Environmental Science and Pollution Research (2018) 25:6044–6060
https://doi.org/10.1007/s11356-017-0979-x

RESEARCH ARTICLE

Time-varying causality between energy consumption, CO_2 emissions, and economic growth: evidence from US states

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Received: 11 August 2017 / Accepted: 7 December 2017 / Published online: 14 December 2017

Abstract

This study is the first attempt to investigate the relationship between CO_2 emissions, energy consumption, and economic growth at a state level, for the 50 US states, through a time-varying causality approach using annual data over the periods 1960–2010. The time-varying causality test facilitates the better understanding of the causal relationship between the covariates owing to the fact that it might identify causalities when the time-constant hypothesis is rejected. Our findings indicate the existence of a time-varying causality at the state level. Specifically, the results probe eight bidirectional time-varying causalities between energy consumption and CO_2 emission, six cases of two-way time-varying causalities between economic growth and energy consumption, and five bidirectional time-varying causalities between economic growth and CO_2 emission. Moreover, we examine the traditional environmental Kuznets curve hypothesis for the states. Notably, our results do not endorse the validity of the EKC, albeit the majority of states support an inverted N-shaped relationship. Lastly, we can identify multiple policy implications based on the empirical results.

Keywords CO_2 emissions · Economic growth · Energy consumption · Causality · Environmental Kuznets curve · USA

Introduction

Over the past few decades, applied econometric patterns have been the instigator in determining the relationship among CO_2 emission, economic growth, and energy consumption. Accordingly, many authors review and classify the existence literature (e.g., Ozturk 2010; Payne 2010a, b; Smyth and Narayan 2015). Notably, one vital and intriguing perspective puts forward the inherent uncertainty of the process, and that is, authors using the prevalent patterns with the common co-variates, by changing only the estimated time period, have no more potential to contribute to the existing literature (Karanfil 2009). Furthermore, most of the studies across the literature examine the relationship between energy consumption and economic growth (and CO_2 emission) at a national level (Akhmat et al. 2014; Ali et al. 2016; Amri 2017; Attiaoui et al. 2017; Bildirici 2017; Dogan and Turkekul 2016; Dogan and Ozturk 2017; Farhani and Ozturk 2015; Rafindadi et al. 2014; Wolde-Rufael 2012). There is an abundance of empirical papers which examine not only the relationship of causalities for the trivariates, but also they test the validity of the environmental Kuznets curve (EKC) hypothesis (inter alia Ang 2007; Apergis and Payne 2009; Halicioglu 2009; Lean and Smyth 2010; Soytas et al. 2007). However, there are only a few authors who used data at a state level (Apergis et al. 2010; Apergis and Payne 2010; Aslan 2011; Narayan et al. 2010). Subsequent research has hardly filled this void. Hence, this is a gap which this study seeks to address. This study contributes to the relevant literature by offering valuable insights about the interrelation among CO_2 emission, economic growth, and energy consumption in the 50 US states by using the time-varying causality for the first time in the relative literature.

In light of the pre-mentioned research, this study further contributes by examining the existence of a time-varying relationship via the application of a time-varying causality for the case of 50 US states over the periods 1960–2010.[1] Regarding the Granger non-causality test in time varying,

Responsible editor: Philippe Garrigues

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[1] We used this time period due to limitation of data set

we apply the method proposed by Sato et al. (2007) and the extension of time-varying causality proposed by Ajmi et al. (2015), which allow the test to be implemented in a simple framework. We investigate the causality from the perspective of the time-varying trivariate relationship among economic growth, energy consumption growth, and CO_2 emission. This pattern allows the researcher to capture the time-varying relationship and, also to perceive the interrelationship between the covariates during the period, which could not be discerned via a time-constant framework. Additionally, as already stressed above, many studies investigated the validity of the EKC hypothesis without taking into the account the time-varying parameters (such as natural disasters, economic crises, new technologies) between the three variables. As time progresses, all of these conclusions could lead to inefficient environment policy implications. The time-varying approach encompasses all these parameters in order to tackle ex ante uncertainty (Ajmi et al. 2015). We can conclude that compared to the conventional time-constant approach, including its offspring, the time-varying method has a better functionality.

We draw evidence from a comprehensive sample of 50 US states, which reveals pronounced time-varying causalities of the examined relationship. The contribution of this paper is fourfold. To begin with, this is the first time to our knowledge that the causality between CO_2 emission, energy consumption, and economic growth is evaluated at the US state level. Secondly, this paper contributes to the existing thin body of time-varying causality literature. Thirdly, it is the first time that time-varying causality is evaluated at a state level. Fourthly, the validity of the EKC hypothesis is evaluated at the US state level.

The rest of the paper is structured as follows. Section 2 succinctly reviews the related literature. Section 3 introduces our sample and outlines our proposed methodology, which is used in the subsequent analysis. We report our empirical results in Section 4. Finally, Section 5 concludes our work reporting some relevant policy implications.

Literature review

Zhang and Cheng (2009) identify three aspects in the literature which adjudicate the relationship among energy consumption, economic growth, and CO_2 emission. The first aspect is related to CO_2 emission and economic growth nexus. The second aspect focuses on the relationship between economic growth and energy consumption. The third aspect based on the relationship between energy consumption, economic growth, and CO_2 emission. Our study contributes to the third aspect, by investigating the trivariate nexus.

The first aspect is about the CO_2 emission—economic growth nexus. Moreover, the research reflects the de facto validity of the EKC hypothesis between the two variables. The EKC hypothesis presumes that CO_2 emission—economic growth nexus implies an inverter U-curve (videlicet, CO_2 emission will increase up to certain level as economic growth increases, and then declines). Grossman and Krueger (1991) first propounded the EKC hypothesis.[2] A vast body of literature has emerged on the impact of EKC. For instance, implementing Johansen cointegration techniques for a group of 88 countries over the periods 1960–1990, Coondoo and Dinda (2008) pointed out that EKC does not exist. Likewise, Robalino-López et al. (2015) applied a cointegration technique for Venezuela over the periods 1980–2025 and they found no credence to this hypothesis. On the other hand, many studies have identified the existence of EKC. Padilla and Serrano (2006) applied a non-parametric estimation and underlined that EKC exists among a group of countries from 1971 to 1999. Similarly, Narayan and Narayan (2010) confirmed the existence of EKC for 35% of 43 developing countries. Along these lines, Esteve and Tamarit (2012a) employed threshold cointegration and Esteve and Tamarit (2012b) employed EKC analysis for the case of Spain and their results support the EKC. The same result is also confirmed for Spain by Sephton and Mann (2013) who used multivariate adaptive regression splines. Fosten et al. (2012) applied nonlinear threshold cointegration and error correction method at the case of UK over the periods 1830–2003 and confirmed the EKC hypothesis. Lastly, Baek (2015) investigated the EKC for Korea over the periods 1978–2007, by employing bound testing cointegration. His core finding is similar to the aforementioned research.

The second aspect of causal ordering between energy consumption and growth is the plethora of empirical studies. They either focus on country-specific case studies or use multi-country samples. As summarized by Payne (2010a, b) and Ozturk (2010), a number of different hypotheses have been proposed and tested. The reported findings are mixed and significantly vary across countries and studies as pointed out by Payne (2010b). In broad terms, no unequivocal consensus seems to have emerged from the empirical scrutiny of the nexus that governs growth and energy consumption. For instance, Karanfil (2008) note that the nexus between energy consumption and growth could be affected by a number of factors. They encompass climate conditions, income level, development level, the structure of the economy, the concomitant national gross output, and the degree of urbanization that significantly differs especially between developed and developing countries. Regime type, institutional arrangements, and national energy policies may also be contributing factors that explain the absence of any clear consensus in the reported findings for this relationship (Adams et al. 2016). Finally,

[2] For extensive survey see Coondoo and Dinda, 2002; Dinda, 2004; Stern, 2004.

but by no means of lesser importance in explaining the diversity of findings, the variety of alternative econometric methodologies employed in the empirical examination as well as the different time horizons add to the contradicting findings reported (Payne 2010b).

Succinctly, the testable hypotheses that have been proposed are as follows. The *growth* hypothesis postulates that energy consumption spurs economic growth since increasing energy production and consumption positively affects GDP. An implication that stems from this hypothesis is that policies aimed at energy conservation may adversely impact growth. The *conservation* hypothesis points to a reverse causal ordering, i.e., increasing real GDP brings about an increase in the consumption of energy. But it may very well bring about a reduction in energy consumption as the production paradigm shifts towards less energy-intensive sectors and production processes. The absence of any causal ordering is proposed by the *neutrality* hypothesis. Energy consumption accounts for a small share in total GDP; hence, there is no significant and traceable effect from energy consumption to GDP and vice versa. In such case, supported by the absence of a Granger causality finding in empirical studies, energy conservation policies do not adversely affect growth. Finally, the fourth hypothesis that has been proposed is that of a bidirectional nexus between them. The *feedback* hypothesis postulates bidirectional Granger causality, and hence, an increase (decrease) in the one variable will Granger cause a corresponding increase (decrease) in the other.

Since the seminal study of Kraft and Kraft (1978), the majority of the empirical studies apply Granger causality tests (Granger 1969, 1980) in order to examine the causal ordering between the covariates. As already mentioned above and summarized by Ozturk (2010) and Payne (2010a, b), even though the general perception is that the two variables in question are causally linked, no strong and unequivocal empirical consensus emerges from the reported empirical findings. For instance, evidence of unidirectional causality from economic growth to energy consumption has been reported by several studies using different methodological approaches (inter alia: Stern 1993, 2000; Soytas et al. 2001; Bowden and Payne 2009; Hossain 2011). On the other hand, a large number of studies have reported findings in favor of a reverse causal ordering from energy consumption to economic growth that renders substantial support the growth hypothesis (inter alia: Kraft and Kraft 1978; Aqeel and Butt 2001; Al-Iriani 2006; Zhang and Cheng 2009; Alkhathlan and Javid 2013). Bidirectional causality and the absence of any nexus have also been found by other studies (inter alia Ghali and El-Sakka 2004; Zhang and Xu 2012; Shahiduzzaman and Alam 2012; Yu and Jin 1992). The important policy implication associated with the empirical investigation of this nexus is the driving motive for such studies that probes into this issue.

The third aspect of causal ordering between energy consumption, economic growth, and CO_2 emission is the voluminous of the empirical investigations. They either cynosure on the causality case studies and/or examine the validity of the EKC hypothesis. Indisputably, sharp information of causalities exists among covariate nexus. Acaravci and Ozturk (2010), using ARDL bounds and VECM framework for 19 European countries for the periods 1960 to 2005 found two-way causality between income, income square, and energy use solely for Switzerland. More crucial is the fact that disclosed the validity of EKC hypothesis only for Denmark and Italy. Ajmi et al. (2015) employed time-varying causality in order to determine the causality between the G7 countries. Their core finding depicts bidirectional causality for income and energy (Japan) and for energy and CO_2 emissions (USA). Moreover, he argued that U-shaped does not exist. Employing the same pattern as Ajmi et al. (2015), Shahbaz et al. (2016) investigated the relationship between 11 countries from 1972 to 2013. The results show two-way causality between income, income square, and energy use only for South Korea. Furthermore, EKC is verified for Pakistan and Turkey. According to Ozturk and Acaravci (2010), EKC hypothesis does not attest for Turkey. Moreover, the authors reveal miscellaneous causality between the variables, employing ARDL bounds and VECM from 1968 to 2005. Ozturk and Acaravci (2013) applied the same framework for the time periods 1960–2007 and their results indicate long-run unidirectional causality running from income, income square, and energy use to CO_2 emission. In an interesting view, Ozcan (2013) provides evidence of 12 Middle East countries, by evaluating panel cointegration over the periods 1990–2008. The findings probe that long-run energy and income causes CO_2 emission but short-run only income causes energy. Notably, the evidence from EKC bears out U-shaped for five counties (Bahrain, Syria, Turkey, Oman, and Yemen) and inverted U-shaped for three countries (UAE, Egypt, and Lebanon). Intriguingly, studies from Pao and Tsai (2011a, b) substantiate the underlying EKC hypothesis for Brazil and BRIC countries, respectively. In addition, evaluating gray prediction model (Brazil) and panel cointegration (BRIC) finds bidirectional causality between energy and income, and income and CO_2 emission, respectively. Another substantial research from Soytas et al. (2007) uses Toda–Yamamoto procedure to analyze the relationship for USA over the periods 1960–2004. The results probe one-way causality running from energy to CO_2 emission and unexpected results for EKC validity, which does not exist. In a much similar vein, Dogan and Turkekul (2016) do not endorse the validity of EKC regarding the case of USA. The authors assessed ARDL bounds and VECM methodology over the periods 1960–2010 and the results revealed bidirectional causalities for the pairs CO_2 emission, income and CO_2 emission, energy consumption. Although, they used the same patterns with Dogan and Turkekul (2016), Farhani and Ozturk

(2015) found identical outcomes regarding the EKC hypothesis but different causality results for the case of Tunisia. In a different vein, Jayanthakumaran et al. (2012), Tang and Tan (2015), and Wang et al. (2011) confirm the EKC hypothesis. As we stressed out above, there are authors who investigate only the relationship between the tri-dimension nexus. Not surprisingly, the majority of the empirical studies employ Granger causality tests. For instance, Chang (2010) examines the case of China and finds miscellaneous causalities among the covariates using Johansen cointegration VECM. In a similar research area but with different results and pattern, Zhang and Cheng (2009) evaluated Toda–Yamamoto procedure and found (i) one-way causality from income to energy and (ii) that energy causes CO_2 emissions. In a similar framework, Soytas and Sari (2009) found a unidirectional causality running from energy to CO_2 emission. Halicioglu (2009) signified four pairs of two-way causalities, energy—CO_2 emission, CO_2 emission—income, CO_2 emission—square of income, and income—square of income for the case of Turkey. Omri (2013), using simultaneous equation models for 14 MENA countries, found a bidirectional causality for energy and CO_2 emission from 1990 to 2011. No trace of two-way causality from Ang (2007) and Menyah and Wolde-Rufael (2010) for France and South Africa, respectively. Ang (2008) supported the bidirectional interrelationship for income and energy for Malaysia over the periods 1971–1999. Lastly, Alam et al. (2012), employed ARDL bounds and dynamic causality for the case of Bangladesh. He endorsed long-run bidirectional relationship for energy and CO_2 emission, and dynamic two-way causality for energy consumption and income. Table 1 summarizes existing studies between energy consumption, economic growth, and CO_2 nexus.

Data and methodology

Data and pretests

For the purpose of our analysis, we use yearly data for the 50 US states,[3] over the periods 1960–2010 (50 observations). The data regarding the energy consumption has been extracted from Energy Information Agency (EIA),[4] whereas, the data for the CO_2 emissions comes from Carbon Dioxide Information Analysis Center (CDIAC).[5] Finally, the data for GDP have been extracted from the Bureau of Economic Analysis.[6] All the variables have been logged as has been suggested from the relevant literature.[7]

Initially, we investigate the level of the integration among our variables by applying several unit root tests (i.e., Elliott et al.— Dickey–Fuller generalized least squares (DF-GLS) 1996; Phillips and Perron—PP 1988; Kwiatkowski et al.—KPSS, 1992). The AIC statistic has been applied to indicate the proper time length, whereas the tests have been applied both on the trend and the drift of the data (Table 2). Accordingly, as a robustness check, we implement the Zivot and Andrews (1992) test (ZA) for possible structural breaks (Table 3). As a result, the tests endorsed that the covariates are integrated of order one I(1).

Time-varying vector autoregressive model

The principal concept of Granger (1969) has an unprecedented impact on the research field. Given a bivariate (x, y) vector autoregressive (VAR) model, Granger (1969) defined the following specification:

$$Y_t = e_0 + \sum_{i=1}^{n} e_i Y_{t-i} + \sum_{i=1}^{n} f_i X_{t-i} + w_i, \tag{3.1}$$

and

$$X_t = g_0 + \sum_{i=1}^{n} g_i X_{t-i} + \sum_{i=1}^{n} h_i Y_{t-i} + z_i, \tag{3.2}$$

in the equations (3.1) and (3.2), X_t and Y_t denote stationary time series and w_i, z_i are assumed to be white-noise errors.

By focusing on the different VAR patterns, Sato et al. (2007) extended the Granger causality test based on the theoretical framework of locally stationary processes (Dahlhaus et al. 1999). Introducing a time-smooth variation in the framework, Sato et al. (2007) constructed a time-varying vector autoregressive model. This dynamic VAR (as called) approach includes a multivariate time series $(x_{t,\ T})$ with dimension (s) and a number of observations(T), $x_{t,\ T} = (x_{1t,\ T}, x_{2t,\ T}, x_{3t,\ T}, \ldots, x_{st,\ T})'$. The computational representation of the function is as follows:

$$x_{t,T} = u\left({}^{t}/_{T}\right) + \sum_{l=1}^{p} A_l\left({}^{t}/_{T}\right) x_{t-l,T} + \varepsilon_{t,T}, \tag{3.3}$$

[3] Alaska (AK), Alabama (AL), Arkansas (AR), Arizona (AZ), California (CA), Colorado (CO), Connecticut (CT), Delaware (DE), Florida (FL), Georgia (GA), Hawaii (HI), Iowa (IA), Idaho (ID), Illinois (IL), Indiana (IN), Kansas (KS), Kentucky (KY), Louisiana (LA), Massachusetts (MA), Maryland (MD), Maine (ME), Michigan (MI), Minnesota (MS), Missouri (MO), Mississippi (MS), Montana (MT), North Carolina (NC), North Dakota (ND), Nebraska (NE), New Hampshire (NH), New Jersey (NJ), New Mexico (NM), Nevada (NV), New York (NY), Ohio (OH), Oklahoma (OK), Oregon (OR), Pennsylvania (PA), Rhode Island (RI), South Carolina (SC), South Dakota (SD), Tennessee (TN), Texas (TX), Utah (UT), Virginia (VA), Vermont (VT), Washington (WA), Wisconsin (WI), West Virginia (WV), Wyoming (WY)

[4] http://www.eia.gov/

[5] http://cdiac.ornl.gov/CO2_Emission/

[6] https://www.bea.gov/index.htm

[7] The software R (https://www.r-project.org/) is used to conduct all statistical analyses.

Table 1 Summary of the existing studies between energy consumption, economic growth, and CO_2 nexus

Study	Region	Period	Methodological framework	Causality	Environmental Kuznets curve
Acaravci and Ozturk (2010)	19 European countries	1960–2005	ARDL bounds, VECM	Long-run: E, Y, $Y^2 \rightarrow$ C: Denmark, Germany, Greece, Iceland, Italy, Portugal, and Switzerland. Short run: Y, $Y^2 \rightarrow$ C: Denmark and Italy. Y, $Y^2 \rightarrow$ E: Greece and Italy. Y, $Y^2 \leftrightarrow$ E: Switzerland	EKC exists for Denmark and Italy
Ajmi et al. (2015)	G7	1960–2010	time-varying Granger causalities	Y → C: Italy and Japan; Y↔E: Japan; Y → E: Italy.E → Y Canada; E↔C: USA; E → C: France	EKC does not exist.
Alam et al. (2012)	Bangladesh	1972–2006	ARDL bounds, dynamic causality	Long run: E → Y; E↔C; C → Y. Short run: E → Y; E → C, Dynamic causality: E↔Y	
Ang (2007)	France	1960–2000	ARDL bounds, VECM	Long-run: Y,$Y^2 \rightarrow$ C; Y,$Y^2 \rightarrow$ EShort run: E → Y,Y^2	
Ang (2008)	Malaysia	1971–1999	VECM	Long-run: C → Y; Y↔EShort run: Y → E	
Chang (2010)	China	1981–2006	Johansen cointegration VECM	Miscellaneous	
Dogan and Turkekul (2016)	USA	1960–2010	ARDL bounds, VECM	C↔Y; C↔E; Y → E	EKC does not exist.
Farhani and Ozturk (2015)	Tunisia	1971–2012	ARDL bounds, VECM	Y, Y^2, E → C	EKC does not exist.
Halicioglu (2009)	Turkey	1960–2005	ARDL bounds, VECM	C↔E; C↔Y; C↔Y^2; Y↔Y^2	
Jayanthakumaran et al. (2012)	China and India	1971–2007	ARDL bounds, VECM	China = long run: Y, $Y^2 \rightarrow$ C; E → CShort run: E → CIndia = long run: Y, $Y^2 \rightarrow$ C; E → C	EKC exists.
Menyah and Wolde-Rufael (2010)	South Africa	1965–2006	ARDL bounds, modified Wald test	C → Y; E → C, Y	
Omri (2013)	14 MENA countries	1990–2011	simultaneous-equations models	E, Y → C; E↔C	
Ozcan (2013)	12 Middle East countries	1990–2008	Panel cointegration	Long run: E, Y → C Short run: Y → E	U-shaped for 5 (Bahrain, Syria, Turkey, Oman, and Yemen) and inverted U-shaped for 3 (UAE, Egypt, and Lebanon)
Ozturk and Acaravci (2010)	Turkey	1968–2005	ARDL bounds, VECM	Miscellaneous	EKC does not exist.
Ozturk and Acaravci (2013)	Turkey	1960–2007	ARDL bounds, VECM	Long run: E, Y, $Y^2 \rightarrow$ C	EKC exists.
Pao and Tsai (2011a)	Brazil	1980–2007	Gray prediction model (GM)	Long run: E↔Y; E↔C; Y↔CShort run: E → Y; E↔C; Y↔C	EKC exists.
Pao and Tsai (2011b)	BRIC	1980–2007	Panel cointegration	Long run: Y → C; E → CShort run: Y↔C; E → CStrong:	EKC exists.

Table 1 (continued)

Study	Region	Period	Methodological framework	Causality	Environmental Kuznets curve
Shahbaz et al. (2016)	11 countries	1972–2013	Time-varying Granger causalities	Y↔C; E↔Y; E → C E → Y, Y^2 (Bangladesh); Y, Y^2 → E (Philippines, Turkey and Vietnam); E↔Y↔ Y^2 (South Korea); Y, Y^2 → C (Indonesia, Turkey) the opposite for (Bangladesh, Egypt, Pakistan)	EKC exists for Pakistan and Turkey.
Soytas and Sari (2009)	Turkey	1960–2000	Toda–Yamamoto procedure	E → C	
Soytas et al. (2007)	USA	1960–2004	Toda–Yamamoto procedure	E → C	EKC does not exist.
Tang and Tan (2015)	Vietnam	1976–2009	Cointegration and VECM	Long run: E → CShort run: E → CGranger: Y↔C	EKC exists.
Wang et al. (2011)	China	1995–2007	Panel cointegration and panel VECM	E↔C; E↔Y; Long run: E, Y → C; C, Y → E	EKC exists.
Zhang and Cheng (2009)	China	1960–2007	Toda–Yamamoto procedure	Y → E; E → C	

Y, Y^2 , E, and C indicate GDP, square of GPD, energy consumption, and CO_2 emissions, respectively. VECM refers to the vector error correct model, ARDL denotes the auto regressive distributed lag procedure, and EKC refers to the environmental Kuznets curve. → and ↔ denote unidirectional causality and feedback hypothesis, respectively

in the expression (3.3), $u(t/T)$ denotes the vector of intercepts, $A_l(t/T)$ represents the autoregressive coefficients, and $\varepsilon_{t,\ T}$ denotes the error vector. Moreover, Ajmi et al. (2015), reconstructed Eq. (3.3) by using the M- and B-spline functions (Eilers and Marx 1996). These M- and B-spline functions are applied in order to estimate the dynamic VAR using a multiple linear regression model. The time-varying vector autoregressive equation obtains the following form:

$$x_t = \sum_{n=0}^{M} u_n y_n(t) + \sum_{l=1}^{p} A_n^l y_n(t) x_{t-l} + \varepsilon_t \qquad (3.4)$$

in the expression (3.4), u_n denotes the vectors and A_n^l represents the B-spline coefficients. Notably, we can test the time-varying Granger causality by employing the Wald tests on the coefficients. To elaborate, by testing if the coefficients are tantamount to zero or not, we test for time-varying Granger causality between two variables. Additionally, by testing the significance of coefficients for every B-spline, we are able to check whether the Granger causality is constant or time-varying. By employing a pairwise pattern, we follow Ajmi et al. (2015) and set a dynamic VAR of order $l = 1$, $M = 3$, and $lag = 1$ for a bivariate VAR model (for more details see Ajmi et al. 2015; Sato et al. 2007).

Empirical study

Table 4 delineates the results of classical (conventional) causality test (Eq. 3.1 and 3.2). The results probe two bidirectional causalities between energy consumption and CO_2 emissions in the case of IL and TX, nine (AR, MI, MS, MT, ND, NH, PA, UT, and WY) unidirectional causality running from energy consumption to CO_2 emissions, and seven (CA, CT, GA, MO, NC, RI, and WA) unidirectional causality for the opposite side. Furthermore, our empirical results also disclose 32 neutrality hypotheses for the rest of the states. Regarding the relationship between economic growth and energy consumption, the results reveal seven (AK, DE, HI, IL, MA, MS, and OH) unidirectional causalities running from economic growth to energy consumption, six (CT, MN, MO, OK, PA, and TX) unidirectional causalities running from energy consumption to economic growth, and the rest support the neutrality hypothesis. Moreover, there is no bidirectional causality for these pair of variables. Lastly, the results probe one (WI) bidirectional causalities between economic growth and CO_2 emissions, eight (AK, AZ, HI, IL, ME, OH, RI, and WV) unidirectional causalities running from economic growth to CO_2 emissions, and five (AR, MO, MS, PA, and TX) for the opposite side.

Table 5 depicts the results for the dynamic Granger causality test (Eq. 3.3). The results probe six (AR, CO, GA, LA, MN, and PA) bidirectional causalities between energy consumption and CO_2 emissions, five (ME, NY, OK, PA, and

Table 2 Unit root test results

	DF-GLS test						Pperron test			
State	Level CO_2	EC	GDP	1st diff. CO_2	EC	GDP	Level CO_2	EC	GDP	1st diff. CO_2
AK	− 0.99[2]	− 1.11[4]	− 1.38[4]	− 5.49***[3]	− 5.98***[3]	− 5.98***[3]	− 0.96[3]	− 0.39[3]	− 0.39[3]	− 43.19***[3]
AL	− 1.85[4]	− 1.63[2]	− 1.63[2]	− 4.45***[3]	− 4.52***[4]	− 4.97***[4]	− 7.05[3]	− 4.13[3]	− 0.62[3]	− 51.20***[3]
AR	− 0.80[4]	− 1.20[4]	− 1.38[1]	− 3.75***[3]	− 4.63***[3]	− 3.85***[3]	− 6.26[3]	− 21.29**[3]	0.22[3]	− 48.80***[3]
AZ	− 0.84[4]	− 1.64[2]	− 1.37[1]	− 3.63***[2]	− 3.77***[3]	− 3.72***[3]	− 2.56[3]	− 13.48[3]	2.32[3]	− 53.65***[3]
CA	− 0.96[2]	− 0.86[3]	− 1.39[3]	− 3.20**[3]	− 4.16***[3]	− 3.68***[2]	− 7.20[3]	− 11.30[3]	1.08[3]	− 50.99***[3]
CO	− 0.72[1]	− 1.67[2]	− 0.94[2]	− 3.92***[2]	− 3.61***[2]	− 3.90***[1]	− 4.90[3]	− 13.35[3]	0.91[3]	− 49.27***[3]
CT	− 2.12[1]	− 0.94[1]	− 1.06[2]	− 3.83***[2]	− 3.56***[2]	− 3.72***[3]	− 11.64[3]	− 5.85[3]	0.73[3]	− 41.61***[3]
DE	− 0.55[2]	− 2.08[2]	− 1.62[1]	− 3.33**[2]	− 3.39**[2]	− 3.66***[2]	− 1.58[3]	− 8.07[3]	2.84[3]	− 51.06***[3]
FL	− 1.23[4]	− 1.90[3]	− 1.43[3]	− 4.29***[3]	− 3.92***[2]	− 3.33**[3]	− 4.23[3]	− 17.13*[3]	1.75[3]	− 44.85***[3]
GA	− 1.17[2]	− 2.91*[1]	− 1.52[2]	− 4.38***[3]	− 3.39***[2]	− 3.75***[2]	− 2.22[3]	− 13.67[3]	2.39[3]	− 41.77***[3]
HI	− 1.02[3]	− 0.99[3]	− 1.39[1]	− 3.37***[2]	− 3.39***[2]	− 3.83***[2]	− 6.84[3]	− 6.05[3]	− 0.90[3]	− 45.81***[3]
IA	− 2.20[1]	− 1.87[1]	− 0.87[3]	− 3.83***[3]	− 3.77***[1]	− 3.62***[2]	− 9.64[3]	− 28.61***[3]	− 2.87[3]	− 58.94***[3]
ID	− 1.63[1]	− 1.45[1]	− 0.83[1]	− 3.66***[2]	− 3.75***[2]	− 3.73***[3]	− 7.81[3]	− 6.60[3]	− 0.64[3]	− 41.00***[3]
IL	− 2.64[3]	− 1.58[2]	− 1.31[1]	− 3.42***[2]	− 3.87***[3]	− 3.17**[2]	− 5.97[3]	− 9.45[3]	0.79[3]	− 43.11***[3]
IN	− 1.32[2]	− 1.29[3]	− 1.19[2]	− 3.49***[2]	− 3.66***[3]	− 3.90***[2]	− 7.62[3]	− 11.77[3]	− 0.92[3]	− 45.02***[3]
KS	− 1.54[2]	− 1.58[2]	− 1.56[1]	− 5.40***[2]	− 4.43***[1]	− 4.54***[2]	− 2.94[3]	− 47.96***[3]	0.12[3]	− 45.83***[3]
KY	− 1.45[2]	− 2.03[1]	− 1.62[2]	− 3.56***[2]	− 3.47***[1]	− 3.23**[2]	− 4.51[3]	− 13.61[3]	0.30[3]	− 52.97***[3]
LA	− 1.68[1]	− 1.05[1]	− 1.36[2]	− 3.87***[3]	− 3.85***[2]	− 3.80***[2]	− 3.42[3]	− 11.07[3]	− 3.15[3]	− 51.05***[3]
MA	− 1.34[2]	− 1.45[2]	− 1.24[1]	− 4.09***[2]	− 4.72***[3]	− 4.85***[3]	− 9.59[3]	− 10.88[3]	0.55[3]	− 55.60***[3]
MD	− 1.84[1]	− 1.47[1]	− 1.20[2]	− 3.61***[3]	− 3.93***[2]	− 3.72***[2]	− 9.66[3]	− 15.66[3]	− 0.74[3]	− 50.61***[3]
ME	− 2.02[3]	− 0.68[2]	− 1.31[1]	− 4.46***[2]	− 3.90***[2]	− 4.91***[3]	− 13.40[3]	− 1.84[3]	1.47[3]	− 59.26***[3]
MI	− 1.82[2]	− 1.52[3]	− 1.45[2]	− 4.36***[3]	− 4.66***[4]	− 4.52***[3]	− 7.25[3]	− 8.81[3]	1.63[3]	− 40.02***[3]
MN	− 1.88[3]	− 0.71[2]	− 1.02[2]	− 4.47***[4]	− 3.69***[4]	− 4.00***[3]	− 7.18[3]	− 14.16[3]	1.04[3]	− 39.32***[3]
MO	− 1.77[3]	− 1.80[3]	− 1.68[2]	− 3.97***[2]	− 9.07***[4]	− 3.49***[4]	− 4.95[3]	− 16.41[3]	1.73[3]	− 35.88***[3]
MS	− 1.80[3]	− 1.57[3]	− 1.22[2]	− 2.93**[3]	− 3.19**[2]	− 3.65***[3]	− 5.42[3]	− 16.76[3]	0.49[3]	− 53.97***[3]
MT	− 1.42[3]	− 1.91[2]	− 1.29[2]	− 3.55***[3]	− 4.06***[3]	− 4.15***[3]	− 12.65[3]	− 10.98[3]	− 2.86[3]	− 43.44***[3]
NC	− 1.59[3]	− 3.23**[3]	− 1.46[2]	− 3.39**[3]	− 14.76***[4]	− 3.47**[2]	− 6.48[3]	− 15.98[3]	2.58[3]	− 51.23***[3]
ND	− 1.76[2]	− 1.99[3]	− 1.89[3]	− 4.37***[3]	− 4.03***[3]	− 4.16***[3]	0.20[3]	− 18.84*[3]	− 4.43[3]	− 53.04***[3]
NE	− 2.21[2]	− 2.38[3]	− 1.18[3]	− 4.21***[3]	− 4.40***[4]	− 4.43***[3]	− 9.16[3]	− 6.53[3]	− 0.68[3]	− 53.03***[3]
NH	− 1.62[3]	− 1.03[2]	− 1.51[3]	− 4.33***[3]	− 4.36***[3]	− 3.89***[3]	− 11.20[3]	− 6.77[3]	1.28[3]	− 30.52***[3]
NJ	− 2.11[3]	− 1.08[2]	− 1.20[2]	− 4.06***[3]	− 4.07***[3]	− 3.84***[3]	− 13.29[3]	− 12.36[3]	2.52[3]	− 57.08***[3]
NM	− 1.32[2]	− 2.48[3]	− 1.49[2]	− 4.57***[3]	− 3.97***[3]	− 3.39**[3]	− 3.50[3]	− 12.04[3]	− 2.08[3]	− 54.22***[3]
NV	− 1.13[2]	− 1.54[2]	− 1.85[3]	− 4.06***[3]	− 3.74***[3]	− 3.65***[3]	− 1.95[3]	− 5.55[3]	1.16[3]	− 46.70***[3]
NY	− 2.44[2]	− 2.10[2]	− 1.19[2]	− 3.38**[3]	− 4.11***[3]	− 3.59***[3]	− 8.38[3]	− 9.51[3]	− 0.07[3]	− 33.07***[3]
OH	− 2.10[2]	− 2.13[2]	− 1.35[2]	− 3.48**[3]	− 3.97***[3]	− 4.58***[3]	− 6.14[3]	− 7.10[3]	0.49[3]	− 54.33***[3]
OK	− 1.21[2]	− 1.50[2]	− 1.29[2]	− 6.09***[4]	− 3.61***[3]	− 3.42**[3]	− 3.66[3]	− 12.56[3]	− 1.92[3]	− 44.06***[3]
OR	− 2.47[2]	− 0.86[1]	− 1.38[2]	− 3.11**[3]	− 4.71***[3]	− 3.86***[3]	− 10.32[3]	− 18.13*[3]	− 1.29[3]	− 48.77***[3]
PA	− 2.23[2]	− 2.29[2]	− 1.57[2]	− 3.48***[3]	− 3.38**[3]	− 3.33**[3]	− 9.23[3]	− 9.25[3]	0.01[3]	− 42.66***[3]
RI	− 2.02[2]	− 2.34[2]	− 0.83[1]	− 4.01***[3]	− 3.39**[3]	− 3.46**[3]	− 7.79[3]	− 10.99[3]	− 0.52[3]	− 54.22***[3]
SC	− 1.50[2]	− 1.89[2]	− 1.98[2]	− 3.92***[3]	− 4.03***[3]	− 3.54**[3]	− 9.06[3]	− 44.83***[3]	− 0.15[3]	− 39.95***[3]
SD	− 1.94[2]	− 1.49[2]	− 1.07[2]	− 3.95***[3]	− 3.58***[3]	− 3.27**[3]	− 14.33[3]	− 5.38[3]	− 1.37[3]	− 49.65***[3]
TN	− 1.34[2]	− 2.26[2]	− 2.09[2]	− 4.11***[3]	− 3.30**[3]	− 3.64***[3]	− 4.37[3]	− 29.86***[3]	0.94[3]	− 48.34***[3]
TX	− 1.34[2]	− 1.98[2]	− 1.22[2]	− 3.25**[3]	− 3.29**[3]	− 3.51**[3]	− 0.60[3]	− 15.16[3]	− 1.22[3]	− 36.35***[3]

Table 2 (continued)

	DF-GLS test						Pperron test			
UT	− 1.96[2]	− 2.44[2]	− 1.74[2]	− 3.20**[3]	− 3.57***[3]	− 3.64***[3]	− 6.90[3]	− 7.98[3]	− 2.70[3]	− 34.44***[3]
VA	− 2.37[2]	− 3.27**[3]	− 1.49[2]	− 3.01**[3]	− 15.39***[4]	− 3.43**[3]	− 9.36[3]	− 15.92[3]	1.55[3]	− 45.16***[3]
VT	− 1.94[2]	− 1.15[2]	− 0.84[1]	− 3.22**[3]	− 3.61***[3]	− 3.14**[3]	− 10.59[3]	− 6.12[3]	− 3.62[3]	− 41.32***[3]
WA	− 1.11[2]	− 2.84*[2]	− 1.11[2]	− 3.50**[3]	− 3.73***[3]	− 4.09***[3]	− 3.53[3]	− 14.39[3]	− 1.51[3]	− 50.18***[3]
WI	− 2.84*[2]	− 2.40[2]	− 1.36[2]	− 3.49**[3]	− 10.43***[4]	− 3.39**[3]	− 8.45[3]	− 16.60[3]	1.21[3]	− 44.52***[3]
WV	− 1.11[2]	− 2.02[2]	− 1.25[2]	− 3.74***[3]	− 3.59***[3]	− 3.94***[3]	− 4.51[3]	− 10.81[3]	− 1.90[3]	− 51.77***[3]
WY	− 1.75[2]	− 1.71[2]	− 1.80[2]	− 3.37**[3]	− 4.49***[3]	− 3.38**[3]	− 0.99[3]	− 6.60[3]	− 4.20[3]	− 61.36***[3]

	Pperron test		KPSS test					
	1st diff.		Level			1st diff.		
State	EC	GDP	CO_2	EC	GDP	CO_2	EC	GDP
AK	− 42.72***[3]	− 42.72***[3]	2.40***[1]	2.40***[1]	2.40***[1]	0.85***[1]	0.90***[1]	0.90***[1]
AL	− 47.24***[3]	− 36.5***[3]	2.06***[1]	2.15***[1]	2.58***[1]	0.30*[1]	0.48**[1]	1.59***[1]
AR	− 58.37***[3]	− 47.16***[3]	2.43***[1]	0.98***[1]	2.57***[1]	0.34*[1]	0.04*[1]	1.58***[1]
AZ	− 51.87***[3]	− 22.52**[3]	2.43***[1]	0.80***[1]	2.60***[1]	0.55**[1]	0.55*[1]	0.81*[1]
CA	− 30.21***[3]	− 23.77**[3]	1.98**[1]	2.17***[1]	2.60***[1]	0.49**[1]	0.94***[1]	0.99***[1]
CO	− 51.62***[3]	− 20.04**[3]	2.47***[1]	0.84***[1]	2.59***[1]	0.60**[1]	0.05*[1]	0.99***[1]
CT	− 45.33***[3]	− 27.45***[3]	0.53**[1]	1.99***[1]	2.60***[1]	0.14*[1]	0.42*[1]	1.18***[1]
DE	− 41.61***[3]	− 41.97***[3]	1.04***[1]	2.04***[1]	2.62***[1]	0.51**[1]	0.21*[1]	1.07***[1]
FL	− 51.97***[3]	− 20.68**[3]	2.40***[1]	1.31***[1]	2.59***[1]	0.79***[1]	0.10*[1]	1.52***[1]
GA	− 51.41***[3]	− 27.80***[3]	2.33***[1]	0.81***[1]	2.60***[1]	0.86***[1]	0.09*[1]	1.52***[1]
HI	− 46.94***[3]	− 22.86**[3]	1.99***[1]	2.00***[1]	2.55***[1]	0.56**[1]	0.63**[1]	1.49***[1]
IA	− 58.52***[3]	− 49.78***[3]	2.43***[1]	0.78***[1]	2.57***[1]	0.09*[1]	0.03*[1]	0.98***[1]
ID	− 51.67***[3]	− 29.57***[3]	1.81***[1]	2.35***[1]	2.59***[1]	0.11*[1]	0.45*[1]	0.70**[1]
IL	− 36.38***[3]	− 42.31***[3]	0.25*[1]	1.16***[1]	2.60***[1]	0.23*[1]	0.42*[1]	1.44***[1]
IN	− 33.52***[3]	− 46.67***[3]	2.24***[1]	1.92***[1]	2.60***[1]	0.26*[1]	0.54**[1]	1.05***[1]
KS	− 67.58***[3]	− 40.12***[3]	2.13***[1]	0.71**[1]	2.58***[1]	0.37*[1]	0.03*[1]	1.18***[1]
KY	− 50.65***[3]	− 50.57***[3]	2.39***[1]	0.62**[1]	2.58***[1]	0.68*[1]	0.08*[1]	1.47***[1]
LA	− 54.96***[3]	− 26.76***[3]	1.74***[1]	1.95***[1]	2.49***[1]	0.63**[1]	0.64**[1]	0.71**[1]
MA	− 49.84***[3]	− 24.34**[3]	0.55**[1]	0.90***[1]	2.61***[1]	0.24*[1]	0.38*[1]	1.05***[1]
MD	− 46.73***[3]	− 34.67***[3]	0.97***[1]	0.55**[1]	2.60***[1]	0.29*[1]	0.06*[1]	1.60***[1]
ME	− 49.17***[3]	− 23.99**[3]	1.46***[1]	2.06***[1]	2.60***[1]	0.11*[1]	0.41*[1]	1.37***[1]
MI	− 40.49***[3]	− 45.65***[3]	0.59**[1]	1.34***[1]	2.59***[1]	0.54**[1]	0.62**[1]	0.91***[1]
MN	− 46.97***[3]	− 46.32***[3]	2.15***[1]	0.51**[1]	2.60***[1]	0.22*[1]	0.07*[1]	1.44***[1]
MO	− 50.40***[3]	− 50.80***[3]	2.15***[1]	0.93***[1]	2.60***[1]	0.41*[1]	0.09*[1]	1.44***[1]
MS	− 50.79***[3]	− 43.87***[3]	2.12***[1]	0.88***[1]	2.57***[1]	0.52**[1]	0.04*[1]	1.27***[1]

Table 2 (continued)

	Pperron test		KPSS test					
MT	− 42.94***[3]	− 37.27***[3]	2.50***[1]	1.90***[1]	2.56***[1]	0.10*[1]	0.19*[1]	0.40*[1]
NC	− 51.01***[3]	− 47.03***[3]	2.20***[1]	1.11***[1]	2.61***[1]	0.53**[1]	0.10*[1]	1.41***[1]
ND	− 48.08***[3]	− 56.33***[3]	2.50***[1]	2.62***[1]	2.51***[1]	0.58**[1]	0.03*[1]	0.21*[1]
NE	− 43.18***[3]	− 62.73***[3]	2.40***[1]	2.16***[1]	2.59***[1]	0.14*[1]	0.20*[1]	1.11***[1]
NH	− 36.94***[3]	− 24.59**[3]	2.10***[1]	2.30***[1]	2.60***[1]	0.29*[1]	0.46**[1]	1.36***[1]
NJ	− 47.57***[3]	− 25.86***[3]	0.82***[1]	2.15***[1]	2.61***[1]	0.27*[1]	0.66**[1]	1.34***[1]
NM	− 49.14***[3]	− 33.10***[3]	2.22***[1]	2.40***[1]	2.59***[1]	0.84***[1]	0.16*[1]	0.37*[1]
NV	− 38.78***[3]	− 23.43**[3]	2.28***[1]	2.55***[1]	2.62***[1]	0.88***[1]	0.77***[1]	0.49**[1]
NY	− 33.91***[3]	− 33.33***[3]	1.38***[1]	0.41*[1]	2.61***[1]	0.26*[1]	0.48**[1]	0.88***[1]
OH	− 55.25***[3]	− 45.48***[3]	0.35*[1]	0.83***[1]	2.60***[1]	0.31*[1]	0.26*[1]	1.43***[1]
OK	− 50.90***[3]	− 25.08**[3]	2.36***[1]	0.39*[1]	2.52***[1]	0.63**[1]	0.07*[1]	0.63**[1]
OR	− 42.21***[3]	− 42.74***[3]	2.32***[1]	1.00***[1]	2.60***[1]	0.22*[1]	0.06*[1]	0.77***[1]
PA	− 45.72***[3]	− 43.49***[3]	0.48**[1]	0.30*[1]	2.61***[1]	0.14*[1]	0.18*[1]	1.59***[1]
RI	− 57.79***[3]	− 25.93***[3]	0.32*[1]	0.40*[1]	2.61***[1]	0.12*[1]	0.10*[1]	1.08***[1]
SC	− 68.33***[3]	− 40.17***[3]	2.47***[1]	0.56**[1]	2.58***[1]	0.22*[1]	0.03*[1]	1.85***[1]
SD	− 49.60***[3]	− 57.14***[3]	2.22***[1]	2.43***[1]	2.60***[1]	0.04*[1]	0.19*[1]	0.50**[1]
TN	− 53.42***[3]	− 42.87***[3]	2.19***[1]	1.67***[1]	2.59***[1]	0.31*[1]	0.10*[1]	1.72***[1]
TX	− 53.17***[3]	− 24.89**[3]	2.33***[1]	0.85***[1]	2.57***[1]	0.79***[1]	0.04*[1]	0.75***[1]
UT	− 45.79***[3]	− 25.77***[3]	2.56***[1]	2.44***[1]	2.61***[1]	0.15*[1]	0.13*[1]	0.33*[1]
VA	− 51.28***[3]	− 28.58***[3]	2.21***[1]	1.11***[1]	2.60***[1]	0.17*[1]	0.10*[1]	1.58***[1]
VT	− 40.45***[3]	− 37.66***[3]	1.69***[1]	1.99***[1]	2.58***[1]	0.18*[1]	0.35*[1]	1.50***[1]
WA	− 50.94***[3]	− 32.19***[3]	2.32***[1]	0.81***[1]	2.61***[1]	0.45*[1]	0.08*[1]	0.81***[1]
WI	− 51.50***[3]	− 41.26***[3]	2.05***[1]	1.06***[1]	2.60***[1]	0.29*[1]	0.09*[1]	1.43***[1]
WV	− 50.36***[3]	− 33.56***[3]	1.76***[1]	0.27*[1]	2.56***[1]	0.65**[1]	0.21*[1]	0.84***[1]
WY	− 48.45***[3]	− 24.39**[3]	2.33***[1]	2.30***[1]	2.43***[1]	0.95***[1]	0.40*[1]	0.19*[1]

***, **, and * denote significant at 1, 5, and 10% level. Numbers in square brackets are selected lags

Table 3 Results from the ZA unit root tests with a structural break

State	Variable	Level	Break	1st diff.	Break	State	Variable	Level	Break	1st diff.	Break
AK	$lnCO_2$	− 3.34	1982	− 7.22***	1981	MT	$lnCO_2$	− 3.65	1988	− 7.00***	1983
	lnEC	− 3.04	1982	− 7.29***	1981		lnEC	− 4.87*	1980	− 7.00***	2008
	lnGDP	− 4.20	1974	− 7.52***	1982		lnGDP	− 4.43	1972	− 6.91***	1981
AL	$lnCO_2$	− 2.88	1965	− 8.46***	1983	NC	$lnCO_2$	− 3.81	1966	− 8.26***	1991
	lnEC	− 3.18	1968	− 7.70***	1986		lnEC	− 8.51***	1966	− 9.52***	1966
	lnGDP	− 2.99	1976	− 6.21***	1971		lnGDP	− 1.67	1983	− 7.23***	2008
AR	$lnCO_2$	− 3.94	1968	− 8.45***	1973	ND	$lnCO_2$	− 3.98	1988	− 9.46***	1975
	lnEC	− 9.28***	1995	− 9.41***	1996		lnEC	− 7.81***	1985	− 8.02***	1983
	lnGDP	− 2.97	1972	− 7.19***	1970		lnGDP	− 3.94	1972	− 8.62***	1981
AZ	$lnCO_2$	− 4.03	1976	− 8.29***	1979	NE	$lnCO_2$	− 3.75	1980	− 8.55***	1973
	lnEC	− 17.69***	1994	− 8.64***	1995		lnEC	− 2.91	1979	− 6.46***	1973
	lnGDP	− 1.23	1977	− 4.95**	1967		lnGDP	− 3.85	1978	− 9.48***	1981
CA	$lnCO_2$	− 3.79	1980	− 7.88***	1983	NH	$lnCO_2$	− 3.22	2003	− 5.29**	1983
	lnEC	− 6.77***	2007	− 6.51***	1982		lnEC	− 2.75	1968	− 5.77***	1983
	lnGDP	− 2.56	1977	− 4.86**	1971		lnGDP	− 2.51	1984	− 5.01**	1975
CO	$lnCO_2$	− 3.67	1979	− 8.08***	1977	NJ	$lnCO_2$	− 5.58***	1974	− 8.84***	1970
	lnEC	− 22.23***	1993	− 8.75***	1994		lnEC	− 5.42**	1974	− 8.95***	1983
	lnGDP	− 1.59	1977	− 5.13**	1967		lnGDP	− 2.13	1983	− 5.27**	1975
CT	$lnCO_2$	− 3.26	1974	− 7.02***	1983	NM	$lnCO_2$	− 5.41**	1970	− 8.64***	1972
	lnEC	− 3.11	2003	− 7.68***	1983		lnEC	− 3.28	1977	− 8.40***	1986
	lnGDP	− 2.27	1981	− 5.24**	1975		lnGDP	− 2.31	1986	− 5.60***	1967
DE	$lnCO_2$	− 2.97	1994	− 10.64***	2008	NV	$lnCO_2$	− 4.36	1971	− 7.26***	1973
	lnEC	− 2.61	1974	− 7.95***	1982		lnEC	− 3.40	2006	− 7.32***	1986
	lnGDP	− 3.83	1999	− 7.11***	2001		lnGDP	− 1.79	2005	− 5.09**	2006
FL	$lnCO_2$	− 3.05	1968	− 6.62***	1984	NY	$lnCO_2$	− 2.73	1979	− 6.41***	1983
	lnEC	− 8.40***	1964	− 10.41***	1965		lnEC	− 3.49	1996	− 6.67***	1983
	lnGDP	− 0.99	1978	− 4.88**	2006		lnGDP	− 2.71	1981	− 5.69***	1976
GA	$lnCO_2$	− 3.33	1971	− 7.27***	1992	OH	$lnCO_2$	− 3.72	1980	− 7.84***	1983
	lnEC	− 8.91***	1967	− 8.96***	1968		lnEC	− 3.51	1962	− 9.04***	1983
	lnGDP	− 1.38	2000	− 5.35***	1975		lnGDP	− 2.53	1998	− 7.27***	1975
HI	$lnCO_2$	− 3.33	1966	− 6.97***	2007	OK	$lnCO_2$	− 4.41	1976	− 7.81***	1963
	lnEC	− 3.21	1966	− 6.97***	2007		lnEC	− 8.96***	1972	− 8.43***	1973
	lnGDP	− 2.97	1984	− 4.84**	1990		lnGDP	− 3.66	1976	− 6.14***	1982
IA	$lnCO_2$	− 4.42	1980	− 9.13***	1973	OR	$lnCO_2$	− 3.11	1974	− 7.91***	1986
	lnEC	− 10.52***	1993	− 10.45***	1994		lnEC	− 4.75	1991	− 6.99***	2004
	lnGDP	− 4.49*	1973	− 7.50***	1979		lnGDP	− 3.22	1976	− 6.45***	1979
ID	$lnCO_2$	− 6.11***	1980	− 6.46***	1986	PA	$lnCO_2$	− 4.30	1980	− 7.06***	1986
	lnEC	− 2.59	1967	− 8.39***	1987		lnEC	− 3.88	1962	− 7.48***	1983
	lnGDP	− 3.14	1972	− 5.18**	1971		lnGDP	− 2.93	1988	− 7.18***	1971
IL	$lnCO_2$	− 3.75	1980	− 7.04***	1992	RI	$lnCO_2$	− 3.46	1991	− 8.58***	1982
	lnEC	− 4.79	1980	− 6.49***	1986		lnEC	− 3.32	1974	− 9.08***	1982
	lnGDP	− 1.91	1998	− 6.84***	1971		lnGDP	− 2.80	1980	− 4.99**	1974
IN	$lnCO_2$	− 3.02	1974	− 8.00***	1983	SC	$lnCO_2$	− 3.73	1969	− 6.97***	1983
	lnEC	− 5.31**	1980	− 6.28***	1972		lnEC	− 9.90***	1981	− 13.84***	1984
	lnGDP	− 2.77	1999	− 7.50***	1971		lnGDP	− 3.46	1987	− 7.01***	1971
KS	$lnCO_2$	− 6.35***	1981	− 8.80***	1979	SD	$lnCO_2$	− 4.34	1980	− 8.11***	1978
	lnEC	− 9.56***	1984	− 13.85***	1985		lnEC	− 3.56	1980	− 8.02***	1978
	lnGDP	− 3.42	1988	− 6.55***	1970		lnGDP	− 4.04	1973	− 8.74***	1974
KY	$lnCO_2$	− 3.67	1963	− 8.25***	1972	TN	$lnCO_2$	− 3.53	1972	− 8.31***	2007

Table 3 (continued)

State	Variable	Level	Break	1st diff.	Break	State	Variable	Level	Break	1st diff.	Break
	lnEC	− 7.71***	1968	− 8.49***	1969		lnEC	− 7.30***	1962	− 29.07***	1962
	lnGDP	− 2.95	1976	− 7.47***	1970		lnGDP	− 1.64	1995	− 7.30***	1971
LA	$lnCO_2$	− 3.97	1979	− 8.07***	1978	TX	$lnCO_2$	− 2.15	1977	− 6.27***	1987
	lnEC	− 4.58	1980	− 8.51***	1964		lnEC	− 7.39***	1989	− 8.90***	1990
	lnGDP	− 3.81	1974	− 6.41***	1981		lnGDP	− 3.48	1974	− 5.71***	1981
MA	$lnCO_2$	− 3.45	1974	− 8.16***	1983	UT	$lnCO_2$	− 5.45**	1987	− 6.04***	1982
	lnEC	− 3.40	1979	− 7.80***	1983		lnEC	− 3.86	1980	− 8.23***	1987
	lnGDP	− 2.51	1983	−4.92**	1988		lnGDP	− 2.53	1986	− 5.35***	1967
MD	$lnCO_2$	− 3.73	1974	− 7.64***	1982	VA	$lnCO_2$	− 2.33	2003	− 7.67***	1982
	lnEC	− 8.54***	1969	− 8.25***	1970		lnEC	− 8.54***	1965	− 9.58***	1966
	lnGDP	− 4.56	1984	− 6.22***	1988		lnGDP	− 2.28	1983	− 5.41***	1970
ME	$lnCO_2$	− 3.59	1974	− 8.81***	1984	VT	$lnCO_2$	− 3.04	1979	− 7.47***	1982
	lnEC	− 3.42	1988	− 8.44***	1965		lnEC	− 4.67	1965	− 7.12***	1972
	lnGDP	− 2.32	1976	− 5.55***	1988		lnGDP	− 6.84***	1987	− 7.45***	1963
MI	$lnCO_2$	− 2.93	1962	− 7.38***	1983	WA	$lnCO_2$	2.82	1992	− 8.75***	1983
	lnEC	− 3.41	2005	− 7.28***	1983		lnEC	− 6.28***	1966	− 9.15***	1967
	lnGDP	− 2.81	1999	− 7.38***	1975		lnGDP	− 2.58	1978	− 5.67***	1972
MN	$lnCO_2$	− 2.96	1979	− 7.36***	1986	WI	$lnCO_2$	− 2.90	1994	− 6.82***	1986
	lnEC	− 7.29***	1969	− 7.89***	1970		lnEC	− 7.87***	1965	− 9.54***	1966
	lnGDP	− 1.95	1977	− 7.77***	1972		lnGDP	− 2.13	1975	− 6.82***	1970
MO	$lnCO_2$	− 3.05	1968	− 6.29***	1993	WV	$lnCO_2$	− 4.71	1972	− 8.64***	1992
	lnEC	− 6.48***	1965	− 8.94***	1966		lnEC	− 4.41	1980	− 8.27***	1986
	lnGDP	− 1.71	1976	− 7.69***	1975		lnGDP	− 6.14***	1974	− 6.03***	1981
MS	$lnCO_2$	− 4.20	1958	− 8.12***	1972	WY	$lnCO_2$	− 4.82*	1976	− 9.71***	1966
	lnEC	− 9.24***	1990	− 8.62***	1991		lnEC	− 4.64	1967	− 7.60***	1979
	lnGDP	− 3.47	1976	− 6.96***	1971		lnGDP	− 3.02	1973	− 6.38***	1981

Break denotes the time of the structure change

***, **, and * significant at the 1, 5, and 10 levels, respectively

TX) unidirectional causality running from energy consumption to CO_2 emissions, and four (KY, NM, NV, and UT) unidirectional causality for the opposite side. Furthermore, our empirical results also disclose 35 neutrality hypotheses for the rest of the states. Regarding the relationship between economic growth and energy consumption, the results reveal five (GI, HI, ID, MS, and PA) bidirectional causalities between economic growth and energy consumption, 15 (IN, MD, MI, MN, MO, NC, NM, NY, OH, OR, SD, VT, WA, WV, and WY) unidirectional causality running from economic growth to energy consumption, and 14 (AK, AR, AZ, CO, FL, LA, MT, ND, OK, TN, TX, UT, and WI) unidirectional causality for the opposite side. Moreover, our empirical results also reveal 16 cases of neutrality hypothesis for the rest of the states. Accordingly, when we analyze the relationship between economic growth and CO_2 emission, the results show five (CO, DE, ID, MO, and UT) bidirectional causalities between economic growth and CO_2 emission, 11 (IL, IN, MD, NC, NM, NV, OH, PA, SD, VT, WV, and WY) unidirectional causalities running from economic growth to CO_2 emission, and 12 (AK, FL, IA, KS, LA, ME, MS, MT, OK, SC, TN, VA, and WI) cases for the opposite side.

The results of the time-varying Granger causality tests (Eq. 3.4) are tabulated in Table 6. The results disclose eight (AR, CO, GA, LA, MN, NH, PA, TX, and UT) bidirectional time-varying causalities between energy consumption and CO_2 emission, six (CA, DE, KY, RI, and WA) unidirectional time-varying causality running from CO_2 emissions to energy consumption, and four (CT, ME, NY, and OK) unidirectional time-varying causality for the opposite side. Additionally, our empirical results also disclose 32 neutrality hypotheses for the rest of the states. Regarding the relationship between economic growth and energy consumption, the results reveal six cases (GA, ID, MO, MS, NJ, and PA) of two-way time-varying causalities between economic growth and energy consumption, 14 cases (HI, IN, MD, MI, NC, NM, NY, OH, OR, SD, VT, WA, WV, and WY) of unidirectional time-varying causality running from economic growth to energy consumption,

Table 4 Classical Granger causality test results

	H: GDP to CO_2	H: CO_2 to GDP	H: GDP to EC	H: EC to GDP	H: EC to CO_2	H: CO_2 to EC		H: GDP to CO_2	H: CO_2 to GDP	H: GDP to EC	H: EC to GDP	H: EC to CO_2	H: CO_2 to EC
AK	0.026**	0.401	0.068*	0.117	0.501	0.175	MT	0.146	0.363	0.272	0.466	0.019**	0.781
AL	0.88	0.986	0.84	0.7	0.638	0.142	NC	0.549	0.992	0.666	0.663	0.446	0.014**
AR	0.287	0.601*	0.424	0.189	0.002***	0.147	ND	0.218	0.472	0.691	0.259	0.049**	0.419
AZ	0.038**	0.173	0.117	0.31	0.475	0.187	NE	0.79	0.707	0.891	0.444	0.129	0.312
CA	0.471	0.871	0.742	0.463	0.248	0.01***	NH	0.782	0.323	0.773	0.217	0.1*	0.132
CO	0.729	0.694	0.59	0.187	0.575	0.384	NJ	0.915	0.698	0.657	0.122	0.426	0.965
CT	0.612	0.288	0.286	0.01***	0.142	0.091*	NM	0.711	0.512	0.803	0.158	0.127	0.313
DE	0.354	0.566	0.083*	0.116	0.711	0.566	NV	0.376	0.182	0.624	0.205	0.118	0.914
FL	0.57	0.214	0.918	0.53	0.132	0.731	NY	0.221	0.149	0.392	0.675	0.386	0.654
GA	0.448	0.728	0.186	0.346	0.169	0.036**	OH	0.091*	0.25	0.065*	0.233	0.863	0.808
HI	0.071*	0.373	0.049**	0.467	0.894	0.984	OK	0.151	0.495	0.241	0.05**	0.441	0.777
IA	0.998	0.954	0.152	0.786	0.214	0.631	OR	0.484	0.392	0.369	0.131	0.752	0.145
ID	0.745	0.466	0.901	0.211	0.452	0.259	PA	0.62	0.041**	0.119	0.05**	0.1*	0.281
IL	0.021**	0.402	0.1*	0.182	0.069*	0.042**	RI	0.045**	0.468	0.371	0.462	0.58	0.098*
IN	0.18	0.322	0.835	0.547	0.646	0.727	SC	0.8	0.978	0.703	0.3	0.134	0.133
KS	0.901	0.131	0.207	0.215	0.252	0.533	SD	0.184	0.884	0.173	0.128	0.865	0.791
KY	0.137	0.225	0.273	0.56	0.637	0.57	TN	0.195	0.574	0.211	0.44	0.402	0.152
LA	0.901	0.257	0.759	0.34	0.167	0.13	TX	0.541	0.001***	0.746	0.00***	0.018**	0.009***
MA	0.408	0.93	0.086*	0.445	0.975	0.481	UT	0.374	0.838	0.631	0.911	0.071*	0.212
MD	0.601	0.449	0.305	0.217	0.868	0.651	VA	0.886	0.245	0.882	0.216	0.218	0.298
ME	0.049**	0.49	0.194	0.338	0.74	0.267	VT	0.946	0.674	0.509	0.577	0.497	0.397
MI	0.255	0.357	0.204	0.49	0.004***	0.152	WA	0.454	0.94	0.789	0.783	0.54	0.001***
MN	0.166	0.117	0.381	0.091*	0.52	0.763	WI	0.064*	0.009***	0.399	0.16	0.379	0.819
MO	0.668	0.05**	0.816	0.01***	0.769	0.02**	WV	0.083*	0.723	0.117	0.856	0.276	0.515
MS	0.883	0.095*	0.098*	0.589	0.044**	0.819	WY	0.601	0.422	0.623	0.856	0.05**	0.801

Values in the table are the *p* values. ***, **, and * denote significant at 1, 5, and 10% level. The number of lags used to implement the test is equal to one

and 11 (AK, AR, AZ, CO, FL, LA, ND, SC, TN, TX, and WI) one-way causalities for the opposite side. Moreover, our empirical results show 19 cases of neutrality hypothesis for the rest of the states. Likewise, when we analyze the relationship between economic growth and CO_2 emissions, the results show five (CO, HI, MO, MS, and UT) two-way time-varying causalities between economic growth and CO_2 emission, 12 cases (ID, IL, IN, MD, NC, NM, NV, OH, PA, SD, VT, WV, and WY) of unidirectional time-varying causalities running from economic growth to CO_2 emission, and 14 (AK, AR, DE, FL, MI, OK, RI, SC, TN, TX, VA, and WI) cases for the opposite side. These different findings for each state are justified by the state differences such as, among others, the composition of GDP for each state over the years, the fuel mix, and the rate of technical progress (Judson et al. 1999).

In order to capture the validity of the traditional EKC hypothesis, we will follow the strand from Ajmi et al. (2015). Ajmi et al. (2015) were the first who proposed the "curve causality" graphs in order to determine the validity of EKC hypothesis. Illustrating the significant time-varying causality running from GDP to CO_2 emissions, they attested the shape of an inverted-U curve between the two variables. In our case, Fig. 1 describes the causality curves for 18 significant states (Table 6). It should be highly stressed that our results reject the EKC hypothesis, albeit, the majority of states verify an inverted N-shape curve. This insinuates that as time goes by, an increasing of income range would fundamentally improve environmental performance.

Concluding remarks

There are a large number of researchers who have studied the relationship between the energy consumption, economic growth, and CO_2 emission. From a methodological point of view, the contribution lies on the fact that for the first time at a state level, this relationship has been examined with time-varying causality for the case of 50 US states over the periods 1960–2010. Our study broadens the understanding of the determinants of the relationship between energy consumption, economic growth, and CO_2 emissions, and deepens the investigation of the validity of the EKC hypothesis at a state level.

Table 5 Results of the dynamic Granger causality tests

	H: GDP to CO_2	H: CO_2 to GDP	H: GDP to EC	H: EC to GDP	H: EC to CO_2	H: CO_2 to EC		H: GDP to CO_2	H: CO_2 to GDP	H: GDP to EC	H: EC to GDP	H: EC to CO_2	H: CO_2 to EC
AK	0.986	0.033**	0.991	0.010***	0.438	0.541	MT	0.931	0.096*	0.14	0.099*	0.144	0.783
AL	0.1*	0.1*	0.087*	0.1*	0.814	0.449	NC	0.001***	0.892	0.002***	0.668	0.367	0.694
AR	0.332	0.314	0.473	0.029**	0.039**	0.02**	ND	0.904	0.687	0.601	0.05**	0.607	0.98
AZ	0.178	0.537	0.771	0.042**	0.467	0.833	NE	0.814	0.677	0.713	0.161	0.217	0.47
CA	0.508	0.243	0.724	0.213	0.2	0.128	NH	0.811	0.998	0.678	0.946	0.565	0.287
CO	0.001***	0.00***	0.735	0.001***	0.018**	0.001***	NJ	0.923	0.31	0.113	0.169	0.35	0.813
CT	0.436	0.313	0.57	0.915	0.447	0.928	NM	0.007***	0.705	0.01***	0.679	0.144	0.1*
DE	0.064*	0.00***	0.162	0.713	0.1*	0.003***	NV	0.01***	0.347	0.528	0.401	0.316	0.085*
FL	0.237	0.01***	0.701	0.002***	0.192	0.141	NY	0.541	0.344	0.006***	0.427	0.023**	0.15
GA	0.782	0.88	0.028**	0.01***	0.025**	0.029**	OH	0.016**	0.183	0.06***	0.358	0.938	0.369
HI	0.001***	0.027**	0.002***	0.067*	0.604	0.603	OK	0.251	0.003***	0.98	0.091*	0.1*	0.111
IA	0.238	0.069*	0.928	0.939	0.612	0.279	OR	0.231	0.708	0.01***	0.64	0.222	0.708
ID	0.001***	0.088*	0.001***	0.037**	0.579	0.583	PA	0.042**	0.778	0.014**	0.03**	0.064*	0.093*
IL	0.003***	0.282	0.207	0.536	0.642	0.704	RI	0.592	0.397	0.712	0.864	0.851	0.371
IN	0.025**	0.22	0.00***	0.784	0.991	0.898	SC	0.689	0.027**	0.721	0.006***	0.125	0.402
KS	0.639	0.043**	0.981	0.183	0.536	0.739	SD	0.008***	0.738	0.009***	0.434	0.672	0.559
KY	0.809	0.33	0.607	0.244	0.391	0.047**	TN	0.798	0.054*	0.552	0.002***	0.941	0.789
LA	0.278	0.02**	0.398	0.01***	0.025**	0.01***	TX	0.696	0.158	0.506	0.029**	0.063*	0.399
MA	0.994	0.126	0.899	0.443	0.158	0.941	UT	0.018**	0.00***	0.133	0.083*	0.127	0.033**
MD	0.016**	0.423	0.1*	0.237	0.566	0.652	VA	0.16	0.068*	0.187	0.183	0.644	0.616
ME	0.155	0.061*	0.258	0.132	0.057*	0.143	VT	0.048**	0.746	0.001***	0.491	0.689	0.832
MI	0.205	0.623	0.033**	0.742	0.625	0.711	WA	0.873	0.736	0.004***	0.922	0.988	0.458
MN	0.269	0.259	0.087*	0.519	0.01***	0.019**	WI	0.932	0.001***	0.815	0.061*	0.807	0.442
MO	0.00***	0.021**	0.00***	0.292	0.203	0.374	WV	0.00***	0.479	0.001***	0.471	0.231	0.81
MS	0.25	0.004***	0.007***	0.05**	0.88	0.531	WY	0.013**	0.177	0.002***	0.209	0.792	0.941

Values in the table are the *p* values. ***, **, and * denote significant at 1, 5, and 10% level. The number of lags used to implement the test is equal to one

The results of the causality test indicate (in the case of classical causality) that there is two bidirectional causalities between energy consumption and CO_2 emissions, nine unidirectional causality running from energy consumption to CO_2 emissions, and seven unidirectional causality for the opposite side. Regarding the relationship between economic growth and energy consumption, the results reveal seven unidirectional causalities running from economic growth to energy consumption, six cases unidirectional causalities running from energy consumption to economic growth. Lastly, the results probe one-bidirectional causality between economic growth and CO_2 emission, eight unidirectional causalities running from economic growth to CO_2 emission, and five for the opposite side. On the side from dynamic Granger causality test, the results show six bidirectional causalities between energy consumption and CO_2 emission, five unidirectional causalities running from energy consumption to CO_2 emissions, and four unidirectional causalities for the opposite side. Similarly, the relationship between economic growth and energy consumption, the results reveals five two-way causalities between economic growth and energy consumption, 15 unidirectional causalities running from economic growth to energy consumption, and 14 unidirectional causalities for the opposite side. Accordingly, when we analyze the relationship between economic growth and CO_2 emissions, the results show five bidirectional causalities between economic growth and CO_2 emission, 11 unidirectional causalities running from economic growth to CO_2 emission, and 12 cases for the opposite side.

Lastly, the results of the time-varying Granger causality tests probe eight bidirectional time-varying causalities between energy consumption and CO_2 emission, six unidirectional time-varying causalities running from CO_2 emissions to energy consumption, and four unidirectional time-varying causalities for the opposite side. Regarding the relationship between economic growth and energy consumption, the results reveals six cases of two-way time-varying causalities between economic growth and energy consumption, 14 cases of unidirectional time-varying causalities running from economic growth to energy consumption, and 11 unidirectional causalities for the opposite side. Finally, when we evaluate the relationship between economic growth and CO_2 emission, the results show five bidirectional time-varying causalities

Table 6 Results of the time-varying Granger causality tests

	H: GDP to CO_2	H: CO_2 to GDP	H: GDP to EC	H: EC to GDP	H: EC to CO_2	H: CO_2 to EC		H: GDP to CO_2	H: CO_2 to GDP	H: GDP to EC	H: EC to GDP	H: EC to CO_2	H: CO_2 to EC
AK	0.733	0.010***	0.691	0.010***	0.407	0.279	MT	0.884	0.129	0.238	0.157	0.115	0.896
AL	0.176	0.176	0.133	0.186	0.896	0.576	NC	0.001***	0.892	0.005***	0.668	0.182	0.173
AR	0.29	0.009***	0.441	0.001***	0.002***	0.018**	ND	0.966	0.993	0.55	0.004***	0.223	0.993
AZ	0.116	0.635	0.673	0.05**	0.5	0.677	NE	0.83	0.801	0.628	0.258	0.129	0.55
CA	0.677	0.331	0.656	0.186	0.122	0.046**	NH	0.861	0.998	0.508	0.952	0.1*	0.06*
CO	0.001***	0.001***	0.827	0.001***	0.021**	0.002***	NJ	0.928	0.39	0.1*	0.073*	0.414	0.906
CT	0.383	0.343	0.313	0.256	0.037**	0.343	NM	0.01***	0.805	0.01***	0.495	0.14	0.152
DE	0.118	0.00***	0.227	0.415	0.15	0.002***	NV	0.004***	0.506	0.334	0.545	0.218	0.156
FL	0.366	0.1***	0.827	0.002***	0.143	0.231	NY	0.656	0.482	0.01***	0.425	0.008***	0.248
GA	0.806	0.6	0.01***	0.007***	0.016**	0.009***	OH	0.034**	0.292	0.01***	0.521	0.979	0.532
HI	0.00***	0.056*	0.00***	0.117	0.76	0.76	OK	0.354	0.004***	0.89	0.166	0.071*	0.125
IA	0.349	0.124	0.975	0.886	0.455	0.428	OR	0.361	0.535	0.003***	0.781	0.354	0.545
ID	0.002***	0.162	0.002***	0.074*	0.656	0.633	PA	0.035**	0.44	0.03**	0.041**	0.05**	0.081*
IL	0.006***	0.304	0.325	0.676	0.21	0.166	RI	0.302	0.041**	0.622	0.893	0.819	0.099*
IN	0.042**	0.162	0.00***	0.843	0.952	0.952	SC	0.705	0.05**	0.721	0.006***	0.122	0.311
KS	0.71	0.05**	0.974	0.224	0.32	0.401	SD	0.01***	0.864	0.003***	0.275	0.762	0.72
KY	0.906	0.484	0.734	0.348	0.557	0.068*	TN	0.908	0.078*	0.716	0.004***	0.848	0.686
LA	0.331	0.032**	0.335	0.033**	0.047**	0.02**	TX	0.756	0.045**	0.639	0.00***	0.01***	0.1*
MA	0.969	0.202	0.748	0.48	0.267	0.823	UT	0.038**	0.00***	0.226	0.127	0.075*	0.041**
MD	0.009***	0.525	0.065*	0.366	0.641	0.643	VA	0.25	0.05**	0.176	0.262	0.571	0.652
ME	0.201	0.088*	0.4	0.229	0.099*	0.24	VT	0.071*	0.733	0.00***	0.569	0.387	0.276
MI	0.3	0.751	0.5**	0.869	0.117	0.302	WA	0.944	0.615	0.003***	0.86	0.947	0.01***
MN	0.415	0.207	0.145	0.344	0.024**	0.032**	WI	0.977	0.001***	0.838	0.087*	0.757	0.611
MO	0.00***	0.008***	0.00***	0.095*	0.284	0.438	WV	0.00***	0.619	0.001***	0.272	0.249	0.912
MS	0.071*	0.002***	0.00***	0.1*	0.536	0.689	WY	0.028**	0.237	0.001***	0.242	0.724	0.961

Values in the table are the *p* values. ***, **, and * denote significant at 1, 5, and 10% level. The number of lags used to implement the test is equal to one

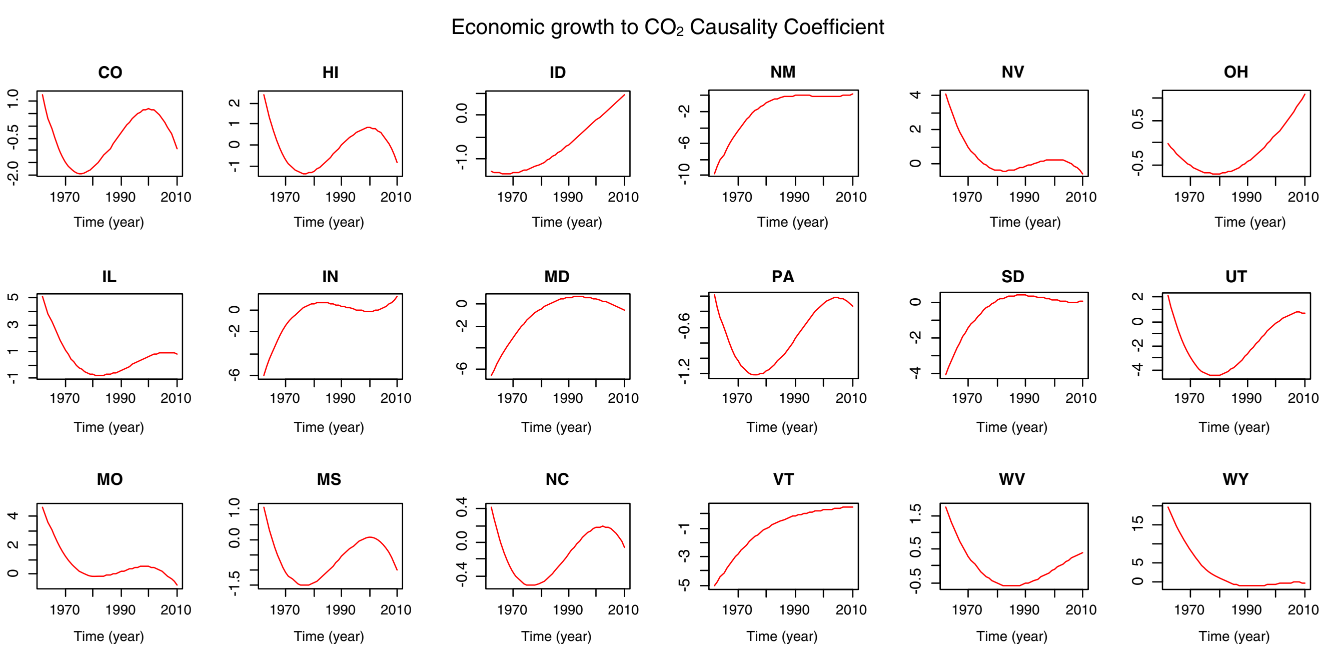

Fig. 1 Pseudo-EKC curve causality

between economic growth and CO_2 emission, 12 cases of unidirectional time-varying causalities running from economic growth to CO_2 emission, and 14 cases for the opposite side. Interestingly enough, regarding the investigation of the existence of EKC hypothesis, our results reject the EKC hypothesis, albeit, the majority of states verify an inverted N-shape curve.

As far as policy implications, our discoveries suggest that these states are in general exceptionally energy-dependent economies but with distinctive significance level. Plausibly, these states necessary will look for an adjusted harmony between energy and economic growth. Nonetheless, those states could be change first: reorganization of energy efficiency buildings; second, enhancement of energy conservation policies in order to have better waste-processing industry; and third, the utilization of alternative energy sources (such as solar panels, wind power, and geothermal power). All these perspectives suggest the reduction of greenhouse gases. Moreover, our outcomes in respect of time-varying framework exhibit different policy implications between the covariates. To elaborate, our results support that USA should pass legislation to mitigate GHGs and moderate environmental degradation. Such policies should aim to decrease energy intensity, increase energy efficiency, and alter the fuel mix towards renewable energy sources. Furthermore, we signify the importance for the decision makers to take into account the time-varying causality between energy consumption, GDP growth, and CO_2 emission.

As next step in our research, we will concentrate on the time-varying field. Presumably, future study should determine the time-varying relationship between these covariates at a state level instead of a national level which is most commonly used. This will be pursued in our future study.

Acknowledgements We would like to thank the editor Philippe Garrigues and the reviewers for their constructive comments on an earlier version of our manuscript. Any remaining errors are solely the authors' responsibility.

References

Acaravci A, Ozturk I (2010) On the relationship between energy consumption, CO_2 emissions and economic growth in Europe. Energy 35(12):5412–5420. https://doi.org/10.1016/j.energy.2010.07.009

Adams S, Mensah Klobodu EK, Osei Opoku EE (2016) Energy consumption, political regime and economic growth in sub-Saharan Africa. Energy Policy 96:36–44. https://doi.org/10.1016/j.enpol.2016.05.029

Ajmi AN, Hammoudeh S, Nguyen DK, Sato JR (2015) On the relationships between CO_2 emissions, energy consumption and GDP: the importance of time variation. Energy Econ 49:629–638. https://doi.org/10.1016/j.eneco.2015.02.007

Akhmat G, Zaman K, Shukui T, Irfan D, Khan MM (2014) Does energy consumption contribute to environmental pollutants? Evidence from SAARC countries. Environ Sci Pollut Res 21(9):5940–5951. https://doi.org/10.1007/s11356-014-2528-1

Alam MJ, Begum IA, Buysse J, Van Huylenbroeck G (2012) Energy consumption, carbon emissions and economic growth nexus in Bangladesh: cointegration and dynamic causality analysis. Energy Policy 45:217–225. https://doi.org/10.1016/j.enpol.2012.02.022

Ali HS, Law SH, Zannah TI (2016) Dynamic impact of urbanization, economic growth, energy consumption, and trade openness on CO_2 emissions in Nigeria. Environ Sci Pollut Res 23(12):12435–12443. https://doi.org/10.1007/s11356-016-6437-3

Al-Iriani MA (2006) Energy–GDP relationship revisited: an example from GCC countries using panel causality. Energy Policy 34(17): 3342–3350. https://doi.org/10.1016/j.enpol.2005.07.005

Alkhathlan K, Javid M (2013) Energy consumption, carbon emissions and economic growth in Saudi Arabia: an aggregate and disaggregate analysis. Energy Policy 62:1525–1532. https://doi.org/10.1016/j.enpol.2013.07.068

Amri F (2017) Carbon dioxide emissions, output, and energy consumption categories in Algeria. Environ Sci Pollut Res 24(17):14567–14578

Ang JB (2007) CO_2 emissions, energy consumption, and output in France. Energy Policy 35(10):4772–4778. https://doi.org/10.1016/j.enpol.2007.03.032

Ang JB (2008) Economic development, pollutant emissions and energy consumption in Malaysia. J Policy Model 30(2):271–278. https://doi.org/10.1016/j.jpolmod.2007.04.010

Apergis N, Payne JE (2009) CO_2 emissions, energy usage, and output in Central America. Energy Policy 37(8):3282–3286. https://doi.org/10.1016/j.enpol.2009.03.048

Apergis N, Payne JE (2010) Structural breaks and petroleum consumption in US states: are shocks transitory or permanent? Energy Policy 38(10):6375–6378. https://doi.org/10.1016/j.enpol.2010.06.015

Apergis N, Loomis D, Payne JE (2010) Are shocks to natural gas consumption temporary or permanent? Evidence from a panel of US states. Energy Policy 38(8):4734–4736. https://doi.org/10.1016/j.enpol.2010.03.016

Aqeel A, Butt MS (2001) The relationship between energy consumption and economic growth in Pakistan. Asia Pac Dev J 8(2):101–110

Aslan A (2011) Does natural gas consumption follow a nonlinear path over time? Evidence from 50 US states. Renew Sust Energ Rev 15(9):4466–4469. https://doi.org/10.1016/j.rser.2011.07.105

Attiaoui I, Toumi H, Ammouri B, Gargouri I (2017) Causality links among renewable energy consumption, CO2 emissions, and economic growth in Africa: evidence from a panel ARDL-PMG approach. Environ Sci Pollut Res 24(14):13036–13048. https://doi.org/10.1007/s11356-017-8850-7

Baek J (2015) Environmental Kuznets curve for CO2 emissions: the case of Arctic countries. Energy Econ 50:13–17. https://doi.org/10.1016/j.eneco.2015.04.010

Bildirici ME (2017) The causal link among militarization, economic growth, CO_2 emission, and energy consumption. Environ Sci Pollut Res 24(5):4625–4636. https://doi.org/10.1007/s11356-016-8158-z

Bowden N, Payne JE (2009) The causal relationship between US energy consumption and real output: a disaggregated analysis. J Policy Model 31(2):180–188. https://doi.org/10.1016/j.jpolmod.2008.09.001

Chang CC (2010) A multivariate causality test of carbon dioxide emissions, energy consumption and economic growth in China. Appl Energy 87(11):3533–3537. https://doi.org/10.1016/j.apenergy.2010.05.004

Coondoo D, Dinda S (2002) Causality between income and emissions: a country group specific econometric analysis. Ecol Econ 40(3):351–367. https://doi.org/10.1016/S0921-8009(01)00280-4

Coondoo D, Dinda S (2008) The carbon dioxide emission and income: a temporal analysis of cross-country distributional patterns. Ecol Econ 265:375–385

Dahlhaus R, Neumann MH, von Sachs R (1999) Nonlinear wavelet estimation of the time-varying autoregressive processes. Bernoulli 5(5): 873–906. https://doi.org/10.2307/3318448

Dinda S (2004) Environmental Kuznets curve hypothesis: a survey. Ecol Econ 49(4):431–455. https://doi.org/10.1016/j.ecolecon.2004.02.011

Dogan E, Ozturk I (2017) The influence of renewable and non-renewable energy consumption and real income on CO_2 emissions in the USA: evidence from structural break tests. Environ Sci Pollut Res 24(11): 10846–10854. https://doi.org/10.1007/s11356-017-8786-y

Dogan E, Turkekul B (2016) CO_2 emissions, real output, energy consumption, trade, urbanization and financial development: testing the EKC hypothesis for the USA. Environ Sci Pollut Res 23(2): 1203–1213

Eilers PHC, Marx BD (1996) Flexible smoothing with B-splines and penalties. Stat Sci 11(2):89–121. https://doi.org/10.1214/ss/1038425655

Elliott G, Rothenberg TJ, Stock JH (1996) Efficient tests for an autoregressive unit root. Econometrica 64(4):813–836. https://doi.org/10.2307/2171846

Esteve V, Tamarit C (2012a) Threshold cointegration and nonlinear adjustment between CO_2 and income: the environmental Kuznets curve in Spain, 1857–2007. Energy Econ 34(6):2148–2156. https://doi.org/10.1016/j.eneco.2012.03.001

Esteve V, Tamarit C (2012b) Is there an environmental Kuznets curve for Spain? Fresh evidence from old data. Econ Model 29(6):2696–2703. https://doi.org/10.1016/j.econmod.2012.08.016

Farhani S, Ozturk I (2015) Causal relationship between CO_2 emissions, real GDP, energy consumption, financial development, trade openness, and urbanization in Tunisia. Environ Sci Pollut Res 22(20): 15663–15676. https://doi.org/10.1007/s11356-015-4767-1

Fosten J, Morley B, Taylor T (2012) Dynamic misspecification in the environmental Kuznets curve: evidence from CO 2 and SO 2 emissions in the United Kingdom. Ecol Econ 76:25–33. https://doi.org/10.1016/j.ecolecon.2012.01.023

Ghali KH, El-Sakka MIT (2004) Energy use and output growth in Canada: a multivariate cointegration analysis. Energy Econ 26(2): 225–238. https://doi.org/10.1016/S0140-9883(03)00056-2

Granger C (1969) Investigating causal relations by econometric models and cross-spectral methods. Econometrica 37(3):424–438. https://doi.org/10.2307/1912791

Granger C (1980) Testing for causality: a personal view point. J Econ Dyn Control 2:329–352. https://doi.org/10.1016/0165-1889(80)90069-X

Grossman G, Krueger A (1991) Environmental impacts of a North American free trade agreement. In: National Bureau of Economics Research working paper, vol 3194. NBER, Cambridge

Halicioglu F (2009) An econometric study of CO_2 emissions, energy consumption, income and foreign trade in Turkey. Energy Policy 37(3):1156–1164. https://doi.org/10.1016/j.enpol.2008.11.012

Hossain MS (2011) Panel estimation for CO_2 emissions, energy consumption, economic growth, trade openness and urbanization of newly industrialized countries. Energy Policy 39(11):6991–6999. https://doi.org/10.1016/j.enpol.2011.07.042

Jayanthakumaran K, Verma R, Liu Y (2012) CO_2 emissions, energy consumption, trade and income: a comparative analysis of China and India. Energy Pol 42:450–460

Judson RA, Schmalensee R, Stoker TM (1999) Economic development and the structure of the demand for commercial energy. Energy J 20(2):29–57

Karanfil F (2008) Energy consumption and economic growth revisited: does the size of unrecorded economy matter? Energy Policy 36(8): 3029–3035. https://doi.org/10.1016/j.enpol.2008.04.002

Karanfil F (2009) How many times again will we examine the energy-GDP nexus using a limited range of traditional econometric tools? Energy Policy 37(4):1191–1194. https://doi.org/10.1016/j.enpol.2008.11.029

Kraft J, Kraft A (1978) On the relationship between energy and GNP. J Energy Dev 3:401–403

Kwiatkowski D, Phillips PCB, Schmidt P, Shin Y (1992) Testing the null hypothesis of stationary against the alternative of a unit root. J Econ 54(1-3):159–178. https://doi.org/10.1016/0304-4076(92)90104-Y

Lean HH, Smyth R (2010) CO_2 emissions, electricity consumption and output in ASEAN. Appl Energy 87(6):1858–1864. https://doi.org/10.1016/j.apenergy.2010.02.003

Menyah K, Wolde-Rufael Y (2010) Energy consumption, pollutant emissions and economic growth in South Africa. Energy Econ 32(6): 1374–1382. https://doi.org/10.1016/j.eneco.2010.08.002

Narayan PK, Narayan S (2010) Carbon dioxide emissions and economic growth: panel data evidence from developing countries. Energy Policy 38(1):661–666. https://doi.org/10.1016/j.enpol.2009.09.005

Narayan PK, Narayan S, Popp S (2010) Energy consumption at the state level: the unit root null hypothesis from Australia. Appl Energy 87(6):1953–1962. https://doi.org/10.1016/j.apenergy.2009.10.022

Omri A (2013) CO_2 emissions, energy consumption and economic growth nexus in MENA countries: evidence from simultaneous equations models. Energy Econ 40:657–664. https://doi.org/10.1016/j.eneco.2013.09.003

Ozcan B (2013) The nexus between carbon emissions, energy consumption and economic growth in Middle East countries: a panel data analysis. Energy Policy 62:1138–1147. https://doi.org/10.1016/j.enpol.2013.07.016

Ozturk I (2010) A literature survey on energy-growth nexus. Energy Policy 38(1):340–349. https://doi.org/10.1016/j.enpol.2009.09.024

Ozturk I, Acaravci A (2010) CO_2 emissions, energy consumption and economic growth in Turkey. Renew Sust Energ Rev 14(9):3220–3225. https://doi.org/10.1016/j.rser.2010.07.005

Ozturk I, Acaravci A (2013) The long-run and causal analysis of energy, growth, openness and financial development on carbon emissions in Turkey. Energy Econ 36:262–267. https://doi.org/10.1016/j.eneco.2012.08.025

Padilla E, Serrano A (2006) Inequality in CO_2 emissions across countries and its relationship within come inequality: a distributive approach. Energy Policy 34(14):1762–1772. https://doi.org/10.1016/j.enpol.2004.12.014

Pao HT, Tsai CM (2011a) Modeling and forecasting the CO_2 emissions, energy consumption, and economic growth in Brazil. Energy 36(5): 2450–2458. https://doi.org/10.1016/j.energy.2011.01.032

Pao HT, Tsai CM (2011b) Multivariate Granger causality between CO_2 emissions, energy consumption, FDI (foreign direct investment) and GDP (gross domestic product): evidence from a panel of BRIC (Brazil, Russian Federation, India, and China) countries. Energy 36(1):685–693. https://doi.org/10.1016/j.energy.2010.09.041

Payne JE (2010a) A survey of the electricity consumption-growth literature. Appl Energy 87(3):723–731. https://doi.org/10.1016/j.apenergy.2009.06.034

Payne JE (2010b) Survey of the international evidence on the causal relationship between energy consumption and growth. J Econ Stud 37(1):53–95. https://doi.org/10.1108/01443581011012261

Phillips PCB, Perron P (1988) Testing for a unit root in time series regressions. Biometrica 75(2):335–346. https://doi.org/10.1093/biomet/75.2.335

Rafindadi AA, Yusof Z, Zaman K, Kyophilavong P, Akhmat G (2014) The relationship between air pollution, fossil fuel energy consumption, and water resources in the panel of selected Asia-Pacific countries. Environ Sci Pollut Res 21(19):11395–11400. https://doi.org/10.1007/s11356-014-3095-1

Robalino-López A, Mena-Nieto Á, García-Ramos JE, Golpe AA (2015) Studying the relationship between economic growth, CO_2

emissions, and the environmental Kuznets curve in Venezuela (1980–2025). Renew Sust Energ Rev 41:602–614. https://doi.org/10.1016/j.rser.2014.08.081

Sato JR, Morettin PA, Arantes PR, Amaro JE (2007) Wavelet based time-varying vector autoregressive modelling. Comput Stat Data Anal 51(12):5847–5866. https://doi.org/10.1016/j.csda.2006.10.027

Sephton P, Mann J (2013) Further evidence of the environmental Kuznets curve in Spain. Energy Econ 36:177–181. https://doi.org/10.1016/j.eneco.2013.01.001

Shahbaz M, Mahalik MK, Shah SH, Sato JR (2016) Time-varying analysis of CO_2 emissions, energy consumption, and economic growth nexus: statistical experience in next 11 countries. Energy Policy 98: 33–48. https://doi.org/10.1016/j.enpol.2016.08.011

Shahiduzzaman M, Alam K (2012) Cointegration and causal relationships between energy consumption and output: assessing the evidence from Australia. Energy Econ 34(6):2182–2188. https://doi.org/10.1016/j.eneco.2012.03.006

Smyth R, Narayan PK (2015) Applied econometrics and implications for energy economics research. Energy Econ 50:351–358. https://doi.org/10.1016/j.eneco.2014.07.023

Soytas U, Sari R (2009) Energy consumption, economic growth, and carbon emissions: challenges faced by an EU candidate member. Ecol Econ 68(6):1667–1675. https://doi.org/10.1016/j.ecolecon.2007.06.014

Soytas U,Sarı R,Özdemir O (2001) Energy consumption and GDP relation in Turkey: a cointegration and vector error correction analysis. In: Economies and Business in Transition: Facilitating Competitiveness and Change in the Global Environment Proceedings. Global Business and Technology Association, pp 838–844

Soytas U, Sari R, Ewing BT (2007) Energy consumption, income, and carbon emissions in the United States. Ecol Econ 62(3-4):482–489. https://doi.org/10.1016/j.ecolecon.2006.07.009

Stern DI (1993) Energy use and economic growth in the USA: a multivariate approach. Energy Econ 15(2):137–150. https://doi.org/10.1016/0140-9883(93)90033-N

Stern DI (2000) A multivariate cointegration analysis of the role of energy in the U.S. macroeconomy. Energy Econ 22(2):267–283. https://doi.org/10.1016/S0140-9883(99)00028-6

Stern DI (2004) The rise and fall of the environmental Kuznets curve. World Dev 32(8):1419–1439. https://doi.org/10.1016/j.worlddev.2004.03.004

Tang CF, Tan BW (2015) The impact of energy consumption, income and foreign direct investment on carbon dioxide emissions in Vietnam. Energy 79:447–454. https://doi.org/10.1016/j.energy.2014.11.033

Wang SS, Zhou DQ, Zhou P, Wang QW (2011) CO_2 emissions, energy consumption and economic growth in China: a panel data analysis. Energy Policy 39(9):4870–4875. https://doi.org/10.1016/j.enpol.2011.06.032

Wolde-Rufael Y (2012) Nuclear energy consumption and economic growth in Taiwan. Energy Sources Part B: Econ Plan Policy 7(1): 21–27

Yu ESH, Jin JC (1992) Cointegration tests of energy consumption, income, and employment. Resour Energy 14(3):259–266. https://doi.org/10.1016/0165-0572(92)90010-E

Zhang XP, Cheng XM (2009) Energy consumption, carbon emissions, and economic growth in China. Ecol Econ 68(10):2706–2712. https://doi.org/10.1016/j.ecolecon.2009.05.011

Zhang C, Xu J (2012) Retesting the causality between energy consumption and GDP in China: evidence from sectoral and regional analyses using dynamic panel data. Energy Econ 34(6):1782–1789. https://doi.org/10.1016/j.eneco.2012.07.012

Zivot E, Andrews D (1992) Further evidence of great crash, the oil price shock and unit root hypothesis. J Bus Econ Stat 10:251–270