RESEARCH ARTICLE

Testing the EKC hypothesis for the USA by avoiding aggregation bias: a microstudy by subsectors

Alper Aslan[1] · Oguz Ocal[2] · Baki Özsolak[3]

Abstract

The aim of this study is to examine the impact of foreign direct investments, economic growth, and energy consumption on carbon dioxide subcomponents in the case of the USA. Dynamic ARDL (DARDL) econometric method is used covering the period 1972–2020. In addition to the total CO_2 emission, the subcomponents of CO_2 emission are examined separately within the framework of the EKC hypothesis in the USA by avoiding aggregation bias for the first time. The CO_2 emission subcomponents used in the study are as follows; CO_2 emissions from liquid fuel consumption, residential buildings, and commercial and public services; electricity and heat production; and other sectors, excluding residential buildings and commercial and public services, and CO_2 emissions from transportation. Each CO_2 emission component is used as a dependent variable and 6 different models were created. Foreign direct investments, trade, and energy consumption are used as control variables. No results supporting the EKC hypothesis are determined in any model, except for model 1, where total CO_2 emission is the dependent variable. In addition, the trade variable has been determined as an important factor in reducing CO_2 emissions in the short and long term. Trade and GDP per capita increasing and energy consumption reducing will show positive results in order to increase the environmental quality in the USA. Moreover, the study in which this EKC hypothesis is tested with CO_2 emission and its subcomponents is an important study in terms of providing the opportunity to analyze the environmental quality from different angles at the same time and to take various measures together in the US economy.

Keywords Environmental Kuznets curve (EKC) · DARDL · CO_2 emissions · Energy consumption USA

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Introduction

The starter of this relation Kuznets (1955) investigated the relation among income inequality and economic improvement which became a phenomenon conceptualized as an inverted U-shaped. After Kuznets, Grossman and Krueger (1995) analyzed the economic improvement and environmental pollution relationship and conceptualized the inverted U-shape for the USA by Panayotou (1993). For the last decades, because of the carbon emissions playing a vital role on environmental pollution, climate change, and sustainable development, the EKC is one of the important subjects in energy-environmental economics research fields for academic researchers. So, the EKC is a notable case of pollution and income relationship (Lieb, 2003). In recent years, there has been some serious environmental problems such as CO_2 emissions, global warming, melting of glaciers, drought, and flood. These are the results of not only human life activities, but also macro-economic relations (financial development, energy depletion, foreign trade) (Ziaei 2015).

Energy is a crucial factor in driving economic improvement. In the same time, energy depletion has led to big amounts of CO_2 (Zhang and Da 2015; Zhang et al. 2018a, b; Zhang and Zhang 2018). Global energy–related CO_2 rises 1.7% in 2018 because of energy demand. US Energy Information Administration (EIA) estimates that world emissions of energy-related CO_2 will be 36 and 45 million metric tons in 2020 and 2040 respectively. "China, India, and the United States accounted for 85% of the net increase in emissions, while emissions declined for Germany, Japan, Mexico, France and the United Kingdom" (IEA Report 2018). USA is one of the biggest emitters of CO_2 in the world, and must reduce CO_2 emissions to cognize its responsibility as a big country and to bypass CO_2 damage, since it is vital to analyze relation among CO_2 and economic improvement (Song et al. 2019). Policy makers have taken a major attention in inspecting new energy sources like nuclear and renewable energy for reducing CO_2 emissions, guaranteeing energy security, and also achieving high-quality economic growth (Aslan and Gozbasi, 2016).

The financial sector is an important part of all globally economies; also, US financial system is well developed and this will attract economic growth and also demand for energy and increase carbon emissions. Financial development and economic activities have a strong correlation (Sadorsky 2011). The financial development (FD) energy depletion relation is well documented in the literature (Sadorsky 2010, 2011; Jalil and Feridun 2011). According to Jensen (1996), FD gives rise to industrial and consumption activities that FD and CO_2 linkage is related to the impacts of FD on economic improvement (Aslan and Gozbasi, 2016). However, Dogan and Turkekul (2016) found that FD has no effect on environmental degradation in which study they analyzed the relations among CO_2, energy depletion, economic improvement, and FD for the USA. The authors also underlined that CO_2 is mostly specified by income, energy depletion, and also by trade openness (TROP). Soytas et al. (2007) analyzed the relation among income, energy depletion, and CO_2 for the USA. The empirical conclusions demonstrate that energy use Granger causes CO_2 in the long term. For the period 1960 to 2010, Dogan and Turkekul (2015) inspected the relation between CO_2 emissions, energy depletion, economic improvement, and FD in the USA. The results do not back up the soundness of the EKC for the USA and the Granger causality test results back up two-way causality among CO_2 and real output, and CO_2 and energy depletion. Mercan and Karakaya (2015) explore the casual relation among economic improvement, energy depletion, and CO_2 for Turkey, Poland, Netherland, Brasil, France, Italy, Mexico, Greece, Korea Republic, Spain, UK, and USA over the period 1970–2011. The findings show that energy depletion affects CO_2 emissions positively, and GDP improvement affected it negatively. Also, Lebe (2016) found

that energy depletion, FD, and TROP affect CO_2 emission positively in which study inquired into the validity of the EKC for Turkey over the period 1960 to 2010 by employing ARDL bound test. Baek (2015) tests the EKC for Finland, Norway, Canada, Sweden, Denmark, Iceland, and the USA over the period 1960 to 2010 by employing the ARDL methodology and yields show that the EKC is not valid for the USA. Azam and Khan (2016) investigated the EKC for USA over the period of 1975–2014 by employing OLS model and results show invalid hypothesis. Kais and Sami (2016) investigated the effect of economic improvement and energy use on CO_2 for fifty eight economies over the period 1990–2012 by using a panel data model and found positive effect on the CO_2 for all panels. Bilgili et al. (2016) research the EKC by using data set of 17 OECD economies for the period of 1977 to 2010 and panel FMOLS and DOLS estimations with variable of CO_2 and GDP, quadratic GDP, and renewable energy consumption. The empirical results support that GDP has positive effect on CO_2 also GDP squared and renewable energy depletion have negative effect.

Over the period 1971 to 2013, Azam et al. (2016) by using the panel FMOLS investigate the efficacy of environmental deterioration proxied by CO_2, energy depletion, trade, and human capital on economic improvement and found a positive relation among CO_2 and economic improvement in the USA. Congregado et al. (2016) examine the EKC by using quarterly data from 1973:1 to 2015:2 in the USA and their findings show validity of EKC only when structural breaks were allowed for. Shahbaz et al. (2017) search the EKC for the USA over the period of 1960 to 2016 by using biomass energy depletion, TROP, and oil prices variables. The empirical results suggest that the relation among economic improvement and CO_2 is not only inverse U-shaped but also N-shaped in the presence of structural breaks and biomass. Over the period 1929–1994, Flores et al. (2014) use state-level data and employ quantile regression fixed effects model to examine income-pollution relation and results support EKC in the USA. Atasoy (2017) investigates the EKC for 50 states in the USA for the period of 1960–2010 using the AMG and the CCEMG estimators. The AMG results point out that the EKC is available for 30 states, and the CCEMG results provide that it is available for 10 states. Also, Apergis et al. (2017) test the EKC for the 48 US states employing CCE estimation and results demonstrate that the EKC is available in 10 states in the USA. But Isik et al. (2019a) examine EKC for US states by employing the same estimation as Apergis et al. (2017) and results did not support, and the AMG estimation results show that only 14 states verify the EKC. Another study of Işık et al. (2019b) tests the EKC for the US states which have the highest level of CO_2, over the period of 1980 to 2015 by using panel estimation method. Findings support EKC only for five states (New York, Florida, Ohio, Michigan, and Illinois).

Over the period 1980–2014, Dogan and Ozturk (2017) search the influence of GDP and energy depletion on CO2 for the USA in the EKC. The ARDL bound tests outcomes demonstrate that EKC is not valid in the log-run. Wang et al. (2017) examine the relation among CO2 emissions, nitrous oxide, and methane as the environmental variables and GDP as the economic variable to test the EKC for the period of 1960 to 2010 in the USA. Empirical results show a wave shape for relation among CO2, nitrous oxide, and GDP per person on the contrary U-shape for methane and GDP per person relation. For the 26 OECD and 52 emerging countries annual data of 1980 to 2010, Özokcu and Özdemir (2017) examined the EKC by using the panel data estimation techniques with per capita income, per capita energy use, and per capita CO2 variables and the empirical results show N-shape and an inverse N-shape relation for cubic form. Employing a PVAR model, Bakirtas and Cetin (2017) test the EKC for Mexico, Indonesia, South Korea, Turkey, and Australia over the period of 1982–2011 with income level, FDI inward, energy depletion, and CO2 variables. Sarkodie and Strezov (2018) test the EKC for Australia, China, Ghana, and the USA by employing the ARDL approach with data over the period 1971–2013 and empirical conclusions do not support the EKC for USA. Aslan et al. (2018a) analyzed the EKC at the sectoral level with sub-element CO2 emissions variables in the USA for the annual data of 1973–2015 by using the rolling window estimation method. The results demonstrate inverse U-shaped EKC for total CO2, residential CO2, electrical CO2, and industrial CO2, but it is not supported for commercial and transport sector. Also, another study of Aslan et al. (2018b) tests the EKC by using bootstrap rolling window estimation method for the period of 1966–2013 in the USA. The empirical conclusions confirmed the inverse U-shaped EKC. Raza and Shah (2018) investigate the effect of trade, economic improvement, and renewable energy on environmental deterioration in G7 economies for the period of 1991 to 2016 by using OLS and FMOLS model and results support the EKC. For China and USA from 1970 to 2014, Koondhar et al. (2018) employed ARDL bound test to examine the energy depletion, air pollution, and economic improvement correlation; the empirical results show that air pollution can expand as the energy depletion enhancement in China and vice versa in USA. Balsalobre-Lorente et al. (2018) analyze the relation among economic improvement and CO2 emissions in Spain, Italy, Germany, France, and the UK for the 1985–2016 period to research the EKC. For these 5 countries, the empirical conclusions demonstrate an N-shaped relation among economic improvement and CO2 emissions. For China, USA, and India over the period of 1965–2017, Farhani and Balsalobre-Lorente (2019) analyze the relation among coal, gas and oil depletion, economic improvement, and CO2 by using OLS, FMOLS, DOLS, and CCR methods to search the EKC. Empirical findings

show inverse U-shape for the USA and India among CO2 and economic improvement and U-shaped for China. Also, Bulut (2019) investigates the EKC hypothesis in the USA with monthly data from 2000 to 2018 by using a cointegration test with a regime shift; the findings support the EKC. But Nasr et al. (2019) applied advanced time series to test the EKC for USA over the period of 1917–2012 and found the inverse U-shaped.

There are lots of research on the EKC hypothesis in many economies and no consensus on the results because of the complexity of the EKC hypothesis based on methodologies, the period of the data, and the geographical dynamics (Shahbaz and Sinha 2018). The previous studies can be grouped into 3 parts with regard to variables. The first is the group which analyzed the strength of EKC by using environmental pollution and economic output variables following Grossman and Krueger (1995) like Selden and Song (1994), Friedl and Getzner (2003), Dinda (2004), Stern (2004), and Galeotti et al. (2009). The second group of researchers used economic improvement and energy depletion variables (Ozturk 2010), and the last group extend the literature by employing energy depletion, carbon emissions, and economic improvement variables with different methods: Narayan and Smyth (2008), Apergis and Payne (2009), Soytas and Sari (2009), Menyah and Wolde-Rufael (2010), Aslan and Gozbasi (2016), Dogan and Ozturk (2017), and Shahbaz and Sinha (2018).

This paper contributes to the existing literature by threefold: these contributions are as follows: (a) using a novel dynamic ARDL simulation model which is recently presented by Jordan and Philips (2018). The new dynamically simulated ARDL method is very successful in estimating phenomenal changes and fixing other independent variables, as well as robotically plotting and displaying changes. In addition, with this new method, it can be used to estimate the graphs of negative and positive changes in variables and their short- and long-term relationships and to produce policies, while Pesaran et al. (2001) ARDL can only predict short- and long-term relationships. (b) The relationship between more than one CO2 emission component in USA and the variables affecting environmental quality was carried out with a dynamic time series analysis and presented a different perspective to the literature for the first time. c Deviated from earlier studies on USA EKC hypothesis, the problem of total bias occurs due to the consideration of total CO2 in EKC studies, six different models were created to analyze the responses of the total emission of CO2 and its 5 subcomponents to macroeconomic indicators and energy consumption values separately, and it was made possible to see the different results of reducing each environmental pollution indicator for the USA that is the largest emitter of CO2 in the world.

The rest of the study is organized as follows: "Model and data" describes the model and data; "Empirical results" provides the empirical results; "Conclusion" concludes the paper.

Model and data

The purpose of this study is to research the impact of foreign direct investments, economic improvement, and energy depletion on carbon dioxide subcomponents in the case of USA. Different models were created to investigate the EKC hypothesis with each CO2 emission source. The CO2 subcomponents are as follows: CO2 emissions from liquid fuel consumption; CO2 emissions from residential buildings and commercial and public services; CO2 emissions from electricity and heat production; CO2 emissions from other sectors, excluding residential buildings and commercial and public services and CO2 emissions from transportation. Following Aslan and Gozbasi (2016), the study established a model for each CO2 subcomponent, along with variables in foreign direct investments (FDI), GDP per capita (GDPPC), trade (TRD), and energy consumption (ENC). The model created following Aslan and Gozbasi (2016) is as follows;

$$Co2_{Total} = \delta_0 + \delta_1 ENC + \delta_2 GDPPC + \delta_3 GDPPC^2 + \delta_4 TRD + \delta_5 FDI + \tau_t \quad (1)$$

$$Co2_{BUILD} = \delta_0 + \delta_1 ENC + \delta_2 GDPPC + \delta_3 GDPPC^2 + \delta_4 TRD + \delta_5 FDI + \tau_t \quad (2)$$

$$Co2_{LIQUID} = \delta_0 + \delta_1 ENC + \delta_2 GDPPC + \delta_3 GDPPC^2 + \delta_4 TRD + \delta_5 FDI + \tau_t \quad (3)$$

$$Co2_{OTHER} = \delta_0 + \delta_1 ENC + \delta_2 GDPPC + \delta_3 GDPPC^2 + \delta_4 TRD + \delta_5 FDI + \tau_t \quad (4)$$

$$Co2_{ELECT} = \delta_0 + \delta_1 ENC + \delta_2 GDPPC + \delta_3 GDPPC^2 + \delta_4 TRD + \delta_5 FDI + \tau_t \quad (5)$$

$$Co2_{TRNST} = \delta_0 + \delta_1 ENC + \delta_2 GDPPC + \delta_3 GDPPC^2 + \delta_4 TRD + \delta_5 FDI + \tau_t \quad (6)$$

In the equations, $GDPPC^2$ means the square of real income per capita. The variables used in the study cover the observation period 1972–2020. All variables used in the study were used in the first difference and by taking logarithm. All variables are taken from the World Development Index (WDI) database. Table 1 shows the variables, abbreviations, and sources used in the research.

The models created in the study are as follows; model 1: dependent variable is CO2 as Total; model 2: dependent variable is BUILD; model 3: dependent variable is LIQUID; model 4: dependent variable is OTHER; model 5: dependent variable is ELECT; model 6: dependent variable is TRNST.

In this study, dynamic ARDL was used as an econometric method. The basic equation of this method used in the studies of Kahn et al. (2019), Sarkodie et al. (2019), and Danish and Ulucak (2020) is as follows following Jordan and Philips (2018);

$$\Delta(r)_t = \sigma_0 + \mu_0(r)_{t-1} + \mu_1(s_1)_{t-1} + ... + \mu_n(s_n)_{t-1}$$
$$+ \sum_{i=1}^{a} \sigma_i \Delta(r)_{t-1} + \sum_{b=0}^{h} \gamma_{ib} \Delta(s_1)_{t-b} + ... \quad (7)$$
$$+ \sum_{b=0}^{h_v} \gamma_{vb} \Delta(s_v)_{t-b} + \omega_t$$

R in Eq. 2 indicates the change in the dependent variable. σ_0 intercept, t-1 denotes the maximum a level of the independent variables at time t with h_v delays, the first difference and the error term. Jordan and Philips (2018) removed the complexity of short-term and long-term coefficient estimates in the DARDL application. Thus, there is no need to estimate the short- and long-term coefficients separately. Besides, the variables must be stationary at I(O) or I (1) level.

We can restate Eq. 1 in error correction format in accordance with ARDL method as follows;

$$\Delta Co2_t = \varphi_0 Co2_{t-1} + \epsilon_1 \Delta GDPPC_t + \vartheta_1 \Delta GDPPC_{t-1}$$
$$+ \epsilon_2 \Delta GDPPC_t^2 + \vartheta_2 \Delta GDPPC_{t-1}^2$$
$$+ \epsilon_3 \Delta FDI_t + \vartheta_3 \Delta FDI_{t-1} + \epsilon_4 \Delta ENC_t + \vartheta_4 \Delta ENC_{t-1} \quad (8)$$
$$+ \epsilon_5 \Delta TRD_t + \vartheta_5 \Delta TRD_{t-1}$$

Table 1 Data and sources

Variable	Data	Source
CO2	CO2 emissions (metric tons per capita)	WDI
BUILD	CO2 emissions from residential buildings and commercial and public services (of total fuel combustion)	WDI
LIQUID	CO2 emissions from liquid fuel consumption (% of total)	WDI
OTHER	CO2 emissions from other sectors, excluding residential buildings and commercial and public services (total fuel combustion)	WDI
ELECT	CO2 emissions from electricity and heat production, total (of total fuel combustion)	WDI
TRNST	CO2 emissions from transport (of total fuel combustion)	WDI
GDPPC	Real GDP per capita (current US$)	WDI
$GDPPC^2$	Real GDP per capita (current US$) (Square of GDPPC)	WDI
TRD	Trade (% of GDP)	WDI
FDI	Foreign direct investment, net inflows (% of GDP)	WDI
ENC	Energy use (kg of oil equivalent per capita)	WDI

Table 2 Unit roots tests results (*first difference*)

Variables	Phillips-Perron	DF-GLS
CO2	− 6.587770***	− 5.773724***
BUILD	− 6.316064***	− 6.003150***
LIQUID	− 5.732887***	− 4.131342***
OTHER	− 7.971800***	− 7.190110***
ELECT	− 5.050765***	− 1.120609
TRNST	− 7.739374***	− 7.624464***
GDPPC	− 1.688010	− 1.906425*
GDPPC^2	− 1.688010	− 1.906425*
TRD	− 5.398856***	− 5.584915***
FDI	− 9.333603***	− 7.409055***
ENC	**− 6.300830*****	− 4.933795***

*, **, and *** denote 10%, 5%, and 1% statistically significance level, respectively

Empirical results

Jordan and Philips (2018) state that in the DARDL method, all variables must be stationary at the first difference at most. Application cannot be performed with variables that are not static at the most I (1) level. The stability of the variables was investigated using GF-GLS and Phillips-Perron (PP) unit root analysis methods. All variables are used by taking their first difference and natural logarithm. Table 2 shows the unit root analysis results.

After investigating the unit root stationarity, the existence of cointegration between variables should be investigated. Coefficient estimation cannot be performed with the DARDL method with variables that do not have cointegration between them. In this study, a total of 6 different models were established, consisting of total CO2 emission and five CO2 emission subcomponents. Cointegration was investigated separately in each model. With the cointegration research, it should be investigated whether there are heteroskedasticity and autocorrelation in the models. In the case of heteroskedasticity or autocorrelation, the coefficient estimates will not be reliable. Table 3 shows the cointegration critical values determined by Pesaran et al. (2001). Critical thresholds of f and t statistics values are given separately in Table 3. The f and t statistics values showing the cointegration of the models are also given in Table 4.

The critical thresholds shown in Table 3 are used to determine whether cointegration exists. When looking at f and t statistics values in Table 4, it is seen that all of them are cointegrated. In addition, Table 4 includes the tests and their results to investigate whether there are heteroskedasticity and autocorrelation. According to the test results, none of the models has autocorrelation or heteroskedasticity problems. Table 4 also shows the DARDL coefficients.

Table 4 shows the long- and short-term DARDL coefficient estimates of 6 different models. In this study, in which the validity of the EKC hypothesis was tested, the GDPPC^2 variable should have a significant and negative coefficient. The EKC hypothesis is valid only in model 1 according to the long-term coefficient of the GDPPC^2 variable. GDPPC^2 variable does not have a negative and significant coefficient in neither short nor long term in any other model. In this case, a parabolic relationship in the form of inverse-U is seen between income and environmental quality in model 1. In the US example, between total CO2 and income, the EKC hypothesis is valid in the long run. When looking at other variables, there is a negative and significant long-term relationship between GDPPC and CO2 emission in model 1. If GDPPC increases by 1%, there is a 0.96% reduction in CO2 emissions. In this case, the increase in income has an increasing effect on the environmental quality in the long term. However, this relationship is not valid in the short term. The GDPPC variable is not significant in both short and long run in any model other than model 1. There is a positive and significant relationship between ENC and CO2 emission both in the short term and in the long term. For CO2 emission in model 1, if the ENC variable increases by 1%, there is an increase of 0.34% in the short term and 1.69% in the long run. As expected, energy consumption increases environmental pollution both in the long and short term. The long-term coefficient of the TRD variable is negative and significant. In this case, it is seen that, in model 1, if trade increases by 1% in the long run, it increases the environmental quality by 0.19%. TRD variable models 2, 3, and 5 also have significant coefficients in the short run. Unlike model 5, it is negative and significant in models 2 and 3. In model 5, a positive and significant relationship is seen between the dependent variable ELECT and TRD. Trade has a positive effect on CO2 emission resulting from electricity and heat generation, thus on environmental pollution.

Table 3 Pesaran et al. (2001) cointegration test bounds

	10%		5%		1%	
	I (0)	I (1)	I (0)	I (1)	I (0)	I (1)
f-stat	2.614	3.746	3.136	4.416	4.306	5.874
t-stat	− 2.570	− 3.660	− 2.860	− 3.990	− 3.430	− 4.600

Table 4 The dynamic ARDL simulations analysis

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Variables	Coefficients					
L.CO2	− .0934836					
L.BUILD		− .1059127				
L.LIQUID			.2274326			
L.OTHER				− .1608862		
L.ELECT					.3887793[**]	
L.TRNST						− .1355751
Δ GDPPC	.052743	.0329569	.0573715	.1185719	− .0212802	− .0087868
L. GDPPC	− .9686108[***]	− .6356423	− .0393575	1.52147	.0557731	.0378765
Δ GDPPC^2	.026366	.0164748	.0286861	.0593009	− .0106397	− .0043927
L. GDPPC^2	− .4843101[***]	− .3178246	− .0196698	.7608691	.0278889	.0189469
Δ TRD	.013611	− .2582733[**]	− .181428[***]	− .1078562	.0867851[**]	.0455845
Δ FDI	.0063127	.0064735	.0060039	− .0279921	− .0132352[**]	− .0156482
Δ ENC	.3445379[**]	.2347927	.1108492	− .5367038	.0155113	− .0238893
L. TRD	− .1923718[**]	− .2073676	− .1029019	− .2712877	.0548957	.1386005
L. FDI	.0133201	.0010116	− .0075888	− .0173605	− .0082392	− .0232362
L. ENC	1.699788[***]	.4051759	.4135486[**]	− 1.081838	− .0352844	− .2424312
Constant	10.83504[**]	30.85704[***]	10.17758[**]	20.18526[**]	10.88213[**]	24.49606[***]
f-stat.	52.290[***]	8.030[***]	6.380[***]	10.530[***]	3.620	9.750[***]
t-stat.	− 11.640[***]	− 6.050[***]	− 4.800[***]	− 6.930[***]	− 4.110[**]	− 6.840[***]
Simulations	5000					
Diagnostic tests	Chi-square [Prob.]					
Breusch-Godfrey LM test for autocorrelation	0.153[0.6956]	0.912[0.33]	0.859[0.35]	0.287 [0.59]	0.819 [0.36]	1.304 [0.25]
Breusch-Pagan /Cook-Weisberg test for heter-oskedasticity	**3.22 [0.07]**	**0.48 [0.48]**	**0.75 [0.38]**	**0.67 [0.41]**	**0.20 [0.65]**	3.42 [0.06]

*, **, and *** denote 10%, 5%, and 1% statistically significance level, respectively. Values in parentheses are probability values

The long-term coefficient of the TRD variable is not significant in any model except model 1. FDI variable has a significant coefficient only in model 5 in the short run. It has an increasing effect on the environmental quality in FDI model 5. When the long-term coefficients of the FDI variable are examined, it is seen that it is not significant in any model. ENC variable does not have a significant coefficient in any model except model 1 in the short run. When looking at the long-term coefficient estimates of the ENC variable, it is seen that it has a positive and significant coefficient in model 3 with only model 1. In model 3, where the CO2 emission resulting from liquid fuel is the dependent variable, energy consumption affects the environmental quality negatively as expected.

The impulse-response graphs between GDPPC and dependent variables (for each model) are shown in Figs. 1, 2, 3, 4, 5, and 6. GDPPC does not show any impact on CO2 emissions from transport. The relationship between GDPPC and other CO2 emission variables follows a fluctuating course, as can be seen in the figures.

Conclusion

In this study, the EKC hypothesis is tested with CO2 subcomponents in the USA. In the study, RGDPPC, RGDPPC^2, FDI, TRD, and ENC variables were used as independent variables in the econometric analysis performed with DARDL method in the 1972–2020 by including the total CO2 emission and 5 subcomponents as dependent variables. Study findings and policy implications can be presented as follows:

1- According to the DARDL coefficient estimates, only the EKC is valid in model 1 where the total CO2 emission is the dependent variable. This result demonstrates the finding that the EKC is valid only for total CO2 use in the USA, and the EKC is not valid in the subcomponents. Simultaneously, in model 1, a negative and significant relation among GDPPC and total CO2 in the long term was determined. In this case, it is seen that the environmental quality is positively affected by the increase in income.
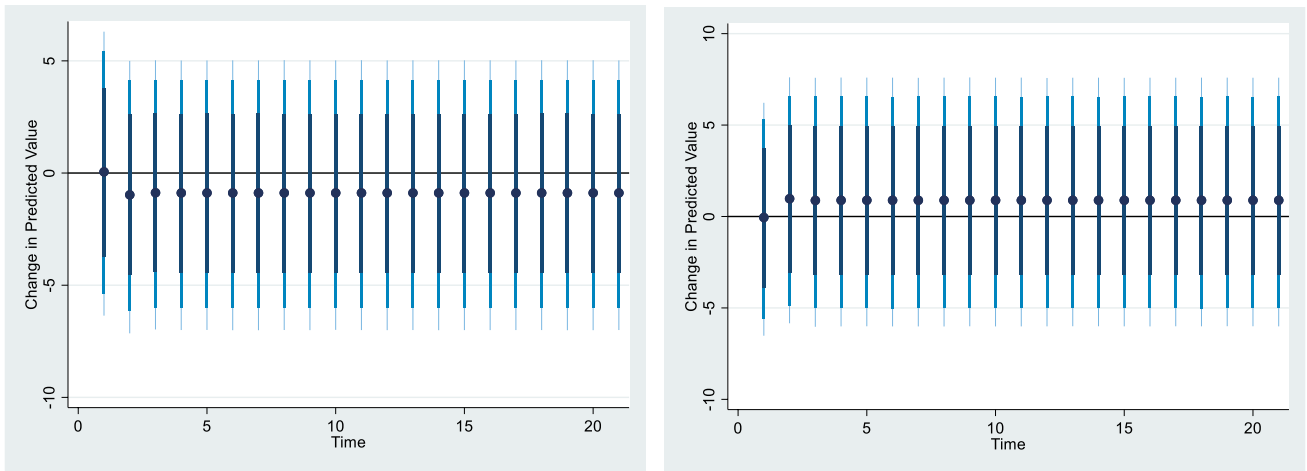
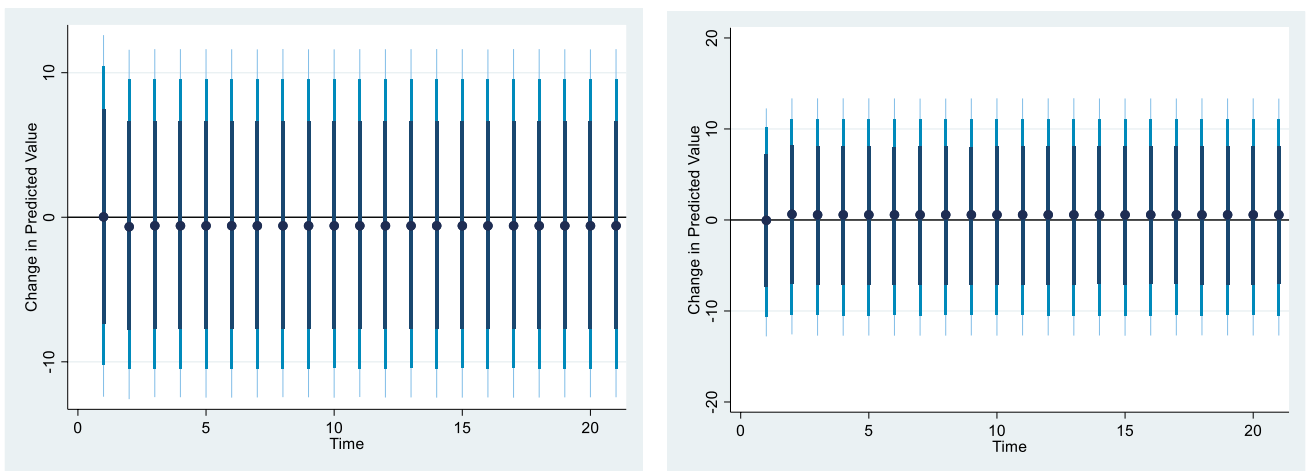**Fig. 1** (±1%) changes in predicted GDPPC on CO2 emissions (model 1)

Fig. 2 (±1%) changes in predicted GDPPC on BUILD emissions (model 2)
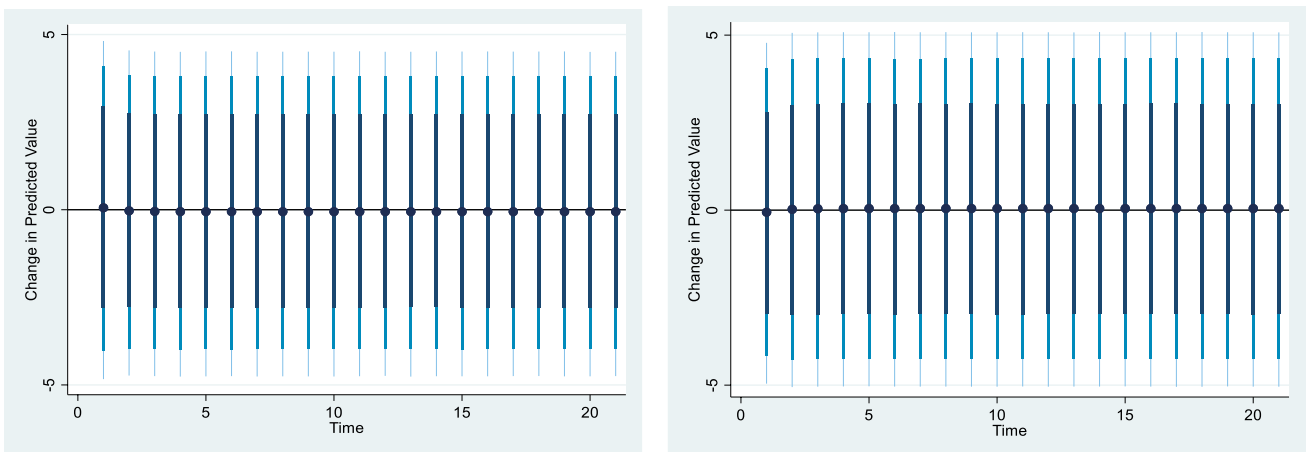

Fig. 3 (±1%) changes in predicted GDPPC on LIQUID emissions (model 3)

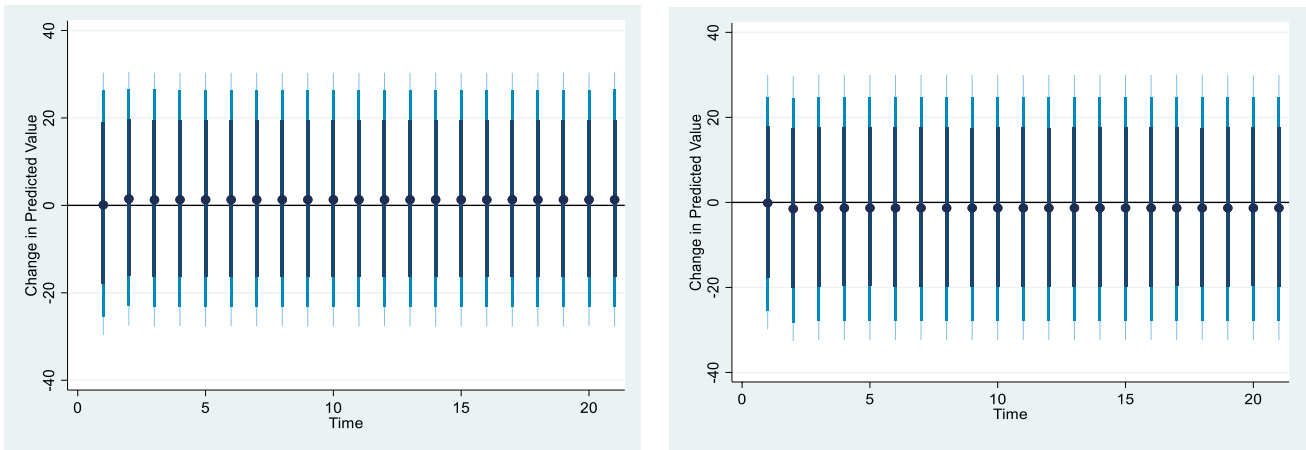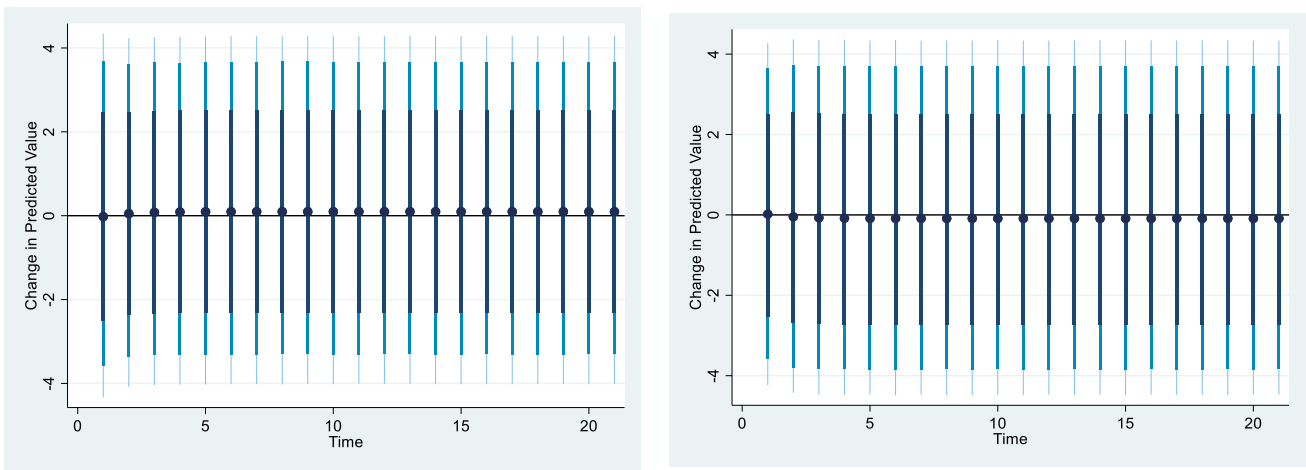**Fig. 4** ($\pm 1\%$) changes in predicted GDPPC on OTHER emissions (model 4)

Fig. 5 ($\pm 1\%$) changes in predicted GDPPC on ELECT emissions (model 5)
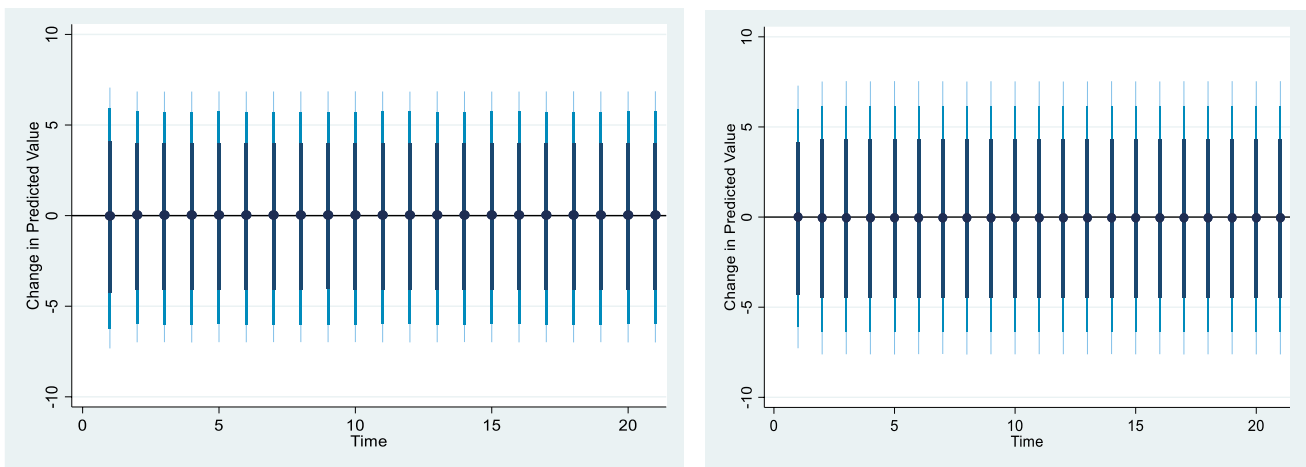

Fig. 6 ($\pm 1\%$) changes in predicted GDPPC on TRNST emissions (model 6)

2- Contrary to model 1, in the other 5 models, there was no significant relation among the GDPPC and the dependent variables in the long term or short term. Similarly, trade variable is not statistically significant in any other model unlike model 1 in the long run. In model 1, the increase in the trade rate in the long term has a positive effect on the environmental quality. In this case, increasing trade rates is an important factor for USA in reducing total CO_2 emissions. When the short-term coefficient estimates of the trade variable are examined, it is seen that it is statistically significant in models 2, 3, and 5. This effect, which is negative in models 2 and 3, is positive in model 5.

3- When the long-term coefficient estimates of the FDI variable are examined, it is seen that there is no statistically significant difference in any model. However, considering the short-term coefficient estimates, FDI only shows a reducing effect on the CO_2 resulting from electricity and heat generation in model 5. Energy depletion has a positive effect on the total CO_2 emission both in the short term and in the long term.

4- On the other hand, energy depletion has a positive long-term impact on CO_2 resulting from liquid fuel, which is the dependent variable in model 2. Energy depletion does not show a significant impact in other models in the short and long run.

As a result, it is seen that environmental pollution in America will decrease in the long term with the increase in income. Therefore, the EKC hypothesis is valid for USA in the long run. On the other hand, it is seen that trade has an important place in increasing the environmental quality of USA. Trade is an important factor in reducing CO_2 emissions from residential buildings, commercial and public services, and CO_2 emissions from liquid fuel consumption in the short term on total CO_2 in the long run. Similarly, in the short term, increasing foreign direct investments in reducing CO_2 emissions resulting from electricity and heat generation will benefit the USA. In future studies, it is recommended to examine the subject with analyses in the focus of structural breaks, again taking into account the CO_2 elements.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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