Economic Analysis and Policy 69 (2021) 182–194

Contents lists available at ScienceDirect

Economic Analysis and Policy

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

Energy

The nexus between CO_2 emissions, energy consumption, and economic growth in the U.S.

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ARTICLE INFO

Article history:
Received 1 August 2020
Received in revised form 7 December 2020
Accepted 7 December 2020
Available online 9 December 2020

JEL classification:
Q01
Q20
Q30
Q53
E20

Keywords:
CO_2 emissions
Climate change
Economic output
GDP
Energy consumption
Renewable energy

ABSTRACT

This study investigates the relationship between carbon dioxide (CO_2) emissions, energy consumption, and economic growth (GDP) in the U.S. at the state level during 1997–2016. This study uses various quantitative approaches including static models as well as dynamic models to measure the impacts of GDP and different types of energy consumption including total, non-renewable, renewable, industrial, and residential energy on CO_2 emissions across states. Results show that a long-run relationship exists among various types of energy consumption and CO_2 emissions at the state level for both static and dynamic models. Total, non-renewable, industrial, and residential energy consumption have a positive impact on CO_2 emissions, while renewable energy consumption has a negative relationship with CO_2 emissions. The findings show an inverted-U shape relationship between CO_2 emissions and GDP which provides enough evidence to validate the Environmental Kuznets Curve (EKC) hypothesis across states. The results are robust across states using both static and dynamic models. Policy makers may use our findings to define applicable polices to reduce CO_2 emissions across U.S. states.

1. Introduction

Sustainable economic growth is the main target of economic policy in most countries around the world. However, economic growth may impact global warming and climate change which are the main global issues and concerns. Economic development and civilization resulted in raising the level of carbon dioxide (CO_2) emissions and other greenhouse gas emissions (GHG) in the atmosphere (Ahmad et al., 2016). Generally, there is a main consensus in the literature that exists regarding the relationship between CO_2 emissions, energy consumption, and economic output (GDP). This view suggests that energy is a vital and necessary resource input factor in the production process along with other factors such as land, labor, capital, and entrepreneurship. Thus, energy consumption influences economic output (Ghali and El-Sakka, 2004). In this view, economic growth and energy consumption determine the level of CO_2 emissions which is the main contributor to GHG emissions (Kasman and Duman, 2015).

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https://doi.org/10.1016/j.eap.2020.12.007

The Environmental Kuznets Curve (EKC) hypothesis indicates that the level of CO_2 emissions will continue to rise until economic growth reaches a turning point, then the level of CO_2 emissions will decrease. An EKC curve displays an inverted U-shaped relationship between CO_2 emissions and economic growth/development. The main interpretation of the EKC curve indicates that promoting economic growth does not have any conflict with having a clean environment in the long run (Munir et al., 2020; Pablo-Romero et al., 2017; Turner and Hanley, 2011).

The Energy Information Administration (EIA) reports that renewable energy sources have been growing among developed and developing economies in order to strengthen new energy resources to reduce GHG (Inglesi-Lotz, 2016). Renewable energies have a vital role to reduce global CO_2 emissions in the long term. EIA reports that renewables are the fastest-growing energy sources, ones with increasing consumption by 3.0 percent each year (Apergis and Payne, 2010). Renewable energy sources are the main attention for policymakers and governments for several reasons: dependency on fossil fuels and specifically oil consumption, depletion of non-renewable energy, and the environmental damage regarding ever-increasing consumption of fossil fuels. One notable example in this regard is the United States which aims to increase the production of renewable energy compared to non-renewable energy in long run. Therefore, investigating the impact of various types of energy consumption including renewable and non-renewable energy consumption on CO_2 emissions is vital for policymakers.

The United States is the second[1] highest contributor to CO_2 emissions by 14% of total CO_2 emissions in the world in 2017 (Muntean et al., 2018). The level of U.S. GHG varies among states due to existing different characteristics, regulations, energy consumption, production, and economic growth across states. Thus, understanding CO_2 mitigation policies and those factors that affect CO_2 emissions are crucial for policymakers (Javid et al., 2014, 2017, 2019). Moreover, many states are bigger than some countries in comparison to their population, energy consumption, production, and economic growth (Salari and Javid, 2016). According to the EIA, energy-related CO_2 emissions varies from 3.8 million tons for the District of Columbia to 105.4 million tons for Wyoming in 2017. Additionally, total energy consumption per capita in the United States including renewable and non-renewable energy consumption is 300.9 Million Btu (MBTU) in 2016, which varies from 176 MBTU in Rhode Island to 897.4 MBTU in Louisiana. Moreover, real GDP per capita varies among the states, therefore, Washington, D.C. has the highest rank by \$159,219 and Mississippi has the lowest rank by \$32,338 in 2016.[2] To show a visual cross-sectional correlation between these variables, Fig. 1 Shows the relationship between total energy consumption and CO_2 emissions per capita across U.S. states.

The relationship between economic growth and CO_2 emissions has been investigated empirically over the last decades. However, the relationship remains controversial among scholars and policymakers. This study aims to empirically estimate CO_2 emissions per capita across states based on the total energy consumption and economic growth of each state as the main explanatory variables. To this end, this study uses rich panel datasets from 1997 to 2016 at the state level to estimate the potential determinants of CO_2 emissions using static and dynamic panel estimation models.

This study has several main contributions to the literature. First, most of the previous literature concentrated on the country-level data and exploited time series techniques while this study implements some panel data empirical strategy and focuses on the state-level data. In other words, while most of the previous studies showed the nexus for data outside of the U.S., we return our focus to U.S. states. Specifically, a series of static models (which includes state and year fixed effects), as well as dynamic models (GMM techniques), are implemented. Therefore, this is the first study to estimate the determinants of CO_2 emissions in the U.S. using panel data at the state level. Second, this study uses various types of energy including total, renewable, non-renewable, industrial, and residential energy consumption to estimate the impact of energy consumption on CO_2 emissions. This a novel approach when we use a panel of US states rather than countries. Third, this study uses both static and dynamic estimation models to estimate CO_2 emissions which allows us to evaluate the robustness of the results. Fourth, this study examines the EKC hypothesis to find the relationship between economic output and CO_2 emissions across states. Therefore, this is the first study to validate the EKC hypothesis across states within the US.

The results of this paper suggest three avenues for policymakers and authorities. First, at the state level, non-renewable, industrial, and residential energy consumption raise CO_2 emissions and generate pollution even after controlling for GDP per capita. Therefore, policies aimed to reduce pollution are required to make a trade-off between these types of energy consumption and their associated rise in production. Second, the fact that EKC holds across US states implies that at higher levels of economic development, an increase in production has the potential to reduce pollution. Another importance of the findings of this paper for policymakers is that an increase in renewable energy consumption has the potential to reduce CO_2 emissions. Therefore, any policy that aims to reduce emissions can consider plans to encourage renewable energy production and consumption.

The rest of the study is organized as follows: Section 2 provides a literature review. Section 3 introduces a theoretical framework. Section 4 describes the methodology and data. Section 5 presents the main results. We depart some concluding remarks in Section 6.

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[1] China is responsible for 28% of total GHG in 2017.

[2] The real GDP per capita for the United States was \$51,688 in 2016.

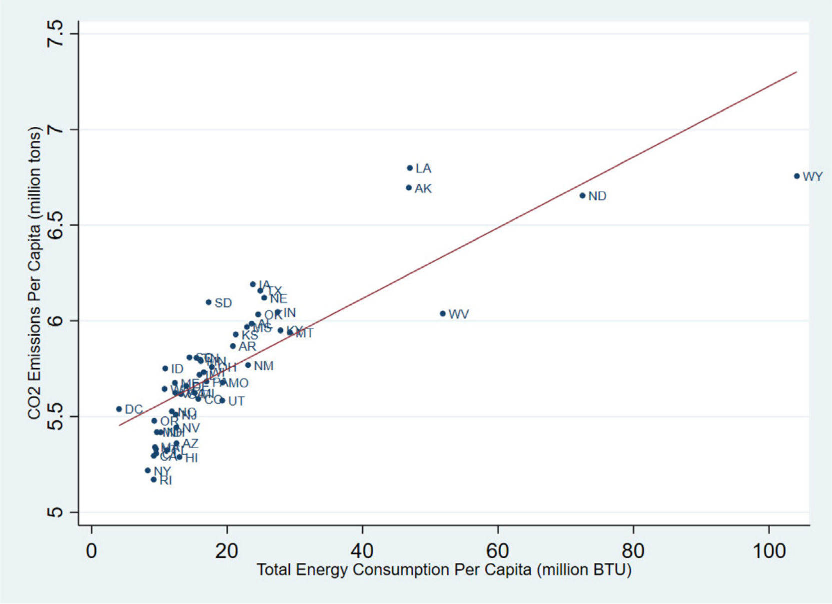

Fig. 1. Relationship between total energy consumption and CO_2 emission per capita across U.S. states in 2016.

2. Literature review

Global warming and climate change are the most important environmental issues around the world in the last decades. GHG and especially CO_2 emissions are responsible to be the main cause of global warming and climate change (Esso and Keho, 2016; Soytas and Sari, 2009).[3] The relationship between climate change, energy consumption, and sustainable economic growth has received the attention of many scholars and policymakers recently. Some economists and policymakers believe that environmental regulations and policies impose constraints on the production possibilities set and it may potentially hurt economic growth in the long-term (Ricci, 2007). A strand of literature in economics investigates the nexus between economic development, energy consumption, and pollution. For instance, Adedoyin et al. (2020a,b) study the effect of coal consumption and coal rent as well as economic growth on CO_2 emissions among BRICS (Brazil, Russia, India, China, and South Africa) countries. Applying time series techniques, they conclude that in order to reach a green and sustainable growth path a series of environmental-related regulations are inevitable. In another study, Bekun et al. (2019b) explore the relationship between energy consumption, CO_2 emissions, and economic growth using annual data from South Africa to validate the energy-led growth hypothesis.

Sheng et al. (2020) investigate the coupling between economic growth and carbon emissions across provinces of China for both short-run and long-run horizons. They find a positive short-run coupling between the two variables across provinces at low and high stages of development while a negative coupling for provinces that are in the intermediate economic development scale. Ehigiamusoe et al. (2020) explore the moderating effect of energy consumption on the nexus between carbon emission and income across 64 middle-income countries. They find no evidence to support the hypothesis of the moderating effect of energy consumption. Awodumi and Adewuyi (2020) explore the role of non-renewable energy consumption in economic growth and carbon emissions across oil-producing African countries and find inconclusive and asymmetric effects. While for some countries energy consumption leads to higher emissions in other countries leads to better environmental quality. In another study, Sun et al. (2020) show that economic production, energy usage, trade openness, and urbanizations are the main contributors to carbon emission for a panel of countries over the years 1992–2015. Some recent studies also emphasize the role of energy consumption and urbanization as well as economic growth on carbon emissions (Abbasi et al., 2020; Adedoyin and Zakari, 2020; Dehghan Shabani and Shahnazi, 2019; Hanif et al., 2019; Khoshnevis Yazdi and Dariani, 2019; Raza et al., 2019; Salazar-Núñez et al., 2020; Wang and Dong, 2019; Wasti and Zaidi, 2020; Wu et al., 2020; Zhang et al., 2019).

Ang (2007) examines the existing dynamic relationship between CO_2 emissions, energy consumption, and output for France using panel data from 1960–2000. She argues that economic growth exerts a causal influence on energy consumption growth as well as CO_2 emissions growth in the long term. Jorgenson and Wilcoxen (1993) use intertemporal general equilibrium modeling to demonstrate the relationship between energy, environment, and economic growth. Coondoo and Dinda (2002) study the Granger Causality relationship between economic growth and CO_2 emissions and

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[3] For studies on the potential health effects of climate change and pollution, refer to NoghaniBehambari et al. (2020), Tavassoli et al. (2020a,b).

found existing various types of causal relationships among different country groups. Zhang and Cheng (2009) examine the existence and direction of Granger between economic growth, energy consumption, and CO_2 emissions in China using data from 1960–2007. They suggest that energy consumption is increasing CO_2 emissions in the long run, while neither CO_2 emissions nor energy consumption causes economic growth. Several studies show the relationship between economic output and CO_2 emissions is an inverted U-shaped relationship. This inverted U-shaped relationship is defined as the Environmental Kuznets Curve (EKC), accordingly EKC hypothesis indicates that economic growth resulted in a gradual degradation of the environment for low-level income regions while increasing economic growth leads to improve environmental conditions after a certain level of growth (Galeotti et al., 2006; Jalil and Feridun, 2011; Jalil and Mahmud, 2009; Jayanthakumaran et al., 2012; Li et al., 2016; Martínez-Zarzoso and Bengochea-Morancho, 2004).

Adedoyin et al. (2020a,b) investigate the effect of climate change protests on CO_2 emissions and find that these protests have a positive effect only in a subset of countries, namely Europe and Asia. In another study, Bekun et al. (2019a) show the co-integration between natural resource rent, energy consumption, economic development, and CO_2 emissions. They find that economic growth and non-renewable energy consumption increase the level of CO_2 emissions, while the consumption of renewable energy will decrease CO_2 emissions.

A relatively large literature establishes the EKC hypothesis. For example, Agboola and Bekun (2019) investigated the long-term relationship between energy consumption and economic growth for the case of an agrarian economy. They confirm the inverted U-shaped pattern of EKC in Nigeria over the years 1981–2014. Similar papers find similar conclusion and document this pattern in the case of other countries (Dasgupta et al., 2002; Destek and Sarkodie, 2019; Katircioğlu and Katircioğlu, 2018; Kotroni et al., 2020; Rashid Gill et al., 2018; Shahbaz and Sinha, 2019; Stern, 2004).

Soytas and Sari (2009) examine the long-run causality between CO_2 emissions, energy consumption, and economic growth in Turkey. They show that there is no evidence to support the existing relationship between CO_2 emissions and economic growth, while they report that energy consumption resulted in having CO_2 emissions. Pao and Tsai (2010) explore the dynamic causal relationship between CO_2 emissions, energy consumption, and output for a panel of BRIC countries from 1971–2005. They find that energy consumption has a positive impact on CO_2 emissions in the long-run equilibrium, while output displays the inverted U-shape pattern with CO_2 emissions. Ito (2017) shows that renewable energy consumption positively contributes to economic growth and reduces CO_2 emissions in the long term, while non-renewable energy consumption resulted in a negative impact on economic growth. Her results suggest that policymakers should invest in the renewable energy sector due to its positive impact on economic growth and negative impacts on CO_2 emissions. Menyah and Wolde-Rufael (2010) examine the causal relationship between CO_2 emissions, GDP, and renewable energy consumption specifically nuclear energy consumption in the U.S. from 1960 to 2007. They report no causality exists between nuclear energy consumption and GDP and show nuclear energy consumption can help to reduce CO_2 emissions.

To the best of our knowledge, there is no study at the state level to estimate CO_2 emissions that explain the heterogeneity issue across U.S. states, a key factor for determining policy changes.

3. Theoretical framework

In this section, we introduce a utility-based economic model in order to support the econometric framework and the link between economic development, energy consumption, and pollution. We extend the utility maximization model of McConnell (1997) and Andreoni and Levinson (2001) and assume that utility of agents is derived from the consumption of a composite good X and is negatively affected by pollution and specifically CO_2 emissions C. The production of composite good requires energy consumption. Therefore, the main channel between pollution and energy consumption is the use of energy in production of intermediate and final goods. Besides, there are efforts in the economy for pollution abatement that bears costs to every individual. These abatements can be denoted by A. The emission is an increasing function of consumption and a decreasing function of abatements. The output of each individual, Y, is allocated to consumption, X, and pollution abatements, A. Each individual maximizes the utility ($U(X, C)$) subject to the resource constraint ($X+A = Y$) and the production function of pollution ($C(X, A)$). Following Andreoni and Levinson (2001), we simplify this model and assume a linear utility function as follows:

$$U = X - C \tag{1}$$

Production of pollution and emission is positively affected by consumption and decreases by the level of abatement efforts. It is assumed to be given by:

$$C = X - X^{\gamma} A^{\zeta} \tag{2}$$

Maximizing the utility function subject to budget constraint and pollution function reveals the following optimum consumption and abatement levels:

$$X^{*} = \frac{\gamma}{\gamma + \zeta} Y, \quad A^{*} = \frac{\zeta}{\gamma + \zeta} Y \tag{3}$$

Given these optimal values, we can find the level of pollution:

$$C = \frac{\gamma}{\gamma + \zeta} Y - \left(\frac{\gamma}{\gamma + \zeta}\right)^{\gamma} \left(\frac{\zeta}{\gamma + \zeta}\right)^{\zeta} Y^{\gamma+\zeta} \tag{4}$$

Differentiating Eq. (4) with respect to income (Y) yields:

$$\frac{\partial C}{\partial Y}=\frac{\gamma}{\gamma+\zeta}-(\gamma+\zeta)\left(\frac{\gamma}{\gamma+\zeta}\right)^{\gamma}\left(\frac{\zeta}{\gamma+\zeta}\right)^{\zeta}Y^{\gamma+\zeta-1} \tag{5}$$

As income starts at low values the slope of pollution-income is positive and at higher levels of income, the slope becomes negative. Therefore, regardless of the shape of the production function, an inverted-U function is established. The higher levels of income lead to higher efforts for abatement and through this channel the higher economic development leads to lower pollution. We provide evidence of this inverted-U relationship in our empirical section.

4. Methodology and data

This study analyzes the relationship between CO_2 emissions, energy consumption (total, non-renewable, renewable, industrial, and residential), and economic output at the state level using annual data from 1997 to 2016.[4] This study uses the annual data at the state level for all 50 U.S. states and the District of Columbia. The CO_2 emissions per capita are measured in metric tons and are obtained from EIA. The real GDP of the states is measured in ten thousand and is converted into 2009 dollars to reflect real values. Data for GDP, total energy consumption, non-renewable energy consumption, renewable energy consumption, industrial energy consumption, and residential energy consumption (measured in thousands of British thermal units per capita) are obtained from the U.S. EIA (2016). Table 1 presents a statistical summary associated with the actual values of variables from 1997 to 2016. Also, Table A.1 provides more detailed information for the summary statistics at the state level. Roughly 90 percent of total energy consumption is due to non-renewable energy consumption while only 9 percent attributes to renewable energy consumption. Compared to the mean of variables, standard deviations are large. This variation is more conspicuous when we look at individual states. For instance, CO_2 emissions per capita varies from 5 metric tons in Washington DC to around 120 metric tons for Wyoming. Total energy consumption per capita varies from 192 for Rhode Island to roughly 1026 for Alaska (measured in thousands of British thermal units per capita).

This study employs various static and dynamic estimation models to measure the impact of explanatory variables on CO_2 emissions at the state level. The statistic estimation models use various ordinary least squares (OLS) models with different specifications to overcome unobserved heterogeneity issues across states.

The choice of a static model that controls for state and year effects is a good starting point in this setting for two main reasons. First, it enables the reader to compare the emission changes in states with higher economic growth compared to states with lower economic growth across years. This comparison acts as a generalized difference-in-difference model. The second advantage lies in the functionality of fixed effects in a static model. Including state fixed effects rules out any unobservable factors that are associated with states and are not evolving by time. In the same manner, adding year fixed effects controls for any time trend features that are common across states. For example, the national-level changes in trade policies that may affect both CO_2 emissions and economic growth as well as energy consumption can be controlled by adding year fixed effects.

However, static estimation models may bias due to structural and statistical endogeneity (unobserved heterogeneity). Although fixed effects account for unobservable factors that are constant by state or by year, they cannot control for unobservable differences across states that also vary by time. For this reason, a dynamic model is preferred. Thus, this study employs various generalized method of moments (GMM) estimators as the main dynamic models to estimate CO_2 emissions at the state level. Building upon the theoretical model introduced in Section 3, we relate the emission to energy consumption and GDP per capita using the following general formula:

$$C=f(E,Y,Y^2) \tag{6}$$

Where, consistent with our theoretical model, C is CO_2 emissions per capita, E is energy consumption per capita, and Y is GDP per capita of each region. The main aim of this study is to examine the causal relationship between energy consumption, GDP, and CO_2 emissions.

This study uses a set of static panel estimation models to estimate CO_2 emissions across U.S. states. The following static model uses to estimate CO_2 emissions at the state level:

$$\ln(\mathrm{CO}_{2it})=\alpha_0+\alpha_1\ln\left(E_{it}^{k}\right)+\alpha_2 ln\left(GDP_{it}\right)+\alpha_3 ln\left(GDP_{it}\right)^2+\varepsilon_{it1} \tag{7}$$

Where CO_{2it} is a measure of CO_2 emissions per capita in state i at time t.[5] E_{it}^{k} is a measure of energy consumption per capita in state i for energy type k,[6] GDP_{it} is real GDP per capita, GDP_{it}^{2} is the square of real GDP per capita, α_0 is a constant term and ε_{i1} is the error term. All variables in the model are used in their logarithmic values. This static model may include a time fixed effect or state fixed effect.

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[4] The longest period of time that data for all variables are available.

[5] From year 1997 to 2016.

[6] Total, non-renewable, renewable, industrial, and residential energy consumption.

Table 1
Summary of variables and descriptive statistics from 1997 to 2016.

Variables	Observations	Mean	Std. Dev.	Min	Max
CO_2 emissions	1,020	24.05	19.44	4.03	129.2
Total energy	1,020	370.77	174.72	174.7	1196
Non-renewable energy	1,020	336.01	172.28	121.61	1172.16
Renewable energy	1,020	34.75	38.14	0.46	204.57
Industrial energy	1,020	133.14	127.27	6.2	699.1
Residential energy	1,020	73.35	12.82	21.9	106.1
GDP per capita	1,020	47.47	17.69	28.26	170.76

Table 2
Unit root tests.

	Unit root L–L–C		Unit root H–T	
	Statistics	P-Value	Statistics	P-Value
Log CO_2	4.56	1.00	0.95	1.00
Log total energy	−0.74	1.00	0.90	0.98
Log GDP per capita	−7.68***	0.00	0.88	0.92
Log Non-renewables energy	2.85	0.90	−0.29	0.38
Log renewables energy	−0.29	0.38	0.93	0.99
Log residuals energy	1.53	0.93	0.67***	0.00
Log industrial energy	−5.28***	0.00	0.86	0.65

***Indicates significance at 10% level.

This study uses dynamic panel estimation models to address the endogeneity issue while estimating CO_2 emissions at the state level. The CO_2 emissions are estimated by using the system GMM estimators including (GMM-BB) (Blundell and Bond, 1998) and (GMM-AB) (Arellano and Bond, 1991), while GMM-BB estimators employ Monte Carlo analysis which is more preferable to other dynamic estimators. Therefore, this study employs the following dynamic panel estimation models to obtain CO_2 emissions at the state level:

$$\ln(CO_{2it}) = \beta_0 + \beta_1 \ln(CO_{2i,t-1}) + \beta_2 \ln\left(E_{it}^k\right) + \beta_3 ln\,(GDP_{it}) + \beta_4 ln\,(GDP_{it})^2 + \varepsilon_{it2} \tag{8}$$

$$\ln(CO_{2it}) = \gamma_0 + \gamma_1 \ln(CO_{2i,t-1}) + \gamma_2 \ln(CO_{2i,t-2}) + \gamma_3 \ln\left(E_{it}^k\right) + \gamma_4 ln\,(GDP_{it}) + \gamma_5 ln\,(GDP_{it})^2 + \varepsilon_{it3} \tag{9}$$

The GMM dynamic models can be one-step system GMM models and two-step GMM models with one lag (Eq. (8)) or two lag (Eq. (9)). The one-step models assume that independent and homoscedastic error terms variance exists across states and times, while two-step system GMM models employ residuals of the first-step estimation to estimate the variance–covariance matrix when there is no assumption for independency and homoscedasticity of error terms (Salari and Javid, 2019, 2016). In order to have the EKC hypothesis to be true, one would expect that the sign of GDP coefficient is positive, meanwhile, the sign of GDP square is negative in the model and both are statistically significant.

5. Empirical results

This section shows the empirical results of both static panel estimation models and dynamic estimation models. Before reporting the results, we check for the possibility of the existence of a unit root in the main variables. In so doing, we use two widely implemented unit root tests: the LLC (Levin–Lin–Chu) unit root test that was first introduced by Levin et al. (2002), and the HT (Harris–Tzavalis) unit root test that was built by Harris and Tzavalis (1999). These results are reported in Table 2. As the statistics and p-values show, there is no consistent and significant evidence that any of the main variables used in this study contain a unit root.

5.1. Static panel estimation models

Table 3 shows OLS regression models with different specifications to estimate CO_2 emissions using total energy consumption per capita and GDP per capita as the main explanatory variables. Columns 1–4 indicate that total energy consumption per capita and GDP per capita at the state level have positive impacts on CO_2 emissions. The results are consistent when applying various time fixed effects and state fixed effects. Regarding the fixed effect model results, all variables are statistically significant at 1% level and signs of the coefficients imply an inverted U-shape relationship between GDP per capita and CO_2 emissions as was predicted by the theoretical framework in Section 3. Therefore, the EKC hypothesis is valid for all static models. The panel elasticity of CO_2 emissions with respect to GDP per capita in the long run for model 4 can be formulated as $\frac{\partial LCO_2}{\partial LGDP} = 3.333 - 0.864 \times \text{LGDP}$. The result implies that the turning point of the EKC occurs at an income level of 3.86[7] (=3.333/0.86, in logarithms), equivalent to 47,798 thousand dollars (in 2009 real dollars). Column 4 shows the most comprehensive static model using both year fixed effects and state fixed effects.

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[7] It is reported based on ten thousands dollars.

Table 3
OLS regression models with different specification models.

Variables	(1)	(2)	(3)	(4)
Total energy	1.315***	1.309***	1.128***	0.670***
	(0.128)	(0.130)	(0.104)	(0.0844)
GDP	4.085**	4.191**	2.434**	3.333***
	(1.732)	(1.899)	(0.964)	(0.645)
GDP^2	−0.563***	−0.575**	−0.367***	−0.432***
	(0.197)	(0.216)	(0.121)	(0.0809)
Constant	−12.04***	−12.24***	−7.489***	−7.045***
	(3.995)	(4.314)	(2.137)	(1.480)
Year fixed effects	NO	YES	NO	YES
State fixed effects	NO	NO	YES	YES
Observations	1,020	1,020	1,020	1,020
R-squared	0.789	0.791	0.990	0.994
Cross-sectional independence test statistics:				
Pesaran's statistics [P-Value]	–	−2.47** [0.013]	36.42*** [0.00]	−2.51** [0.018]

Note: Values in parentheses below coefficients are standard errors.
**Indicate significance at 5% level.
***Indicate significance at 1% level.

Referring to the full specification model (column 4), conditional on fixed effects and covariates, doubling the total energy usage (an increase of 100 percentage) is associated with a 67 percentage rise in CO_2 emissions. To put these numbers into perspective, we use the mean and standard deviations reported in Table 1. An increase of one standard deviation from the mean of total energy consumption, equivalent to 47 percentage change, is associated with 0.38 standard deviation increase from the mean of CO_2 emission, equivalent to 31 percentage change. The comparison is more intuitive when we return our focus to state level energy consumption data. For instance, Rhode Island has the lowest per capita energy consumption while Alaska has the largest (refer to Appendix Table A.1). If Alaska reduces energy consumption down to the per capita levels of Rhode Island, a reduction equivalent to 81 percentage change, the estimations of column 4 suggest that CO_2 emissions will diminish by almost 54 percentage points. This reduction will close the gap of CO_2 emissions between the two states by almost 60 percent. Therefore, the coefficients are not only statistically significant but also economically meaningful and large.

Next, we implement the same approach as column 4 of Table 4 and instead of total energy consumption, we use other types of energy including total, non-renewable, renewable, industrial, and residential energy consumption as the main explanatory variables. Table 4 reports the static analysis using various energy consumption to estimate CO_2 emissions at the state level. The findings indicate that all energy consumption except renewable energy consumption increases the level of CO_2 emissions at the state level. Thus, energy consumption for all types of energy except renewable energy has a positive and statistically significant impact on the CO_2 emissions at the state level. Moreover, GDP per capita has a positive impact on CO_2 emissions while GDP square per capita has a negative impact on the level of CO_2 emissions at the state level which supports the EKC hypothesis.

Non-renewable energy consumption has the most impact on CO_2 emissions. Conditional on fixed effects and covariates, a 10 percentage rise in non-renewable energy consumption is associated with a 6.24 percentage increase in CO_2 emissions while the same increase in residential or industrial consumption is associated with 2.99 and 1.60 percentage rise in CO_2 emissions, respectively (columns 5 and 4). To put these numbers into perspective, an increase of one standard deviation from the mean of non-renewable, industrial, and residual energy consumption increases CO_2 emissions by 4.2, 2.9, and 1.5 percentage, respectively. These rises in pollution can be translated into a rise of 0.16, 0.10, and 0.03 standard deviation from the mean of CO_2 emissions.

As expected, renewable energy consumption does not have a significant impact on CO_2 emissions. and the coefficient in column 3 is statistically insignificant.

5.2. Dynamic panel estimation models

Static estimation models may not be appropriate to measure and capture economic outcomes while using panel data. Therefore, this study uses dynamic panel estimation models to estimate and measure economic behaviors over time to address endogeneity issues more precisely. This section reports the empirical results of dynamic panel estimation models to estimate CO_2 emissions at the state level. Table 5 presents one-step dynamic system GMM models and two-step dynamic system GMM models to estimate CO_2 emissions using total energy consumption as the main explanatory variable while controlling for GDP per capita. All the models suggest that total energy consumption and GDP per capita have strong positive effects on CO_2 emissions while GDP square per capita has a statistically negative impact on CO_2

Table 4
Static analysis and various energy types.

Variables	(1)	(2)	(3)	(4)	(5)
Total energy	0.670^{***} (0.0844)				
Non-renewable energy		0.624^{***} (0.107)			
Renewable energy			0.022 (0.0196)		
Industrial energy				0.160^{***} (0.0391)	
Residential energy					0.299^{***} (0.0930)
GDP	3.333^{***} (0.645)	3.582^{***} (0.698)	4.450^{***} (0.514)	4.603^{***} (0.852)	4.191^{***} (0.548)
GDP^2	-0.432^{***} (0.0809)	-0.448^{***} (0.0880)	-0.524^{***} (0.0639)	-0.562^{***} (0.104)	-0.495^{***} (0.0689)
Constant	-7.045^{***} (1.480)	-7.326^{***} (1.635)	-5.800^{***} (1.020)	-6.657^{***} (1.635)	-6.468^{***} (1.151)
Year fixed effects	YES	YES	YES	YES	YES
State fixed effects	YES	YES	YES	YES	YES
Observations	1,020	1,020	1,020	1,020	1,020
R-squared	0.994	0.993	0.990	0.992	0.991
Cross-sectional independence test statistics:					
Pesaran's statistics [P-Value]	-2.51^{***} [0.01]	-2.42^{***} [0.01]	-2.94^{***} [0.003]	-2.63^{***} [0.008]	-2.97^{***} [0.002]

Note: Values in parentheses below coefficients are standard errors.
***Indicates significance at 1% level.

Table 5
Results of dynamic models for total energy consumption.

	One-Step System GMM		Two-Step System GMM	
Variables	(1)	(2)	(3)	(4)
$(CO_2)_{t-1}$	0.525^{***} (0.0210)	0.473^{***} (0.0279)	0.515^{***} (0.0130)	0.466^{***} (0.0127)
$(CO_2)_{t-2}$		0.0603^{**} (0.0238)		0.0514^{***} (0.00810)
Total energy	0.833^{***} (0.0318)	0.829^{***} (0.0318)	0.863^{***} (0.0238)	0.871^{***} (0.0235)
GDP	2.122^{***} (0.548)	1.835^{***} (0.574)	2.800^{***} (0.893)	2.115^{***} (0.557)
GDP^2	-0.306^{***} (0.0717)	-0.272^{***} (0.0749)	-0.394^{***} (0.117)	-0.307^{***} (0.0731)
Constant	-7.067^{***} (1.062)	-6.481^{***} (1.114)	-8.514^{***} (1.791)	-7.223^{***} (1.127)
Observations	918	867	918	867
Wald chi2	7557.74	7494.85	8086.48	7832.54
Sargan test [P-Value]	494.82^{***} [0.00]	498.67^{***} [0.00]	48.61 [1.00]	46.61 [1.00]
Arellano–Bond Test:				
Order 1 [P-Value]			-4.70^{***} [0.00]	-4.56^{***} [0.00]
Order 2 [P-Value]			−0.74 [0.45]	−1.09 [0.27]

Note: Values in parentheses below coefficients are standard errors.
**Indicate significance at 5% level.
***Indicate significance at 1% level.

emissions. All models confirm that the positive sign of GDP per capita and negative sign of GDP square per capita as expected, supporting the EKC hypothesis. Moreover, both one lagged CO_2 emissions and two lagged CO_2 emissions are statistically significant to explain the level of CO_2 emissions at the state level.

Table 6
Results of two-step system GMM models for different types of energy.

Variables	(1)	(2)	(3)	(4)	(5)
$(CO_2)_{t-1}$	0.466***	0.401***	0.748***	0.694***	0.725***
	(0.0127)	(0.0106)	(0.0117)	(0.0187)	(0.0118)
$(CO_2)_{t-2}$	0.0514***	0.0502***	0.107***	0.142***	0.0757***
	(0.00810)	(0.00670)	(0.00909)	(0.0126)	(0.00966)
Total energy	0.871***				
	(0.0235)				
Non-renewable		0.717***			
		(0.0159)			
Renewable			−0.0564***		
			(0.00396)		
Industrial				0.218***	
				(0.00663)	
Residential					0.384***
					(0.0151)
GDP	2.115***	1.688***	1.739*	1.834***	1.618**
	(0.557)	(0.385)	(0.951)	(0.421)	(0.742)
GDP^2	−0.307***	−0.234***	−0.232*	−0.251***	−0.236**
	(0.0731)	(0.0502)	(0.125)	(0.0551)	(0.0965)
Constant	−7.223***	−5.496***	−2.653	−3.830***	−3.783**
	(1.127)	(0.745)	(1.823)	(0.796)	(1.469)
Observations	867	867	867	867	867
Wald chi2	7832.54	24073.67	126869.58	6851.03	13392.34
Sargan Test [P-Value]	46.61 [1.00]	48.28 [1.00]	50.92 [1.00]	50.08 [1.00]	49.86 [1.00]
Arellano–Bond Test:					
Order 1 [P-Value]	−4.56*** [0.00]	−4.57*** [0.00]	−5.63*** [0.00]	−5.50*** [0.00]	−5.18*** [0.00]
Order 2 [P-Value]	−1.09 [0.27]	−2.19** [0.02]	−3.59*** [0.00]	−3.30*** [0.00]	−1.55 [0.11]

Note: Values in parentheses below coefficients are standard errors.
*Indicate significance at 10% level.
**Indicate significance at 5% level.
***Indicate significance at 1% level.

Additionally, the results of GMM models (for both one-step and two-step) are quite similar to those of static models. For instance, a 10 percentage rise in total energy consumption is associated with an 8.71 percentage rise in CO_2 emissions (compared to 6.70 for the static model). In the preferred model of two-step GMM (column 4), the elasticity of CO_2 emissions with respect to GDP per capita, in the long run, can be calculated as $\frac{\partial LCO_2}{\partial LGDP} = 2.115\text{-}0.307 \times LGDP$. This equation implies that the turning point of the EKC occurs at an income level of 6.889 (=2.115/0.307, in logarithms).

Next, we use the preferred GMM model (the two-step of column 4 of Table 5) and estimate CO_2 emissions as a function of various types of energy consumption. Table 6 reports the results of the two-step system GMM model using two lagged values of the dependent variable to explore the effect of different types of energy consumption. All energy consumption including total, non-renewable, industrial, residential energy consumption except renewable energy consumption have a positive impact on CO_2 emissions at the state level. However, renewable energy consumption has a statistically negative impact on CO_2 emissions. Thus, using renewable energy consumption as the main source of energy is encouraged at the state level due to its impact on the level of CO_2 emissions. In all models, the EKC hypothesis is confirmed and validated.

The results of Table 6 can also be compared to the static model reported in Table 3. For instance, a 10 percentage change in non-renewable, industrial, and the residential energy consumption is associated with 7.1, 2.2, and 3.8 percentage change in CO_2 emissions, respectively, which are comparable with those implied marginal effects of 6.2, 1.6, and 2.9 reported in Table 4. The interesting distinction is the marginal effects of renewable energy consumption in column 3. While the static models imply that there is no statistically and economically significant relationship between renewable energy consumption and CO_2 emissions, the results of the dynamic model imply a negative correlation. Although its magnitude is relatively small compared to the marginal effects of other types of energy consumption, it is strongly significant at 1% level. For example, a 10 percentage rise in renewable energy consumption is associated with a 0.56 percentage reduction in CO_2 emissions.

Moreover, we report the results for Sargan tests and Arellano–Bond tests after each GMM estimations at the bottom of Tables 4 and 5. The statistics and their respective p-values strongly reject the overidentification restriction assumptions and suggest that Two-Step estimations are preferred to One-Step GMM models.

Table A.1
Summary of statistics at the state level.

State	CO_2	Total energy	Non-renewable energy	Renewable energy	Industrial energy	Residential energy	GDP
AK	60.93	1026.03	1002.18	23.90	544.15	76.84	64.36
AL	28.75	428.72	369.21	59.49	190.68	80.47	35.49
AR	22.42	391.62	349.50	42.09	153.36	80.46	34.13
AZ	15.36	233.32	214.35	18.98	37.77	59.85	39.46
CA	10.18	218.81	196.73	22.07	53.47	40.23	51.34
CO	18.94	291.24	277.63	13.61	79.90	67.55	50.34
CT	11.11	228.34	216.78	11.56	29.39	73.33	62.98
DC	5.93	312.67	310.90	1.77	8.61	62.55	155.80
DE	17.00	332.84	327.80	5.05	111.15	76.22	65.07
FL	13.30	232.00	219.05	12.95	29.45	66.52	39.58
GA	17.74	322.31	295.58	26.72	92.68	75.68	44.24
HI	15.21	220.42	205.52	14.88	54.07	24.92	47.95
IA	27.16	446.33	375.33	70.99	205.51	79.22	44.51
ID	10.76	355.15	258.70	96.46	127.83	78.67	34.36
IL	18.02	312.87	300.73	12.14	96.72	76.85	50.54
IN	34.37	449.75	435.02	14.72	207.22	85.39	42.35
KS	25.84	394.16	373.70	20.46	138.59	82.51	42.92
KY	33.86	442.26	425.80	16.45	186.86	86.43	37.30
LA	50.30	929.30	896.99	32.29	628.52	78.81	44.50
MA	11.63	223.41	213.21	10.19	32.55	66.57	58.23
MD	12.83	257.75	247.10	10.67	40.07	73.81	50.59
ME	15.09	336.06	217.11	118.91	123.08	71.12	37.55
MI	17.71	298.71	283.95	14.76	80.84	78.90	41.10
MN	18.25	349.90	318.20	31.70	117.95	75.54	49.81
MO	22.54	319.21	308.63	10.59	64.68	87.39	42.00
MS	21.66	403.68	380.84	22.84	143.95	76.93	30.77
MT	33.69	422.31	295.23	127.02	151.12	82.08	35.83
NC	15.70	288.84	270.04	18.81	72.29	76.04	43.22
ND	78.30	679.97	598.31	81.56	340.03	96.11	48.08
NE	25.78	420.82	374.01	46.82	156.96	85.91	46.91
NH	13.39	236.24	202.16	34.08	36.28	68.51	46.97
NJ	13.59	283.52	277.28	6.23	42.31	67.65	54.98
NM	28.43	340.94	327.38	13.56	111.30	56.39	39.67
NV	16.97	269.40	247.05	22.34	71.44	61.69	47.87
NY	9.77	201.32	180.08	21.23	24.76	58.55	58.14
OH	21.59	340.73	331.76	8.97	116.00	80.39	43.76
OK	28.30	421.85	395.77	26.08	152.69	82.34	38.53
OR	10.80	281.63	161.81	119.83	76.06	66.84	43.84
PA	20.63	306.86	294.94	11.92	101.92	74.44	45.16
RI	10.73	192.24	187.11	5.13	26.84	60.83	44.75
SC	18.01	368.23	341.59	26.64	135.94	78.90	36.19
SD	17.80	401.09	285.40	115.71	134.75	82.50	42.17
TN	19.02	361.93	334.61	27.32	112.16	86.07	40.47
TX	29.39	521.27	508.79	12.48	275.72	67.65	47.41
UT	25.31	295.20	287.23	7.96	88.33	58.76	41.12
VA	14.86	315.88	298.76	17.11	67.31	78.92	49.92
VT	10.10	236.16	193.33	42.86	40.08	68.56	40.26
WA	11.57	319.30	176.19	143.10	91.27	74.12	52.00
WI	18.35	330.69	304.28	26.41	114.65	76.86	44.01
WV	57.70	407.29	388.86	18.44	166.15	86.36	33.89
WY	119.86	908.87	854.30	54.59	505.11	81.54	58.33
Total	24.05	370.77	336.02	34.75	133.14	73.35	47.47

6. Conclusion

Sustainable economic growth is the main target for most countries while it may cause more pollution in a given region. Global warming and climate change have already raised many concerns among policymakers and political elites, particularly for the U.S. which has the second-highest CO_2 emission ranking across countries.

This study analyzes the factors affecting CO_2 emissions in the U.S. using panel data at the state level from 1997 to 2016. This study measures the impact of various types of energy consumption and economic growth on the level of CO_2 emissions using various static and dynamic estimation models. The results indicate that total, non-renewable, industrial, and residential energy consumption per capita at the state level have a statistically positive impact on the level of CO_2 emissions, while interestingly renewable energy consumption has a negative impact on the level of CO_2 emissions. Therefore, shifting to renewable energy as the main source of energy compared to non-renewable energy will increases the growth process and enhance environmental quality. Moreover, the findings indicate that the EKC hypothesis is validated and there is enough evidence for both static and dynamic models that supports existing EKC across U.S. states.

The results of this paper have three important policy implications for state authorities and governments of other countries. First, regardless of the level of economic development, non-renewable, residual, and industry energy consumption leads to higher pollution. On the other hand, energy consumption is at the core of economic growth and output production. Therefore, policymakers need to use cost–benefit principles to find an optimum point for energy consumption. Using tax incentives or abatement efforts, authorities can then guide the economy towards the optimal level of energy consumption. Second, although an increase in income is correlated with higher levels of production which in turn leads to higher pollution, this channel will stop after a threshold for income and economic growth. The validation of EKC suggests that higher levels of economic development will eventually reduce pollution. This is an important finding for policymakers trying to find the optimum level of abatement efforts and designing tax incentives. For example, an optimum carbon tax is based on the benefits in terms of reductions in pollution and the costs in terms of reduction in output and GDP per capita. In designing the optimum policy, policymakers should take into account that after a threshold, the economic growth and economic development will reduce pollution without any policy intervention. Third, the results of the GMM suggest that renewable energy consumption does indeed decrease pollution even when we control for GDP per capita. This suggests an alternative way for energy consumption is using renewable energy consumption that is environmentally friendly. Policymakers who aim to reduce pollution may use various instruments such as tax incentives to encourage producers to switch to renewable energy sources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

See Table A.1.

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