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RESEARCH ARTICLE

The influence of biomass energy consumption on CO_2 emissions: a wavelet coherence approach

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Abstract In terms of today, one may argue, throughout observations from energy literature papers, that (i) one of the main contributors of the global warming is carbon dioxide emissions, (ii) the fossil fuel energy usage greatly contributes to the carbon dioxide emissions, and (iii) the simulations from energy models attract the attention of policy makers to renewable energy as alternative energy source to mitigate the carbon dioxide emissions. Although there appears to be intensive renewable energy works in the related literature regarding renewables' efficiency/impact on environmental quality, a researcher might still need to follow further studies to review the significance of renewables in the environment since (i) the existing seminal papers employ time series models and/or panel data models or some other statistical observation to detect the role of renewables in the environment and (ii) existing papers consider mostly aggregated renewable energy source rather than examining the major component(s) of aggregated renewables. This paper attempted to examine clearly the impact of biomass on carbon dioxide emissions in detail through time series and frequency analyses. Hence, the paper follows wavelet coherence analyses. The data covers the US monthly observations ranging from 1984:1 to 2015 for the variables of total energy carbon dioxide emissions, biomass energy consumption, coal consumption, petroleum consumption, and natural gas consumption. The paper thus, throughout wavelet coherence and wavelet partial coherence analyses, observes frequency properties as well as time series properties of relevant variables to reveal the possible significant influence of biomass usage on the emissions in the USA in both the short-term and the long-term cycles. The paper also reveals, finally, that the biomass consumption mitigates CO_2 emissions in the long run cycles after the year 2005 in the USA.

Keywords Biomass energy · Fossil energy · CO_2 emissions · Wavelet coherence · Signal processing · Energy consumption

Introduction

Energy is a vital factor of production for an economy since all economic activities are materialized through the usage of energy. An increase in energy demand of countries has similar

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features to growth and advancement, and, hence, the level of energy consumption is evaluated as an advancement indicator (Sadorsky, 2009). One monitors that the literature observing the impact of energy on growth has been expanding rapidly. Numerous works in the energy literature support the positive relationship between growth and energy consumption (Yu and Hwang 1984; Ang 2007; Narayan and Smyth 2008; Abosedra et al. 2009; Ozturk 2010; Lin and Moubarak 2014; Bildirici 2013). Increases in the world population, transportation, industrialization, and urbanization along with economic advancements result in an increase in energy demand. IEA (2012) reveals that the world primary energy demand grew by 26 % from 2000 to 2010 and that a considerable part of this demand is provided by fossil energy sources such as oil, coal, and natural gas. Additionally, Fig. 1 shows that the share of fossil energy sources in world energy supply is about 81 %. In other words, the world depends on fossil fuels. This dependency leads to two important problems on a global scale. The first problem is dealt with energy security. The energy security problem defined as energy supply failures and energy price shocks has several outcomes. It (i) breaks down trade balances of countries, (ii) leads to inflationary pressures in countries, and (iii) affects the production and competitive power of countries negatively (Bang 2010; Lilliestam and Ellenbeck 2011) and hence, (iv) increases prominently the dependency of energy-importing countries (Ozturk 2010). The second problem refers to environmental problems induced by fossil sources. Fossil energy sources bring about several environmental concerns such as global warming, climate change, local air pollution, and acid rains (Lau et al. 2012; Nejat et al. 2015; CSCC 2001]. Therefore, the relevant energy policies that can decrease the dependency of fossil sources and minimize the environmental damages are needed to reach sustainable economic growth. On the other hand, these policies may include some risks and costs as well. In comparison between advantages and costs of energy resources, the renewable energy sources might have some potential advantages compared with other energy sources (IPCC 2011; Kroetz and Friedland 2008).

Renewable energy sources are considered as clean sources and technologies. If renewable energy sources are used in an optimal manner, their environmental effects will be quite restricted and they will produce quite a little secondary waste (Panwar et al. 2011). Therefore, in general, the public and policy makers are very interested in renewable energy sources (Apergis and Payne 2014). The renewable energy sources are biomass, biofuels, hydrogen, hydropower, geothermal, solar, wind, and ocean wave energy, respectively. The biomass is one of the most considered sources among renewables (Bilgili 2012a). It is argued that biomass is more attractive than other renewable energy sources due to several reasons. The first reason is about the share of biomass sources in the world primary energy demand. The biomass energy meets 10 % of the world primary energy demand (IEA 2012). Besides, the share of biomass in the world renewable energy demand is 76 % (IEA 2014). The second reason is that there exist huge amounts of renewable biomass sources in the world and that the world uses only 7 % of biomass energy potential (Narayan 2007). Table 1 depicts that biomass-based electricity production and the use of biofuels have increased lately.

Biomass energy has important political, economic, and environmental advantages and hence, might be a preferable candidate to replace fossil energy sources. Biomass might save energy-importing countries from politically unstable fossil fuel-exporting countries (McCarl et al. 2010).

Therefore, biomass might decrease energy dependency and support national energy security (Loo and Koppejan 2010). The substitution of fossil fuels with biomass helps to mitigate energy imports of energy-importer countries, and thus these countries may decrease trade deficits (Walter 2006; Hoekman 2009). In addition, biomass energy may renew infertile soils and increase the biological diversity and water retention and fertility of the soil (Demirbas et al. 2009). Thereby, biomass energy can increase employment in rural areas improving

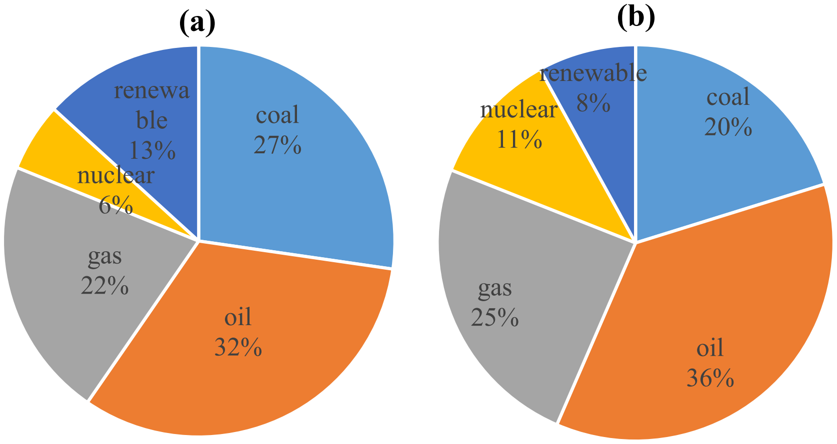

Fig. 1 The shares of primary energy sources in the world in 2010. (**a**) The shares of energy demand. (**b**) The shares of energy supply. Data Source, IEA (2012)

Table 1 Biomass/biofuels energy production and consumption in the world (2012)

	Electricity generation[a]		Biofuel production[b]		Biofuel consumption[b]	
	Total	% share	Total	% share	Total	% share
US	71.409	19	939.558	49	898	48
Brazil	35.237	9	449.200	24	406.6	22
Germany	44.628	12	68.070	4	75.7	4
China	44.668	12	58.900	3	58.9	3
World	*384.217*		*1901.348*		*1866.2*	

Data sources: IEA (2014) and EIA (2015a)

[a] Biomass and waste electricity net generation (Billion Kilowatt-hours)

[b] Thousand barrels per day

agricultural economy, and thus, it can decrease poverty in developing countries (Demirbas et al. 2009). Furthermore, biomass can enhance economic growth through improvements in sectoral growths. Therefore, one may suggest that policy makers promote the usage of biomass energy in rural and/or urban economies (Bildirici 2014). Furthermore, biomass helps central banks ensure price stability, enhances global competition, and stimulates economic productivity (Hoekman 2009). Some papers in literature have explicit empirical evidences yielding that biomass energy consumption supports economic growth. Payne (2011) obtains a unidirectional causal relationship from biomass energy consumption to GDP for the USA. Ozturk and Bilgili (2015) find that biomass energy consumption affects GDP positively for 51 sub-Saharan African countries. Bilgili and Ozturk (2015) reveal that biomass usage improves the growths of G7 countries. Besides, biomass energy presents a solution for environmental problems of global warming, climate change, air pollution, and acid rains since biomass energy might decrease CO_2 and other pollutant gas emissions (Loo and Koppejan 2010; Hill et al. 2006; Georgescu et al. 2011; Bilgili 2012a, b; Openshaw 2010). As a result of these advantages, biomass has been considered as an alternative energy source within the scope of national energy policies lately (Demirbas et al. 2009).

This paper focuses on environmental impacts of biomass. The purpose of the paper is, then, to examine biomass consumption on CO_2 emissions in the USA.

As known, the USA is the greatest energy consumer, producer, and importer in the world. According to EIA (2015a) data, in 2010, the percentage shares of the USA in the world energy supply, in the world energy demand, in the world oil import, and in the world gas import are 15, 20, 23, and 20 %, respectively. Besides, one might argue that the USA is responsible for about 20 % of the world CO_2 emissions. Therefore, the energy policies of the USA affect, directly and indirectly, the environment and CO_2 emissions. On the other hand, the US economy rests on cheap and easily accessible oil, natural gas, and coal (Bang 2010), but the USA procures an important part of energy demand through import. Hence, the USA is a country that is foreign-dependent in energy and that may experience energy security problems.

Figure 2 depicts the energy production and consumption of the USA during the period of 1980–2012. The difference in favor of energy consumption indicates the energy dependency of the USA. This dependency poses a political and economic risk.

According to EIA (2015a) data, the share of oil in total energy import is 85 % for the USA in 2014. Therefore, it might be claimed that oil import essentially breaks down the trade balance of the USA. Increases in the energy demand of developing countries have raised energy prices and have worsened the trade balance of the USA more lately. Additionally, the energy dependency causes increases in

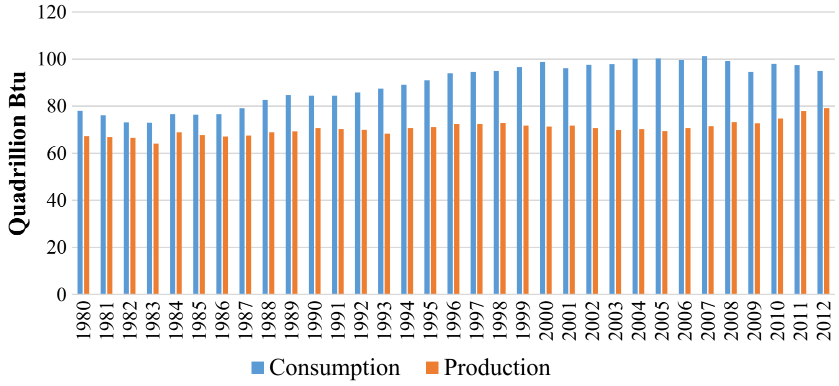

Fig. 2 Energy balance in the USA between 1980 and 2012. Data source: EIA (2015a)

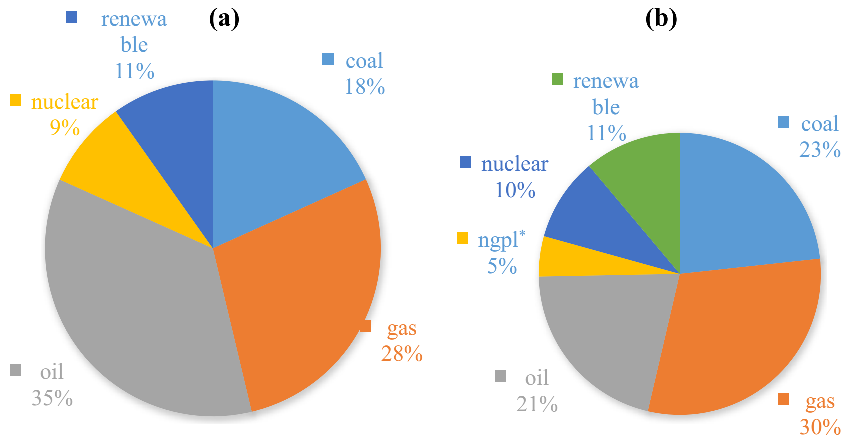

Fig. 3 **a** Primary energy consumption in the USA in 2014 and **b** primary energy production in the USA in 2014. **ngpl* natural gas plant liquids. Data Source, EIA (2015a)

military and defense expenditures of the USA to reach world oil sources (Cui et al. 2011). In fact, ensuring energy security has been the basic policy goal for the USA since oil shocks in 1970s, and fluctuations in oil prices stemming from political instability in oil fields have raised the importance of this goal (Rhodes 2007; Wang et al. 2014). However, the USA did not achieve success about ensuring energy security (Bang 2010). Thereby, the USA began to be interested in renewable energy sources, especially in biomass, more. The share of renewable energy in energy supply and energy demand of the USA continuously increased, and this share reached 11 % in 2014 as is given in Fig. 3a, b.

As seen in Fig. 4, biomass has greater share than other renewable sources have. Besides, the USA is one of the most successful countries in utilizing biomass sources and thus generating energy (Table 1). Therefore, the biomass energy may decrease CO_2 emissions and energy dependency of the USA (Payne 2011). The USA updated the Renewable Fuel Standard (RFS2) due to these advantages of biomass. For instance, procuring oil demand through biofuels is the main goal within the scope of renewable energy policies (Sorda et al. 2010).

Further, an increase in the biomass production of the USA will have important effects on world oil prices, energy markets, energy technology, and monopoly powers of OPEC countries (Khanna and Chen 2013). Therefore, the empirical findings of this paper are expected to provide policy makers in the USA and in other countries with some important policy implications about decreasing CO_2 emissions and ensuring energy dependency and energy security. Within this purpose, the rest of the paper is as follows: the "Environmental problems stemming from fossil energy sources" section presents environmental problems stemming from fossil energy sources. The literature toward the effects of biomass energy on CO_2 emissions is examined in the "Literature review" section. The "Methodology and materials" section is devoted to revealing methodology and findings. The "Wavelet estimation output" section concludes the paper with a summary of the findings and some policy proposals.

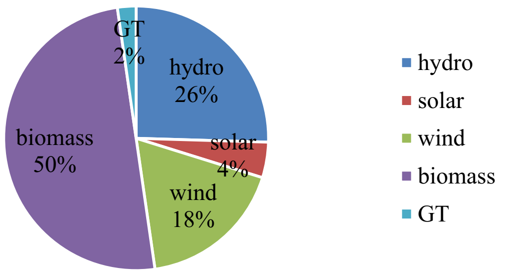

Fig. 4 Renewable energy demand sources in the USA in 2014. Data Source, EIA (2015a)

Environmental problems stemming from fossil energy sources

Global warming, air pollution, greenhouse gases, and CO_2 emissions

The most significant environmental problem based on fossil energy is global warming and thus climate change. The problem challenging the structure of the global society is considered one of the most significant problems in the twenty-first century (Tingem and Rivington 2008). Climate change affects not only the environment but also the economic, social, and geopolitical elements; local politics; and lifestyles of people (Maslin 2004). Escobar et al. (2009) denote that increases in global temperatures cause poverty, flood, water scarcity, and malaria, and thus, there are 150,000 deaths every year. Therefore, this problem induces scientific and socioeconomic concerns. As average temperature, deviating from its 1000-year trend, tends to increase, the concerns about global warming increase more and more (Wuebbles and Jain 2001).

Besides, climate change projections developed for the period of 1990–2100 indicate that global surface temperatures will increase 1.4–5.8 °C/2.5–10.4 °F at the end of the century. In addition to increases in temperatures, quick changes in

Table 2 The changes observed in climatic variables

Climatic variable	Period	Trend/change
Surface air temperature and sea surface temperature	1851–1995	0.65 ± 0.15 °C
Alpine glaciers	Last century	Warming of 0.6–1.0 °C in alpine regions
Extent of snow cover in the Northern Hemisphere	1972–1992	10 % decrease in annual mean
Extent of sea ice in the Northern Hemisphere	1973–1994	Downward since 1977
Extent of sea ice in the Southern Hemisphere	1973–1994	No change. Possible decrease between mid 1950s and early 1970s
Length of the Northern Hemisphere growing season	1981–1991	12 ± 4 days longer
Precipitation	1900–1994	Generally increasing outside tropics, decreasing in Sahel
Heavy precipitation	1910–1990	Growing in importance
Antarctic snowfall	Recent decades	5–20 % increase
Global mean sea level	Last century	1.8 ± 0.7 mm/year

Data source, Wuebbles and Jain (2001)

climatic variables were observed in the last century. These developments refer some potential danger through global warming and climate change clearly as listed in Table 2.

Increases in the natural greenhouse effect are regarded as the reason of global warming. If the natural greenhouse effect had not been present, the average surface temperature of the world would have been 60 °F colder than the current degree (Karl et al. 2009). However, the natural greenhouse effect and global temperatures grew as the intensity of greenhouse gases in the atmosphere increased as a result of human activities in the last 50 years (IPCC 1990). Many studies yield that the increase in the intensity of greenhouse gases result in global warming (Wuebbles and Jain 2001).

Among greenhouse gases, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and hydrofluorocarbons (HFCs)[1] have the greatest global warming potentials Cicerone et al. (2001). Additionally, CO_2 is the most worrisome gas among these gases (Wuebbles and Jain 2001; Reay and Grace 2007). It is estimated that the share of CO_2 in human-based greenhouse gases is 53 % historically (Griffin 2003). Indeed, the dangerous effects and global warming potentials of other sera gases are greater than those of CO_2 (Stowell 2005).

As seen in Table 3, global warming potential of CH_4 is twenty three times as great as that of CO_2. However, the intensity of CO_2 in the atmosphere is very strong while intensities of other gases are relatively weak (Maslin 2004). Besides, the intensity of CO_2 in the atmosphere grows rapidly, and increases in human-based CO_2 intensity are cumulative, because the life cycle of CO_2 in the atmosphere is very long (Karl et al. 2009). For instance, the average intensity of CO_2 was 278 parts per million (ppm) prior to the industrial revolution, was 316 ppm in 1959, 365 ppm in 1998, and reached 396 ppm in 2013 (Narayan 2007; Maslin 2004; Keeling and Whorf 1998; Swapnesh et al. 2014). The science world agrees that this is a human activity-based increase (Stowell 2005). Increases in population, transportation, urbanization, and industrialization raise energy demand, and this demand is mainly met by fossil energy sources.

Global CO_2 emissions stemming from the abovementioned increases have grown rapidly especially in recent years (Fig. 5). Therefore, fossil energy sources, such as oil, coal, and natural gas, are regarded as the main source of the increase in CO_2 emissions (Nejat et al. 2015; Berners-Lee et al. 2012). For instance, in 2010, the shares of CO_2, CH_4, and N_2O in human activity-based greenhouse gas emissions are 90, 9, and 1 %, respectively. The 69 % of these gases are related to energy consumption (IEA 2014). Global CO_2 emissions arising from only energy consumption corresponds to 30.2 $GtCO_2$. Electricity and heat production, transportation, manufacturing industry, and housing account for 41, 22, 20, and 6 % of these emissions, respectively (IEA 2014). Electricity and heat production rests on mainly coal around the world (IEA 2013). Between 68 and 98 % of electricity production is carried out through coal in Australia, China, India, and South Africa (IEA 2012). Coal has the greatest carbon intensity among fossil fuels (IEA 2013). Coal accounts for 43 % of fossil fuel-based CO_2 emissions in 2010. The shares of oil and gas are 36 and 20 %, respectively (IEA 2012).

Fossil sources are also the main source of toxic gases such as sulfur dioxide (SO_2), particulate matter (PM), ozone (O_3), carbon monoxide (CO), and nitrogen oxide (NO_2) that have great effects on health and welfare (NRC 2007). Additionally, nitrogen and sulfur emissions reach the atmosphere and lead to acid rains as a result of air pollution (Menz and Seip 2004). Acid rains may go thousands of miles away from the source through wind when they fall on the land (Ellerman 2000).

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[1] HFCs include HFC23, HFC134a, and HFC152a

Table 3 Basic greenhouse gases, sources of gases, and global warming potential (Gwp) of gases

Greenhouse gas	Concentrations* (preindustrial)	Concentrations* (1998)	Human source	GWP
Carbon dioxide (CO2)	278	365	Fossil-fuel combustion, land-use changes, cement production	1
Methane (CH4)	0.7	1.75	Fossil fuels, rice paddies, waste dumps, livestock	23
Nitrous oxide (N2O)	0.27	0.31	Fossil-fuel combustion, fertilizer, industrial processes	296
HFCs				
HFC 23 (CHF3)	0	1.4×10^{-5}	Electronics, refrigerants	12,000
HFC 134a (CF3CH2F)	0	7.5×10^{-6}	Refrigerants	1300
HFC 152a (CH3CHF2)	0	5.0×10^{-7}	Industrial processes	120

Sources, Maslin (2004); Akorede et al. (2012)

GWP global warming potential 100 years

[a] Expressed in ppm (part per million)

Besides, acid rains change the characteristic of the land. Therefore, energy is closely related to environmental problems such as global warming, air pollution, acid rains, and soil pollution and is the main responsible for pollutant gas emissions (Karl et al. 2009; Akorede et al. 2012; NRC 2007).

Energy-based CO_2 emissions, sources, and sectors: the case of the USA

The greatest greenhouse gas emitter has been the USA since the industrial revolution in the world. The USA, which has 4.5 % of the world population, is responsible for 30 % of greenhouse gases in the atmosphere (Karl et al. 2009). While the USA was world's greatest CO_2 emitter until 2007, China took USA's place as of this year. While global energy-based CO_2 emissions are 31.7 $GtCO_2$ in 2012, the shares of China and the USA in these emissions are 26 and 16 %, respectively (IEA 2014; IEA 2009a, b). However, CO_2 emissions per capita in the USA are much greater than those in China. CO_2 emissions per capita in the USA are 16.15 t while those in China are 6.08 t (IEA 2014). Therefore, it may be argued that the greatest share in the world's CO_2 emission problem belongs to the USA.

Table 4 and Fig. 6 depict greenhouse gas emissions and the sources of CO_2 emissions in the USA in 2012. As seen, the greatest share in greenhouse gas emissions belong to the CO_2 and the main source of CO_2 emissions is fossil fuel combustion. When fossil-fuel based CO_2 emissions are examined by sectors, the greatest three shares belong to electricity generation, transportation, and manufacturing industry. As presented in Fig. 7, in 2012, the shares of electricity generation, transportation, and manufacturing industry are 40, 34, and 15 %, respectively. Electricity is mainly generated through coal in the USA. The carbon intensity of coal is greater than those of oil and gas, and coal is regarded as a dirty fuel (Cotton et al. 2014). According to EIA (2015a) data, the share of coal in electricity generation is about 40 % in 2000s. Therefore, the greatest emitter of CO_2 is the electricity generation sector. Gasoline and diesel oil are mainly utilized in the transportation sector.

The transportation sector depends on oil, which is another pollutant (IEA 2009b), and thus, the transportation sector causes CO_2 emissions. The third sector is the manufacturing industry. Industrial processes emit CO_2 emissions due to chemical reactions that do not require oxygen. The production of various chemicals exemplifies these processes. Additionally, many industrial processes utilize electricity

Fig. 5 Global CO_2 emissions from fossil-fuel burning, cement manufacture, and gas flaring (1751–2010). Source: CDIAC (2015)

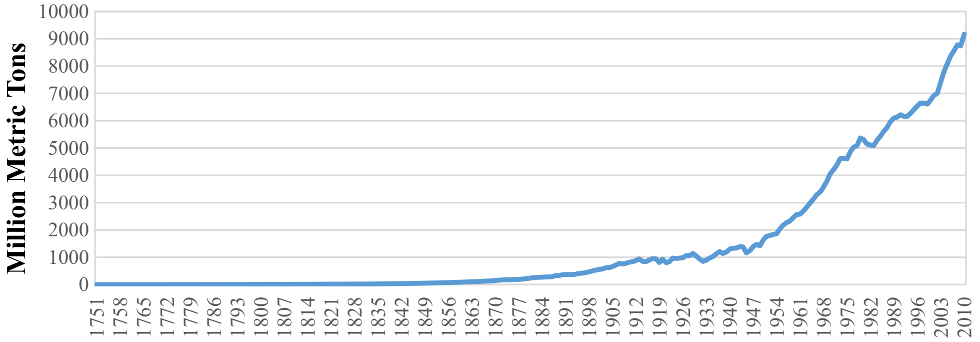

Table 4 The sources of CO_2 emissions (million metric tons) in the USA

	Emissions	% share
Fossil fuel combustion	5062.3	93.4
Non-energy use of fuels	128.9	2.4
Iron and steel and metallurgical coke production	54.3	1
Other	173.2	3.2
Total CO2	*5418.7*	*100*

Source, EPA (2015)

directly or indirectly. Thereby, the CO_2 emissions of the manufacturing industry are high.

Literature review

The following literature review explores, first, the impact of total energy usage on pollutants in several countries, and, later, aims at specifically revealing the possible significant influence of biomass energy consumption on CO_2 emissions and/or on environmental pollutants in the USA.

Akhmat et al. (2014) considered the nexus between energy consumption and environmental pollutants and found out that an increase in energy consumption leads to an increase in environmental pollutants in SAARC countries. Asongu et al. (2016) followed data of 24 African countries and explored as well that there appears to be a long-run relationship between energy consumption, CO_2 emissions, and GDP. Sarkodie and Owusu (2016) observe the data for Ghana and confirm Akhmat et al. (2014) and Asongu et al. (2016). They reveal that the major contribution to the fluctuations in CO_2 emissions stem from energy use. An identical output is obtained by Gul et al. (2015). They exhibit that energy consumption has a significant impact on carbon emissions in Malaysia. Wang et al. (2016) analyzed Chinese data and reached the evidence that there exists a bidirectional causality between economic growth and energy use and energy use and CO_2 emissions. Tsai et al. (2016) keep track the relevant US data and conclude that the CO2 emissions generated from low-carbon energy increase the CO_2 emission growth generated from fossil fuels. On the contrary from Tsai et al. (2016), Lee and Chong (2016), by observing the US data, explored specifically the role of fossil fuels in significant increases in carbon dioxide emissions in the residential and commercial sectors through electricity and coal consumptions, respectively.

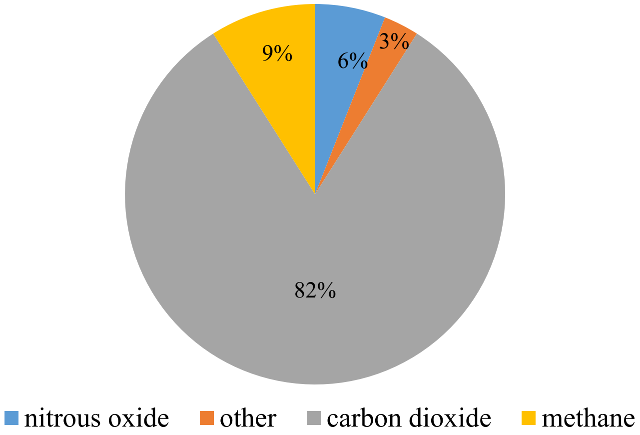

Fig. 6 The US greenhouse gas emissions by gases in 2012. Source, EPA (2015)

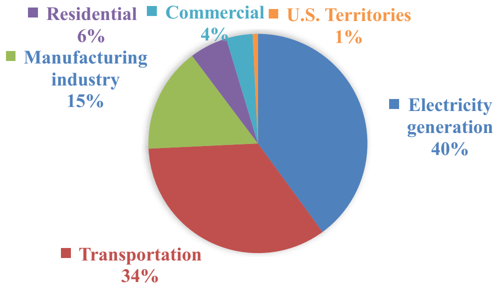

Fig. 7 The US sectoral distribution of fossil-based CO_2 emissions in 2012. Source, EPA (2015)

One may expand the relevant literature evidence exhibiting the potential responses of GHG emissions to the impulses of biomass energy consumption in the USA.

Muller et al. (2011) kept track of the influence of solid waste combustion, sewage treatment, stone quarrying, marinas, and oil- and coal fire-powered plants on air pollution in the USA and revealed that coal-fired electric generation might have the largest pollutant effect. Murray et al. (2014) reached a limited impact of subsidies (renewables) in reducing GHG emissions and explored, in some cases, the positive influence of substitutes to the emissions in USA. Novan (2015) analyzed the marginal impact of renewable electricity on pollution in the USA and exhibited that different renewables, e.g., wind turbines versus solar panels, result in different marginal external benefits. Borenstein (2012) revealed that electricity generation from renewable sources is more expensive than conventional approaches and that electricity generation from renewables mitigates the pollution externalities in the USA. Muller and Mendelsohn (2009) emphasized the marginal damages of emissions from SO2, VOC, NOx, PM2.5, PM10, and NH3 and explored that the marginal damage of emissions in urban areas (the nation's largest cities) can be over 150 times greater than the marginal damage in the rural areas of the USA. Then, what might be a possible policy proposal to reduce the emissions? Marron and Toder (2014), for instance among other possible ones, considered a carbon tax policy that might discourage the greenhouse gas emissions resulting in climate change and suggested that policy makers should follow a well-designed tax to mitigate the risk of climate change, minimizing the cost of emission reductions. Klier and Linn (2015) observed the effect of taxes to passenger vehicles to reduce CO_2 emissions in France, Germany, and Sweden and found, however, some mixed output.

One may consider, as well, specifically the contribution of biomass fuels, among other alternative energy sources, on air pollution through some possible channels. It is stated in literature that biomass may decrease environmental pollution and CO_2 emissions through two channels in literature. First, biomass is a carbon-neutral source. Wuebbles and Jain (2001) denote that when biomass is utilized as a fuel, CO_2 emissions are emitted, and these emissions are nearly equal to those of coal. However, biomass already absorbs CO_2 emissions which are equal to CO_2 emissions that are emitted before they reach the atmosphere. For this reason, net carbon emissions of biomass fuels are zero along their lifecycles, and hence, biomass fuels are considered carbon-neutral sources. When biomass is evaluated in terms of gases except for CO_2, one may claim that biomass produces far fewer pollutant gas emissions than others do. Therefore, these advantages will emerge when fossil sources are substituted with biomass sources (Haus et al. 2014; Demirbas 2009). Such a substitution seems to be possible (Breeze 2004), because biomass may be converted to solid, liquid, and gas and may be used in many sectors. Akorede et al. (2012) specify that biomass may be solid, such as straw or wood chips; be liquid, such as vegetable oils and animal slurries which can be converted to biogas; and be gaseous (biogas). Besides, they remark that some biomass can be converted to biofuels for transportation. Torregrosa et al. (2013) state that biofuels that are obtained from vegetable oil sources seem to be an excellent substitute for petroleum-based fuels due to their easy productions, utilizations, storage, and the considerable reduction achievable in pollutant emissions, such as CO_2. According to McCarl et al. (2010), bioenergy producers or consumers will not need to buy greenhouse gas or carbon emission permits while they are producing biopower or consuming liquid biofuels. Sims and Bassam (2003) remark that the bioenergy project can save both dollars and carbon emissions with regard to a coal-based power station. Besides, biomass can reduce local emissions, use limited resources better, improve biodiversity, and protect the natural habitat and landscape.

Second, energy agriculture is advanced to produce biomass energy. As Breeze (2004) denotes, CO_2 in the atmosphere is not static. Considerable parts of carbon cycles are especially plants. A large amount of carbon is held in soil, and carbon is transmitted to plants through soil. Therefore, all components of plants are included in coal, oil, and gas. Thereby, fossil sources may be substituted with biomass sources, and CO_2 emissions in the atmosphere may be reduced since CO_2 emitted during biomass burning will disappear due to new biomass fuel production. Eventually, this substitution will increase production of energy plants, and these plants will hold a large amount of carbon in the soil. McCarl et al. (2010) denote that agriculture, especially energy agriculture, might have an important role in decreasing greenhouse gas emissions. Agricultural products, plant residues, and residuals might be utilized as inputs in power plants and in the production of liquid biofuels. Thereby, CO_2 emitted in burning processes will be absorbed by plants. Hall et al. (2000) emphasize that the absorption of CO_2 emissions through photosynthesis by biomass sources can present solutions in reducing global warming, saving environment, afforestation, and planting spoiled lands.

Empirical literature yields that biomass may decrease CO_2 emissions. For instance, Schwaiger and Schlamadinger (1998) aimed at analyzing possibilities of increasing fuel-wood use for Austria, Finland, France, Portugal, and Sweden for the year 2020 in terms of 1995 by observing environmental, socioeconomic, and technical aspects. The scenarios indicate that fuel wood has significant but limited possibilities to reduce total greenhouse gas emissions in these five countries. Besides, the scenarios show that the greatest relative reductions will be in Sweden and Finland. Wahlund et al. (2004) revealed that especially woody biomass can reduce CO_2 emissions in Sweden. Gustavsson et al. (2007) examined that an increased use of biomass can reduce CO_2 emissions and oil use in Sweden by setting up four scenarios. These scenarios are (i) reducing CO_2 emissions, (ii) reducing oil use, (iii) simultaneously reducing both CO_2 emissions and oil use, and (iv) producing ethanol to replace gasoline. They explored that optimizing biomass use for a target to mitigate CO_2 emissions or to reduce oil use will cause prominent success of relevant target with output of 17.4 TgC/year and 350 PJ oil/year, respectively. This target will bear a monetary cost of €130–330 million/year. Khanna et al. (2011) yield that about as much as 5.5 % of coal-based electricity generation can be produced in the USA by transforming about 2 % of agricultural lands to bioenergy plants. Suttles et al. (2014) investigated the effects of bioelectricity and biofuels, based on biomass that originates from forests, on CO_2 emissions in European Union and the USA through global computable general equilibrium. Findings show that mandated consumption of bioenergy can majorly reduce CO_2 emissions. García et al. (2015) found that 16 % percent of electricity consumption from current fossil fuels will substitute biomass sources, and greenhouse gas emissions will reduce by 17 % by the year 2035 in Mexico.

Some papers in literature examined the effects of biofuels on pollutant gas emissions by comparing them with fossil-based sources. According to Rashedul et al. (2014), fewer carbon, smoke, particulates, CO, and hydrocarbon are emitted from biodiesels compared to those from fossil sources. Utlu (2007) reveals that CO_2, carbon, and smoke intensity will diminish by 14, 17.1, and 22.5 %, respectively, when diesel is employed in the transportation sector as a fuel. Senatore et al. (2008) exhibited that biodiesel may lessen net

CO_2 emissions by 78 % in terms of petro diesel. Panwar et al. (2009) explored that when 10 % of castor seed oil production is converted to biodiesel production, the CO_2 emissions will decline annually by 79.782 t. Fangsuwannarak and Triratanasirichai (2013) claimed that palm diesel oil results in more CO_2 emissions than biodiesel fuel does. Bilgili (2012b) searched the impact of biomass and fossil fuel consumption on CO_2 emissions for the USA and explores that fossil fuels and biomass have positive effects and negative effects, respectively, on CO_2 emissions. Hayfa and Rania (2014) investigated the relationship between electricity production through biomass and CO_2 emissions for 15 countries through panel data methods. They found that electricity production through biomass reduces CO_2 emissions.

This paper, hence, after observing the findings of relevant literature introduced above, aims at filling the gap in related literature to some extent through time series and frequency analyses of business cycles to obtain all possible short-, medium-, and long-term influences of biomass on CO_2 emissions in the USA.

Methodology and materials

Methodology

Spectral analysis of economic time series consists of time and frequency dimensions. Fourier analysis finds that any periodic and some non-periodic functions can be shown as a function of sines and cosines.[2] Fourier transformation (FT) of a signal or a function yields decomposition of time series into frequency domain in which it becomes easier to investigate predominant business cycles (Merrill et al. 2008) and seasonal characteristics (Wen 2002). Nevertheless, FT does not give information about when various frequencies appear in the time horizon, namely, it lacks time information. A frequency spectrum measures current oscillations in a signal or a function lacking of transition type (gradual or abrupt) among periods and jumps or structural changes. Given a signal or a function $h(t)$, Eq. 1 shows FT of it as below:[3]

$$H(\kappa) = \int_{-\infty}^{\infty} h(t)\exp(-i2\pi\kappa t)dt = \int_{-\infty}^{\infty} h(t)[cos(2\pi\kappa t)-i\ \ sin(2\pi\kappa t)]\,dt \tag{1}$$

where $H(\kappa)$ represents the FT of function $h(t)$, hence, is a function of frequency κ, and $i = \sqrt{-1}$ is the complex or imaginary number. Aguiar-Conraria et al. (2013) states that Fourier techniques are applicable only with stable statistical properties and that, however, most of economic time series follow unstable statistical properties such as time-varying moments of distribution (non-stationary), strong time trends, and complexity.

In addition to frequency analysis, wavelet methods consider time series in both time and frequency domain at the same time. Wavelet analysis evaluates how cycles, trends, or seasonality extracted from the transformation of a time series change over time. Gençay et al. (2002) suggests wavelet transformation as a best device for analyzing non-stationary time series due to the favor of a scaling tool; wavelet transformation may focus on a wide range of frequencies, which provides the ability to capture events that are local in time. That is why wavelet methodology has become popular in economics and finance literature including those of Gençay et al. (2002, 2005), Crowley (2007), Kim and In (2007), Aguiar-Conraria et al. (2011), Vacha and Barunik (2012), and Khalfaoui et al. (2015). A wavelet function can be written as below:

$$\phi_{(s,v)}(t) = \frac{1}{\sqrt{s}}\phi\left(\frac{t-v}{s}\right),\quad v\in\mathbb{R}\ \ and\ \ s\in\mathbb{R}^{+}. \tag{2}$$

The mother wavelet $\phi(.)$ is scaled by s and located by v in order to obtain a wavelet daughter $\phi_{(s,\,v)}(t)$ which is a square differentiable function of time, $(.)\in L^2(\mathbb{R})$.[4] Parameter v is the location or translation parameter that shows where the wavelet centered or located in time. Parameter s is scale or dilation parameter that compresses or enlarges the wavelet to detect cycles or trends in different frequencies. For instance, an increasing scaling s generates long wavelets, which capture long-run (low frequency) properties of time series whereas a decreasing s compresses it to measure short-run (high frequency) dynamics. Thus, there is an inverse relation between scale and frequency.

The continuous wavelet transformation (CWT) of a considered time series $h(t)\in L^2(\mathbb{R})$ with respect to wavelet $\phi_{(s,\,v)}(t)$ is defined as

$$W_h(s,v) = \int_{-\infty}^{\infty} h(t)\frac{1}{\sqrt{s}}\bar{\phi}\left(\frac{t-v}{s}\right)dt,\quad v\in\mathbb{R}\ \ and\ \ s>0, \tag{3}$$

where $W_h(s, v)$ represents CWT and the bar over the mother wavelet function denotes complex conjugation.[5]

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[2] If $f(x)$ is a non-periodic function, its Fourier transform $F(x):\mathbb{R}\rightarrow\mathbb{C}$ returns a complex-valued function, which has complex weights for different frequency contributions under integral as a similar way to the coefficients in the periodic functions' case.

[3] There is an alternative representation of Fourier transformation analogous (identical) to Eq. 1. Since sines and cosines are 2π-periodic functions, $w = 2\pi\kappa$ denotes radian frequency: $H(w) = \int_{-\infty}^{\infty} h(t)e^{-iwt}dt = \int_{-\infty}^{\infty} h(t)\ [\cos(wt)-i\sin(wt)]\ dt$

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

[5] The conjugate of a complex number, $c + di$, is simply $c - di$. If the value is real rather than complex, its conjugate is itself. In economic applications complex wavelets are more popular, thus the conjugation becomes important.

In addition to square differentiability, any mother wavelet should satisfy admissibility condition which provides recovery of function $h(t)$ from its wavelet transformation. The admissibility condition is defined as

$$C_{\overset{\grave{E}}{A}} \int_{0}^{\infty} \frac{|\Phi(\kappa)|^2}{\kappa} d\kappa < \infty, \tag{4}$$

where $C_{\varnothing}$ is the admissibility constant and $\Phi(\kappa)$ is the FT of wavelet $\phi(t)$. This condition implies that the wavelet does not have any zero frequency components, $\Phi(0) = \int_{-\infty}^{\infty} \overset{\grave{E}}{A}(t)\,dt = 0$, thus it must have negative and positive oscillations that cancel out each other, that is, it has a zero mean. Furthermore, the wavelet is generally normalized to have unit energy, $\int_{-\infty}^{\infty} \left|\overset{\grave{E}}{A}(t)\right|^2 dt = 1$, which provides the comparison of the wavelet transforms at each scale s and the transforms of the other time series (Torrence and Compo 1998).

There exist various wavelet functions following particular features in the relevant literature such as Haar, Daubechies, Mexican hat, Cauchy, Coiflets and Morlet, etc. Since wavelet transformation merges information coming from signal $h(t)$ and wavelet $\varnothing(t)$, it is crucial to choose the most appropriate wavelet which fits best with the data. Aguiar-Conraria et al. (2008) suggests choosing a complex wavelet as it presents a complex transformation, which has information on both amplitude (from mid-cycle phase of the period to the peak point or through the point) and phase (horizontal angle of the wave). The phase differences become important while analyzing the position of the variables in the cycles.

In the analysis, we prefer to use complex Morlet wavelet, first introduced by Grossmann and Morlet (1984), which can be defined as

$$\overset{\grave{E}}{A}_{\gamma}(t) = \frac{1}{\pi^{1/4}}\left(\exp(i\gamma t) - \exp\left(\frac{-\gamma^2}{2}\right)\right)\exp\left(\frac{-t^2}{2}\right), \tag{5}$$

where parameter γ denotes the central frequency parameter of Morlet wavelet $\varnothing_{\gamma}(t)$. In Eq. 5, if the location parameter is set, $\gamma > 5$ as the value of term $\exp(-\gamma^2/2)$ becomes negligibly small. This yields a simplified version of the Morlet wavelet function as below:

$$\overset{\grave{E}}{A}_{\gamma}(t) = \frac{1}{\pi^{1/4}}\exp(i\gamma t) - \exp\left(\frac{-t^2}{2}\right) \tag{6}$$

Economic and financial applications often set $\gamma = 6$, since it provides a parameter choice conversion between scale and frequency thus the Morlet wavelet might be considered as a function of frequency as will be seen in further discussions about the use of complex Morlet wavelets for economic applications by Aguiar-Conraria et al. (2013), Madaleno and Pinho (2014), Aguiar-Conraria et al. (2008), Rua and Nunes (2009), Crowley (2005), and Percival and Walden (2000).

The admissibility condition of the wavelets, introduced in Eq. 4, is a sufficient condition for time series to return back to its original form from their wavelet decomposition. Admissibility condition ensures to get $W_h(s, v)$ CWT from time series $h(t)$ and go from wavelet transformation to $h(t)$ as a new representation below:

$$h(t) = \frac{1}{C_{\overset{\grave{E}}{A}}} \int_{-\infty}^{\infty} \left[W_h(s,v)\phi_{(s,v)}(t)dv\right]\frac{ds}{s^2}, \quad v \in \mathbb{R} \ \ and \ \ s > 0. \tag{7}$$

CWT should maintain the energy of time series $h(t)$, by applying unit energy property of wavelets. The energy of $h(t)$ preserved by its wavelet transformation, $\|h\|^2$ can be written as

$$\|h\|^2 = \frac{1}{C_{\overset{\grave{E}}{A}}} \int_{0}^{\infty}\left[\int_{-\infty}^{\infty} |W_h(s,v)|^2 dv\right]\frac{ds}{s^2}, \quad v \in \mathbb{R} \ \ and \ \ s > 0, \tag{8}$$

where $|W_h(s, v)|^2$ is the wavelet power spectrum which shows the distribution energy of the time series $h(t)$ in both frequency and time space. In addition to analysis of a single time series, wavelet analysis can be applied for the search of time-frequency interactions between two time series such as cross wavelet power, wavelet coherency, and phase differences. While the wavelet power spectrum depicts the variance of a single time series, the cross wavelet power of the time series measures the local covariance between two time series at each time and frequency. The cross wavelet power of two time series, $W_{xy}(s, v)$, can be stated as first introduced by Hudgins et al. (1993) as

$$W_{xy}(s,v) = W_x(s,v)W_y(s,v), \tag{9}$$

where $W_x(s, v)$ and $W_y(s, v)$ are the continuous wavelet transforms of time series $x(t)$ and $y(t)$, respectively. s is scale and v is location parameter as they appear in CWT formula in Eq. 3. While the cross wavelet transform shows regions where two time series show high common power, the wavelet coherency works like a traditional correlation coefficient which depicts where two time series move together but do not necessarily have high common power. Following Aguiar-Conraria et al. (2013), wavelet coherency between $x(t)$ and $y(t)$ can be defined as follows:

$$R_{xy}(s,v) = \frac{\left|s\left(W_{xy}(s,v)\right)\right|}{\sqrt{s(W_x(s,v))s\left(W_y(s,v)\right)}}, \tag{10}$$

where R_{xy} shows local correlation parameter which ranges from zero (no coherency) to 1 (strong coherency) in time and frequency space. Besides, S denotes the smoothing

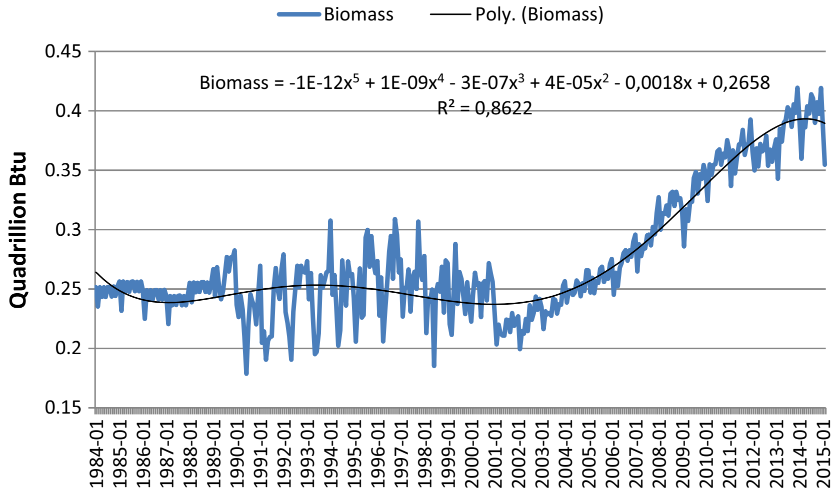

Fig. 8 The US biomass consumption from 1984:1 to 2015:2 in Btu and its polynomial representation (*solid black* line)

parameter, which is necessary; otherwise, coherency would be equal to 1 for all scales and times (Liu 1994).[6]

The phase difference defines phase relationships between two time series for instance lead-lag relation or whether they are negatively or positively correlated. The phase difference $\varphi_{x,y}$ between time series $x(t)$ and $y(t)$ can be written as

$$\varphi_{x,y} = tan^{-1}\left(\frac{\mathfrak{I}\left(W_{xy}(s,v)\right)}{\mathfrak{R}\left(W_{xy}(s,v)\right)}\right), \quad \text{with } \varphi_{x,y}\in[-\pi,\pi]. \qquad (11)$$

For a given a complex wavelet transformation, $\Im\left(W_{xy}\right)$ and $\Re\left(W_{xy}\right)$ denote the imaginary and real part of the wavelet transformation, respectively. A phase difference of zero depicts that the time series move together at an explicit frequency. If $\varphi_{x,y}\in(0,\pi/2)$,then, the series move in phase, where $y(t)$ leads $x(t)$. If $\varphi_{x,y}\in(-\pi/2,0)$, then the series moves again in phase; however, now $x(t)$ leads $y(t)$. A phase difference of π or $-\pi$ implies an antiphase association, namely, a negative correlation. If $\varphi_{x,y}\in(-\pi,-\pi/2)$,then the series moves out of the phase, where $y(t)$ leads and if $\varphi_{x,y}\in(\pi/2,\pi)$, then the series moves again out of the phase where $x(t)$ leads.

Materials

Data covers monthly period of 1984:1–2015:2. The dataset comprises the variables of (i) total energy CO_2 emission (million metric tons of carbon dioxide), (ii) biomass energy consumption (quadrillion Btu), (iii) coal consumption (quadrillion Btu), (iv) petroleum consumption (excluding biofuels; quadrillion Btu), and (v) natural gas consumption (excluding supplemental gaseous fuels; quadrillion Btu). The data source is the US Energy Information Administration, Monthly Energy Review (EIA 2015a).

Figures 8, 9, and 10 yield the movements and trends of the variables. One notices that the trend estimations of the related variables yield satisfactory values for goodness of fit criteria, R^2. It ranges from 0.7968 to 0.8622. Hence, one might comprehend the trends of fluctuations of the variables observing relevant graphs for the period of 1984:1–2015:2.

Figures 8, 9 and 10, hence, provide one with initial inspection about biomass consumption, total energy CO_2 emissions, petroleum consumption, natural gas consumption and coal consumption, respectively, through their polynomial or ARMA representations.

In Fig. 8, the polynomial representation of biomass consumption is [Biomass = $-1\text{E-}12x^5 + 1\text{E-}09x^4 - 3\text{E}{-}07x^3 + 4\text{E}{-}05x^2 - 0.0018\times + 0.2658$] and the ARMA(5.4) representation of total energy CO_2 emissions is [TEnergyCO_2 = 467.246 + 0.648[AR(2)] − 0.299[AR(4)] + 0.609[AR(5)] + 0.983[MA(1)] −0.403[MA(2)] − 0.962[MA(3)] −0.138[MA(4)]].

One may figure out that biomass consumption and CO_2 emission tend to move to opposite directions during the majority of the periods. Biomass consumption declines first till the end of 1987 and later increases until the beginning of 1993. The trend of biomass consumption diminishes first between 1994 and 2003 and later rises after 2003.

Throughout ups and downs, the average slopes of biomass consumption for the period 1984:1–2003:6 and 2003:7–2015:2 are −4.26E−05 and 1.28E−03, respectively, and the related slope estimations are found significant.

Figure 9 indicates that total energy CO_2 emissions, on the other hand, tend to increase first till mid of 2000s and later appears to go down. Throughout its fluctuations, the average slopes of total energy CO_2 emissions for the period 1984:1–2003:6 and 2003:7–2015:2 are 0.499 and −0.487, and the relevant slope estimations are found significant. The overall initial inspection through graphical illustrations and estimated average slopes may indicate that biomass consumption and total energy CO_2 emissions move opposite directions in the USA for the period of 1984:1–2015:2. This result, however,

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[6] Grinsted et al. (2004) provides an example of a derived smoothing parameter of the cross wavelet coherency generated from complex Morlet wavelet transformation.

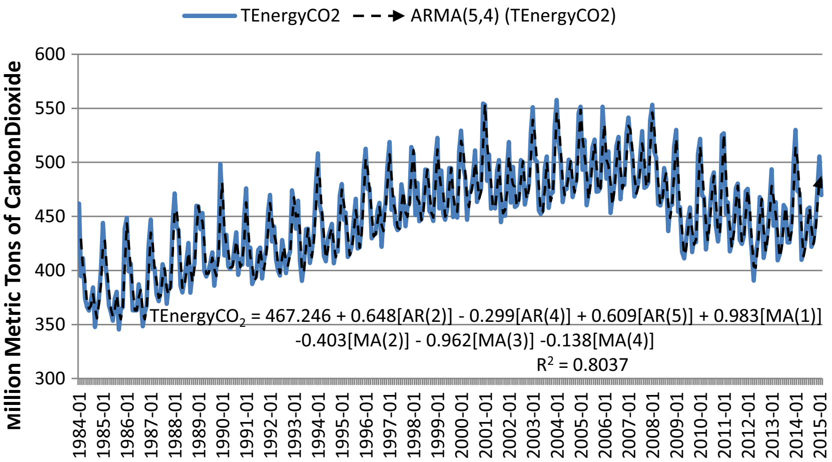

Fig. 9 The US total energy-related CO_2 emissions from 1984:1 to 2015:2 in MMt-CO_2 and its ARMA (5.4) representation (*dashed black arrow*)

does not exhibit an explicit long run causality and/or equilibrium between biomass consumption and CO_2 emissions.

Figure 10 yields the movements of petroleum, natural gas, and coal consumption, respectively. This paper considers these as controlled variables in the model to be estimated. The polynomial representation of petroleum is [Petroleum = 8E−12x^5 − 8E−09x^4 + 2E−06x^3–0.0003x^2 + 0.0175× + 2425]. The MA representations of natural gas and coal are [Ngas = 1.857 + 1.109[AR(1)] − 0.477[AR(2)] + 0.2009[MA(1)] + 0.260[MA(2)]] and [Coal = 1.675 + 1.946[AR(1)] −1.949[AR(2)] +0.947[AR(3)] −1.309[MA(1)] +1.309[MA(2)] −0.321[MA(3)], respectively.

One notices, as well, that there exist severe ups and downs of the related variables. The average slopes of petroleum, natural gas, and coal are 0.00110, 0.00192, and 0.00053, respectively. After 2007, the consumptions of petroleum and coal tend to decline, while the usage of natural gas tends to go up.

Wavelet estimation output

Figure 11a yields wavelet coherency between biomass consumption (Biomass) and carbon dioxide emissions (CO_2). The black contour represents the 5 % significance level based on [ARMA (1, 1)] model. AR (1) and MA (1) indicate the estimations from autoregressive with one lag and moving average with one lag, respectively. The color codes in Fig. 11a ranges from blue to red. The blue color points out weak coherency between biomass and CO_2, while the red color denotes powerful wavelet coherency between the variables. One notices the color bar located on the right-hand side of Fig. 11a, as well, exploring the degree of coherence ranging from low energy of association (e.g., 0.2) to high power of correlation (i.e., 0.9) between the biomass and CO_2.

Eventually, Fig. 11a provides the readers with wavelet coherency estimation results considering (i) all time points of sample period 1984:1–2015:2 and (ii) all relevant frequencies ranging from 1 year (high frequency) to 8 years (low frequency). Figure 11a explores, hence, first, the strong coherencies between biomass and CO_2 at high frequency band (1–1.5 year) during the first and second halves of 1990s, during the end of 2000s, and at the beginning of 2010s. Figure 11a depicts, as well, that biomass and CO_2 move together during mid of 1980s and during the first half of 2000s at high frequency band (1.5–2.5 years). Considering 2.5–5.0-year frequency interval, one may observe that biomass and CO_2 yield slightly

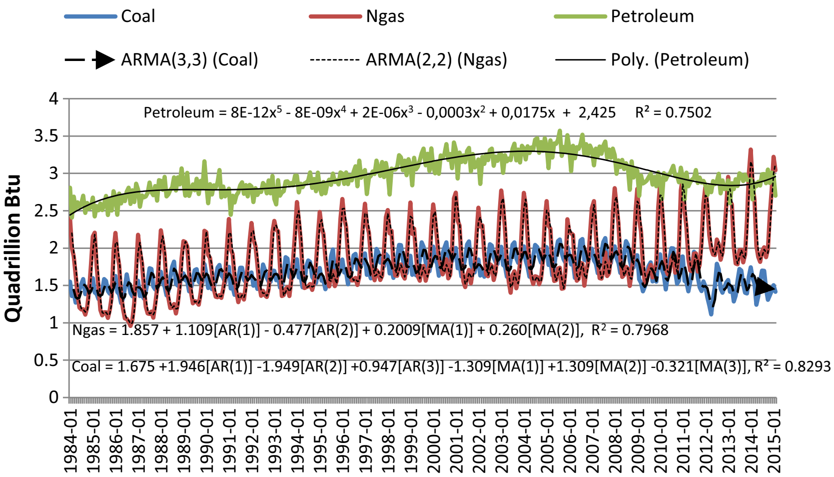

Fig. 10 The US petroleum (*green line*), natural gas (*red line*), and coal (*blue line*) consumption in Btu from 1984:1 to 2015:2 and their polynomials (*solid black line*), ARMA(2.2) (*dashed black line*) and ARMA (3.3) (*dashed black line*) representations, respectively

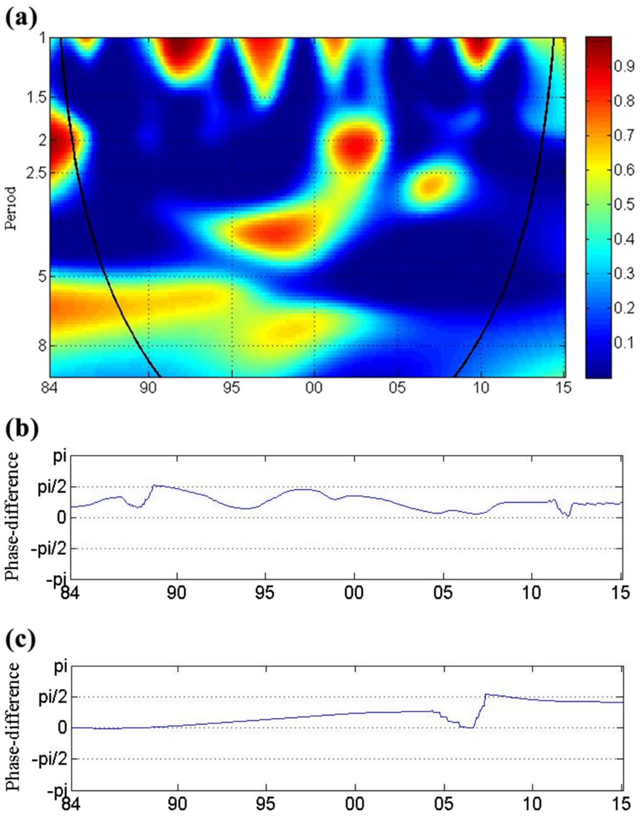

Fig. 11 **a** The wavelet coherency between the US biomass consumptions and total energy-related CO_2 emissions from 1984:1 to 2015:2 and color bar on the right. **b** The phase difference between the US biomass consumption and total energy-related CO_2 emissions at 1~4 year frequency band from 1984:1 to 2015:2. **c** The phase difference between the US biomass consumption and total energy-related CO_2 emissions at 4~8 year frequency band from 1984:1 to 2015:2

strong comovements during the period of 1995–2000 and share weakly correlated 3-year cycle between 2005 and 2010. Figure 11a plots also common but slightly powerful 5–8-year cycles during 1986–2003.

Figure 11b follows phase differences at 1~4-year frequency band. The related outcome explores that (i) the biomass and CO_2 variables are in phase, (ii) there exists positive correlation between variables, and (iii) biomass is leading CO_2 during the whole period at the 1~4-year frequency interval. Figure 11c reveals approximately the same results as Fig. 11b. Figure 11c indicates that, except the years 2007 and 2008, biomass energy consumption and CO_2 emissions from total energy usage follow positive comovements at 4~8-year frequency band, and biomass leads CO_2 emissions for the whole period.

As for the years 2007 and 2008, this time period employs the information that (i) variables are out of phase and follow negative correlation, (ii) CO_2 is leading biomass consumption, and, (iii) since there exists no comovements (see Fig. 11a), the outcome (i) and (ii) are not statistically significant and so the 2007 and 2008 outcome obtained from the phase difference analyses are not valid. Overall, Fig. 11a–c provides the information that (a) biomass consumption might lead CO_2 emissions to increase at some shorter cycles (high frequency) and (b) biomass consumption might slightly cause CO_2 emissions to accumulate at some longer cycles (low frequency).

Figure 12a reexamines the wavelet coherency of biomass consumption and total energy CO_2 emissions by adding some controlled variables into the system. These controlled variables are coal consumption, natural gas consumption, and petroleum consumption, respectively.

Thereby, Fig. 12a is expected to depict more specific wavelet analyses. Then, partial wavelet coherency between biomass and CO_2, with the employment of controlled variables into the system, states that the comovements of biomass and CO_2 follow stronger comovements than the comovements of Fig. 11a. As given in Fig. 11a, the color codes in Fig. 12a spans, as well, from blue to red. The blue color figures out

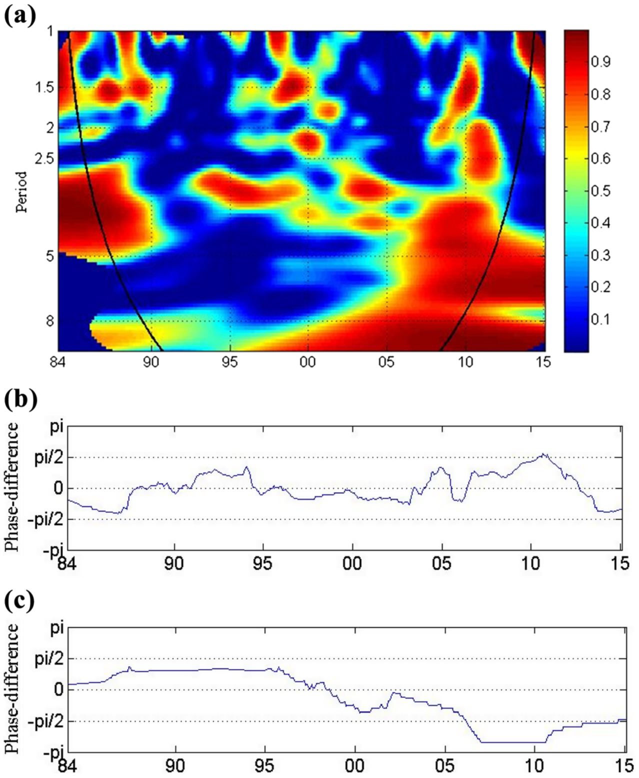

Fig. 12 **a** The partial wavelet coherency between the US biomass consumption and total energy-related CO_2 emissions from 1984:1 to 2015:2 (after adding controlled variables of coal, natural gas, and petroleum consumption into wavelet model). **b** The phase difference between the US biomass consumption and total energy-related CO_2 emissions at 1~4-year frequency band from 1984:1 to 2015:2 (after employing the controlled variables of coal, natural gas, and petroleum consumption into the wavelet model). **c** The phase difference between the US biomass consumption and total energy-related CO_2 emissions at 4~8-year frequency band from 1984:1 to 2015:2 (after considering the controlled variables of coal, natural gas, and petroleum consumption within the wavelet model)

weak (partial) coherency between biomass and CO_2, whereas the red color depicts stronger (partial) wavelet coherency between the variables.

Figure 12b reveals phase differences at 1~4-year frequency band and displays a positive correlation between biomass and CO_2. Throughout the positive correlation path of the variables, one may monitor that (i) CO_2 emissions lead biomass consumption during periods of 1984–1988, 1990, 1994–2004, 2006, and after the period of 2013, (ii) biomass consumption leads CO_2 emissions during periods of 1989, 1991–1993, 2005, and 2007–2012.

Figure 12c exhibits phase differences at the 4~8-year frequency band and reveals a positive correlation between biomass and CO_2 during the period of 1984–2005 and explores a negative correlation between the variables during the period of 2006–2015. These positive correlations between the variables, however, seem to be significant for the period 1997-2005. Throughout the positive correlation relation, the biomass consumption causes CO_2 to increase during the period of 1984–1997, and CO_2 emissions cause biomass consumption to increase during 1998–2005. Within the negative correlation path, on the other hand, one notices that biomass consumption causes CO_2 emissions to diminish during the 2006–2015 period.

Overall, throughout the phase difference analyses depicted by Fig. 12b, c, one may claim that (i) biomass and CO_2 affect each other positively during some time periods at shorter cycles (1~4-year cycles), (ii) biomass and CO_2 continue to affect each other positively during 1984–2005 at longer cycles (4~8-year cycles), and (iii) biomass has a negative impact on CO_2 during 2006–2015 at longer cycles (4~8-year cycles).

Ultimately, considering the statistical significances of coherencies, one may disregard the blue colored areas to make interpretations about comovements of the variables and conclude that biomass consumption has contributed to CO_2 emissions positively at short run cycles during some periods and that biomass, on the other hand, except 1985–1990, has significantly diminished CO_2 emissions in the long run cycles after the year 2005.

Moreover, the most remarkable observations from the partial coherence analyses are that (i) biomass consumption and CO_2 tend to share commonly a long run permanent cycle after 2000, (ii) CO_2 emissions augment the biomass consumption within that cycle for the period of 2000–2005, and (iii) biomass consumption deadens the CO_2 emissions within the same permanent cycle in the USA after 2005.

Researchers may specifically need to inspect that energy policies led to attenuate the CO_2 emissions in the USA for the period of 1984:1–2015:2. Further, particularly the researchers and the US administrator might consider the empirical evidence of this paper exploring that some environmental biomass energy policies implemented in the USA which succeeded to diminish emissions permanently after the year 2005. These policies might be (i) recent technological advances in biomass production/consumption, (ii) incentive policies to induce the efficient usage of biomass, (iii) efficient demand side strategies, and (iv) policies for fair and easy access to the electricity from biomass sources.

CO_2 emissions facts underpinning the wavelet estimation output

Some facts about emissions from fossil fuels and biomass consumption underpin the output of the wavelet coherence analyses of this paper. Figure 13 depicts that the USA experiences a sharp increase in biofuels consumption as she diminishes relatively the consumption of wood and waste energy consumption after 2005. The biofuel consumption boosted from 21.91 trillion Btu (1995:1–2004:12) to 125.20 trillion Btu (2005:1–2015:2).

The common types of biofuels are ethanol, methanol, biodiesel, biofuel gasoline, and vegetable oil, respectively. Figure 14 reveals that there exists relatively a decline in coal and petroleum consumption whereas there appears to be an increase in natural gas consumption for the period of 2005:1–2015:2 in comparison with the period of 1995:1–2004:12 in the USA.

The overall total fossil fuel consumption contracted from 6856.68 trillion Btu (1995:1–2004:12) to 6802.38 trillion Btu (2005:1–2015:2). Although both biomass and fossil fuels can contribute to the greenhouse gases, one may claim that greenhouse gas (GHG) emissions from biomass consumption might be considerably lower than GHG emissions from fossil fuel consumption. EIA (2015b) explores that biofuels (biodiesel, ethanol, methanol) yield, on average, 47.762 kg CO_2 per million BTU as fossil fuels (diesel, gasoline, natural gas) produce, on average, 69.39 kg CO_2 per million BTU in the US transportation sector. EIA (2015b) expresses as well that total CO_2 emissions from fossil fuel (coal, natural gas, petroleum) and total CO_2 emissions from biomass (wood, waste, ethanol, biodiesel) are 155.69 million metric tons and 24.94 million metric tons, respectively, for the period of 2005:1–2015:2. Then, the CO_2 emitted by biomass is one sixth of the CO_2 emitted by fossil fuel energy sources in the US within the same time horizon.

The Biomass Energy Centre (2015) may support, as well, the wavelet estimation output exhibiting that the US administration succeeded in downsizing GHG emissions, specifically after 2005, through expansion of biomass usage and a slight shrinkage of fossil fuel consumption. The Biomass Energy Centre (2015) reveals that life-cycle CO_2 emissions of fossil fuel (hard coal, oil, natural gas) is 88.33 (kg/Gj), whereas life-cycle CO_2 emissions from biomass (wood chips and wood pellets) is 10.83 (kg/Gj) during the first half of the 2000s. It underlines, as well, CO_2 emissions of fuels for transport and yields that the life-cycle CO_2 emissions of fossil fuel (petrol, diesel) and biomass (bioethanol, biodiesel) are 13.0 (kg/gal) and 3.42 (kg/gal), respectively.

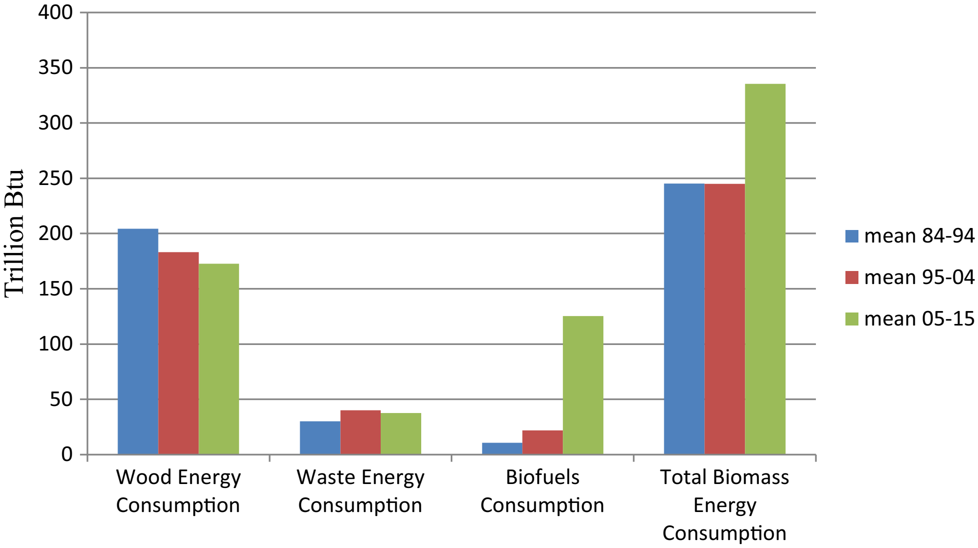

Fig. 13 The mean values of the components of biomass consumed in the USA from 1984:1 to 2015:2 in three subperiods of 1984–1994, 1995–2004, and 2005–2015

Conclusion and policy implications

Environmental pollution and global warming appear to be the most serious concern of the world today and in the future. CO_2 emissions seem to be one of the greatest contributors to global warming and environmental pollution. The fossil fuel usage, on one hand, contributes CO_2 emissions greatly. The world countries have been, however, demanding intensively for fossil fuel energy since it is more available than are other energy sources and, hence, is easy to access. Kaygusuz (2012) reveals that fossil fuel energy sources meet 80 % of the demand for energy in the world in 2008 and that they will be compensating 78 % of the global demand in 2030.

Renewable energy sources, in terms of their positive impacts on climate and environment, have been potential alternatives to fossil fuel energy sources for the last two decades. EREC (2011) announces that renewable energy consumption helped EU to mitigate CO_2 emissions from 1990 to 2009 by 7 %. Diakoulaki et al. (2006) confirm EREC (2011) report by exploring the evidence that the consumption of natural gas and renewables reduced CO_2 emissions in Greece from 1990 to 2002. According to the EU Committee report (2008), EU aims at diminishing CO_2 emissions by 20 % and aspires to reach 20 % usage of energy consumption from renewables by 2020. EREC (2011) states that biomass has the greatest share in total renewable energy sources in EU and foresees that biomass might meet 10 % of the demand for energy in EU by 2020. The available works in the literature observing the impact of biomass on CO_2 emissions are, however, limited. Besides, the majority of these works mainly consider the technological and cost barriers in producing energy from biomass as well as the potential positive role of biomass on environment as in Khanna et al. (2011), Rogers and Brammer (2012), Acaroğlu and Aydoğan (2012), and Berglund and Börjesson (2006).

One may indicate, throughout empirical evidences of available papers that relevant literature might need to launch additional works through statistical/econometrical models to explore the influence of biomass usage on pollution and climate

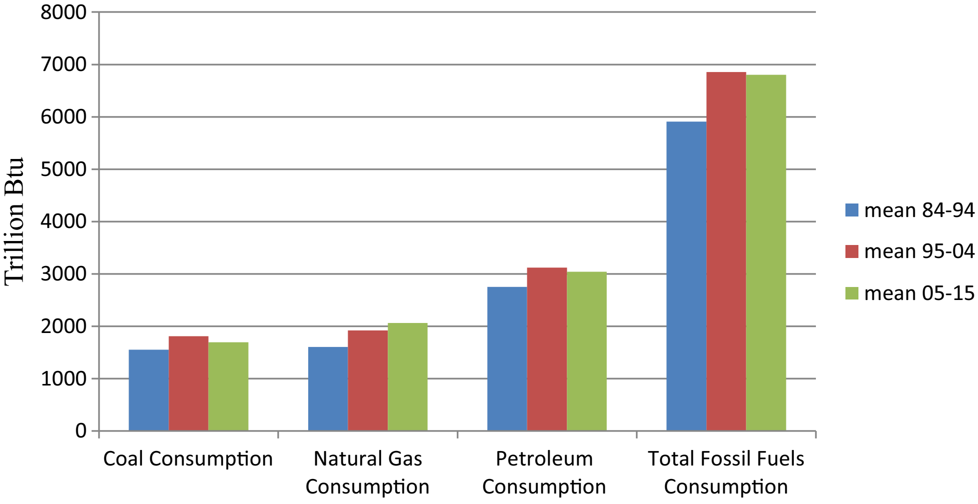

Fig. 14 The mean values of the components of fossil fuels consumed in the USA from 1984:1 to 2015:2 through three subperiods of 1984–1994, 1995–2004, and 2005–2015

change. To the best of our knowledge, Bilgili (2012b) appears to be the sole work following cointegration analyses with structural breaks to exhibit, if it exists, the effects of biomass and fuel oil on CO_2 emissions in the USA. Bilgili (2012b) yields that the fuel oil and biomass effects on CO_2 emissions are positive and negative in the USA, respectively. Bilgili (2012b), however, considers naturally the time dimension in his time series cointegration model following Gregory and Hansen (1996) and Hatemi-J (2008). We, in this work, aim at following both time and frequency dimensions to depict the impact of biomass on CO_2 emissions through a wavelet coherency model. Wavelet coherency models have some superior features in comparison with time series and panel data models. Wavelets can catch comovements of variables in time and frequency domains. Wavelet analyses are, therefore, able to inspect structural breaks of the data within transitory and permanent cycles through time and frequency in estimating the dependency between two variables as depicted in Aguiar-Conraria et al. (2013), Aguiar-Conraria and Soares (2011), and Bilgili (2015).

Employing US monthly data for the period of 1984:1–2015:2 and following partial continuous wavelet coherency and phase differences, we reveal the output stating that (i) biomass consumption increased CO_2 emissions in the USA at short run cycles during some periods, and (ii) biomass, on the other hand, lowered CO_2 emissions in the long run cycles after the year 2005 in the USA.

The policies behind the success of the US administration to diminish CO_2 emissions after 1990 through biomass usage might be explained by the Energy Policy Act (EPACT) incentives of 1992 and 2005 (EPA 2015) and Biomass Research and Development Act of 2000 (BR&D 2015). Gielecki and Poling (2005) underline the significant effect of EPACT tax incentives implemented in the 1990s and the beginning of 2000s to promote energy production from renewables of wind and biomass. Then, the US administration reconsidered the EPACT in 2005. The Biomass Research and Development Act mainly suggest that the US Department of Energy and the US Department of Agriculture coordinate to enhance the energy production from biomass (BR&D 2015; NACDNET 2015). Further, EPACT of 2005 aims at following the policies of (i) federal renewable energy production tax credit, (ii) grants for forest biomass utilization, and (iii) grants for forest biomass utilization research and development (NACDNET 2015; US GPO 2005).

Finally, this paper, upon the results of continuous wavelet coherence analyses, may suggest that policy makers follow specifically long-run incentive policies to boost biomass production in the USA. To this end, policy makers may continue effectively to implement (i) the Energy Policy Act and (ii) the Biomass Research and Development Act. Besides the production of biomass, the US administration may follow (iii) an effective demand side management (DSM) programs to stimulate individuals to consume electricity from biomass through EIA-DSM's planning and monitoring the behavior of electricity consumption in the USA (EIA DSM 2015) and (iv) policies for fair and easy access to the energy from biomass sources.

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