growth nexus in Central America. Appl Energy 2011;88(1):343–7.

[66] Apergis N, Payne JE. On the causal dynamics between renewable and non-renewable energy consumption and economic growth in developed and developing countries. Energy Syst 2011;2(3–4):299–312.

[67] Tiwari AK. A structural VAR analysis of renewable energy consumption, real GDP and CO_2 emissions: evidence from India. Econ Bull 2011;31(2):1793–806.

[68] Yildirim E, Saraç Ş, Aslan A. Energy consumption and economic growth in the USA: evidence from renewable energy. Renew Sustain Energy Rev 2012;16(9):6770–4.

[69] Apergis N, Payne JE. Renewable and non-renewable energy consumption-growth nexus: evidence from a panel error correction model. Energy Econ 2012;34(3):733–8.

[70] Shahbaz M, Zeshan M, Afza T. Is energy consumption effective to spur economic growth in Pakistan? New evidence from bounds test to level relationships and Granger causality tests. Econ Model 2012;29(6):2310–9.

[71] Salim RA, Rafiq S. Why do some emerging economies proactively accelerate the adoption of renewable energy? Energy Econ 2012;34(4):1051–7.

[72] Ocal O, Aslan A. Renewable energy consumption–economic growth nexus in Turkey. Renew Sustain Energy Rev 2013;28:494–9.

[73] Pao HT, Fu HC. Renewable energy, non-renewable energy and economic growth in Brazil. Renew Sustain Energy Rev 2013;25:381–92.

[74] Bildirici ME. Economic growth and biomass energy. Biomass- Bioenergy 2013;50:19–24.

[75] Lin B, Moubarak M. Renewable energy consumption–Economic growth nexus for China. Renew Sustain Energy Rev 2014;40:111–7.

[76] Al-mulali U, Fereidouni HG, Lee JY. Electricity consumption from renewable and non-renewable sources and economic growth: evidence from Latin American countries. Renew Sustain Energy Rev 2014;30:290–8.

[77] Salim RA, Hassan K, Shafiei S. Renewable and non-renewable energy consumption and economic activities: further evidence from OECD countries. Energy Econ 2014;44:350–60.

[78] Ohler A, Fetters I. The causal relationship between renewable electricity generation and GDP growth: a study of energy sources. Energy Econ 2014;43:125–39.

[79] Pao HT, Li YY, Fu HC. Clean energy, non-clean energy, and economic growth in the MIST countries. Energy Policy 2014;67:932–42.

[80] Ozturk I, Bilgili F. Economic growth and biomass consumption nexus: dynamic panel analysis for Sub-Sahara African countries. Appl Energy 2015;137:110–6.

[81] Bilgili F, Ozturk I. Biomass energy and economic growth nexus in G7 countries: evidence from dynamic panel data. Renew Sustain Energy Rev 2015;49:132–8.

[82] Solarin SA, Ozturk I. On the causal dynamics between hydroelectricity consumption and economic growth in Latin America countries. Renew Sustain Energy Rev 2015;52:1857–68.

[83] Hamit-Haggar M. Clean energy-growth nexus in sub-Saharan Africa: evidence from cross-sectionally dependent heterogeneous panel with structural breaks. Renew Sustain Energy Rev 2016;57:1237–44.

[84] Dogan E. Analyzing the linkage between renewable and non-renewable energy consumption and economic growth by considering structural break in time-series data. Renew Energy 2016;99:1126–36.

[85] Bilgili F, Koçak E, Bulut Ü, Kuşkaya S. Can biomass energy be an efficient policy tool for sustainable development? Renew Sustain Energy Rev 2017;71:830–45.

[86] Koçak E, Şarkgüneşi A. The renewable energy and economic growth nexus in Black Sea and Balkan countries. Energy Policy 2017;100:51–7.

[87] DŞ Armeanu, Vintilă G, Gherghina ŞC. Does renewable energy drive sustainable economic growth? Multivariate panel data evidence for EU-28 countries. Energies 2017;10(3):381.

[88] Rafindadi AA, Ozturk I. Impacts of renewable energy consumption on the German economic growth: evidence from combined cointegration test. Renew Sustain Energy Rev 2017;75:1130–41.

[89] Saad W, Taleb A. The causal relationship between renewable energy consumption and economic growth: evidence from Europe. Clean Technol Environ Policy 2018:1–10.

[90] U.S. Energy Information Administration (EIA) - Independent Statistics and Analysis, International. ⟨https://www.eia.gov/renewable/data.cfm#summary⟩ [Accessed 8 November 2016].

[91] Federal Reserve Economic Data, Federal Reserve Bank of St. Louis, Link: ⟨https://fred.stlouisfed.org⟩ [Accessed 8 November 2016].

[92] Wen Y. The business cycle effects of Christmas. J Monet Econ 2002;49(6):1289–314.

[93] Merrill S, Grofman B, Brunell TL. Cycles in American national electoral politics, 1854–2006: statistical evidence and an explanatory model. Am Political Sci Rev 2008;102(1):1–17.

[94] Gençay R, Selçuk F, Whitcher B. An introduction to wavelets and other filtering methods in finance and economics. Waves Random Media 2002;12(3):399. [-399].

[95] Aguiar-Conraria L, Azevedo N, Soares MJ. Using wavelets to decompose the time–frequency effects of monetary policy. Phys A: Stat Mech Appl 2008;387(12):2863–78.

[96] Crowley PM. A guide to wavelets for economists. J Econ Surv 2007;21(2):207–67.

[97] Crowley PM. An intuitive guide to wavelets for economists. Bank of Finland Research Discussion Paper; 2005. ⟨https://papers.ssrn.com/sol3/papers.cfm?Abstract_id=787564⟩ [Accessed 22 December 2017].

[98] Kim S, In F. On the relationship between changes in stock prices and bond yields in the G7 countries: wavelet analysis. J Int Financ Mark, Inst Money 2007;17(2):167–79.

[99] Vacha L, Barunik J. Co-movement of energy commodities revisited: evidence from wavelet coherence analysis. Energy Econ 2012;34(1):241–7.

[100] Reboredo JC, Rivera-Castro MA, Ugolini A. Wavelet-based test of co-movement and causality between oil and renewable energy stock prices. Energy Econ 2017;61:241–52.

[101] Torrence C, Compo GP. A practical guide to wavelet analysis. Bull Am Meteorol Soc 1998;79(1):61–78.

[102] Grossmann A, Morlet J. Decomposition of Hardy functions into square integrable wavelets of constant shape. SIAM J Math Anal 1984;15(4):723–36.

[103] Madaleno M, Pinho C. Wavelet dynamics for oil-stock world interactions. Energy Econ 2014;45:120–33.

[104] Rua A, Nunes LC. International comovement of stock market returns: a wavelet analysis. J Empir Financ 2009;16(4):632–9.

[105] Percival DB, Walden AT. Wavelet methods for time series analysis 4. Cambridge University Press; 2000.

[106] Hudgins L, Friehe CA, Mayer ME. Wavelet transforms and atmopsheric turbulence. Phys Rev Lett 1993;71(20):3279–82.

[107] Aguiar-Conraria L, Magalhães PC, Soares MJ. The nationalization of electoral cycles in the United States: a wavelet analysis. Public Choice 2013;156(3–4):387–408.

[108] Liu PC. Wavelet spectrum analysis and ocean wind waves. Wavelet analysis and its applications 4. Academic Press; 1994. p. 151–66.

[109] UCSUSA, Union of Concerned Scientists, Science for a Healthy Planet and Safer World, May; 2013. ⟨https://www.ucsusa.org/clean_energy/smart-energy-solutions/increase-renewables/renewable-energy-electricity-standards-economic-benefits.html#.WoN7lq5l-Ul⟩ [Accessed 21 December 2017].

[110] U.S. Energy Information Administration (EIA). Monthly energy review; 2018. ⟨https://www.eia.gov/totalenergy/data/monthly/#electricity⟩ [Accessed 5 May 2018].

[111] U.S. Energy and Employment Report; 2017.⟨https://www.energy.gov/sites/prod/files/2017/01/f34/2017%20US%20Energy%20and%20Jobs%20Report_0.pdf⟩ [Accessed 6 May 2018].

[112] U.S. Energy and Employment Report; 2017.⟨https://www.energy.gov/downloads/2017-us-energy-and-employment-report⟩ [Accessed 6 May 2018].

[113] U.S. Energy and Employment Report, A Joint Project of the Energy Futures Initiative, and the National Association of State Energy Officials, NASEO Public Policy Conference, February 9, Washington, DC; 2018. ⟨http://energyoutlook.naseo.org/data/energymeetings/presentations/Foster-EFI.pdf⟩. [Accessed 6 May 2018].

[114] Solar Jobs Census; 2017.⟨https://solarstates.org/#states/jobs⟩ [Accessed 20 March 2017].

[115] Horn PUS. Renewable Energy Jobs Employ, Inside Climate News, May 30; ⟨https://insideclimatenews.org/news/26052017/infographic-renewable-energy-jobs-worldwide-solar-wind-trump⟩ [Accessed 8 June 2018].

[116] Clean Technica. Wind Energy Is An Engine For Job Creation Across The US, Pinterest, February 4th 2018 by Guest Contributor; ⟨https://cleantechnica.com/2018/02/04/wind-energy-engine-job-creation-across-us/⟩ [Accessed 25 March 2017].

[117] Clean Technica. Renewable Energy Has More Economic Benefits Than You Know; 2018.⟨https://cleantechnica.com/2018/03/10/renewable-energy-economic-benefits-know/⟩ [Accessed 25 March 2017].

[118] US Department of Energy. Office of Energy Efficiency and Renewable Energy, Wind vision: A new era for wind power in the United States; 2018.⟨https://www.energy.gov/eere/wind/wind-vision⟩ [Accessed 10 May 2018].

[119] US Department of Energy. Office of Energy Efficiency and Renewable Energy, Biomass Fueling America's Growing Clean Energy Economy; July 25 2014. ⟨https://www.energy.gov/eere/articles/biomass-fueling-america-s-growing-clean-energy-economy⟩ [Accessed 10 May 2018].

[120] The Geothermal Energy Association. U.S. Geothermal Electric Power Sector: Good for America's Energy System and Economy; Nov 2015. ⟨http://www.geo-energy.org/reports/2017/GEOTHERMAL%20IS%20GOOD%20FOR%20AMERICA.pdf⟩. [Accessed 20 April 2018].

[121] Blodgett L. Geothermal Basics-Economic Benefits, Geothermal Energy Association, April 3; 2014. ⟨http://geo-energy.org/geo_basics_benefits.aspx⟩ [Accessed 20 April 2018].

[122] U.S. Energy Information Administration (EIA). Direct Federal Financial Interventions and Subsidies in Energy in Fiscal Year 2016; April, 2018. ⟨https://www.eia.gov/analysis/requests/subsidy/pdf/subsidy.pdf⟩. [Accessed 22 April 2018].