Decoupling of CO_2 emissions and income in the U.S.: A new look from EKC

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Abstract

This paper attempts to analyze decoupling between CO_2 emissions and income growth in the U.S. through the lens of Environmental Kuznets curve (EKC). Many states in the U.S. have achieved absolute decoupling in recent years, which means that CO_2 emissions have decreased while the economy grows. This is partly due to the adoption of low-emission technologies, such as coal to gas switching, nuclear power, and economic restructuring towards a more sustainable economy. We argue that understanding decoupling is crucial to implement effective climate change policies. This study suggests that, after 2015, EKC has taken on the U-shaped form with many states currently located on the negatively sloped portion of the curve. It is not desirable as emissions may eventually begin to increase as the economy grows. To support this claim, we estimate panel fixed effects rolling-window EKCs using two-stage least square with two instrumental variables, unemployment rate and the trend variable. Empirical results show how the inverted U-shaped EKC has transformed into the U-shaped EKC in the U.S. This transformation is probably caused by the recent increases in emissions in transportation sector, strong electricity demand in recent years with cold winter seasons, reversals of eco-friendly energy policies, and manufacturers' onshoring. Stakeholders should make efforts to transform the U-shaped EKC back to an inverted U-shaped EKC even in cases where absolute decoupling is observed.

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1 Introduction

The U.S. has recently achieved the decoupling[1] of income growth and CO_2 emissions (Saha and Muro 2016), in other words, income has increased while CO_2 emissions have decreased.[2] In the U.S. states, per capita personal income (hereafter income unless indicated otherwise) has increased by 25% on average across states, from about $40,000 per capita personal income in 2000 to around $50,000 per capita personal income in 2018. Between 2000 and 2018, states' CO_2 emissions per person (hereafter emissions unless indicated otherwise) have decreased by 20% on average across states, from 24.9 metric tons/person to 19.9 metric tons/person.[3] GDP grew by 4% (from $14.8 to $15.4 trillion), while energy-related CO_2 emissions declined by 6% (from 5.6 to 5.2 billion metric tons) between 2010 to 2012 (Aden 2016).

Saha and Muro (2016) identified several reasons for the decoupling of income growth and CO_2 emissions in the US. These include switching from coal to gas, adopting nuclear power in electricity generation, and industries transitioning towards low-emission practices. Detailed examples from Saha and Muro (2016) show how certain states experienced declines in CO_2 emissions. For instance, some states like Delaware, Georgia, Maine, North Carolina, and Virginia reduced emissions by expanding their service sectors. Nevada achieved a decrease by decreasing production from energy-intensive manufacturing industries. Connecticut, Delaware, Maryland, New Jersey, and Oregon reduced emissions by shifting from commodities manufacturing to advanced manufacturing. Moreover, New York and other Northeastern states increased their nuclear power generation, which helped lower emissions. Other factors contributing to the decrease in emissions include offshoring of US manufacturing, de-localization, and the Clean Air Act, as discussed in Autor et al. (2013), Pierce and Schott (2016), and Gilli et al. (2017). Additionally, environmental regulations and changes in emission intensity between 1990 and 2008 in the US were highlighted in Shapiro and Walker (2018).

The objective of this paper is to investigate whether absolute decoupling is currently taking place in the U.S. through an analysis of the Environmental Kuznets curve (EKC). Many previous studies have used EKC to investigate the relationship between income and emissions, which argues that an inverted U-shaped association exists between emissions and income. Grossman and Krueger (1991) first introduced EKC hypothesis and suggested

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[1] The concept of decoupling emissions from income growth involves measuring the ratio of changes in emissions to changes in income, which is referred to as decoupling elasticity. Coupling is defined when $0.8 < \epsilon < 1.2$, decoupling when $0 < \epsilon < 0.8$, and strong decoupling when $\epsilon < 0$, where ϵ is decoupling elasticity (Tapio 2005).

[2] CO_2 emissions are a major contributor to climate change, leading to rising global temperatures and a range of environmental and societal impacts. To address this issue, the Paris Agreement was established, aiming to pursue efforts to limit the temperature increase to 1.5 degrees Celsius (UNFCCC, 2015). Net zero emissions are critical to achieving these goals, meaning that any remaining emissions are offset by removing an equivalent amount of CO_2 from the atmosphere. Mitigating climate change is essential to safeguarding our planet and future generations, and requires immediate action and commitment from individuals, governments, and businesses worldwide (IEA, 2021).

[3] A process is called absolute decoupling when emissions decrease steadily with economic growth (Heger and Vashold 2021). A process is called relative decoupling when the economy grows faster than the growth rate of emissions (Heger and Vashold 2021). The U.S. has shown absolute decoupling. Note that the actual emissions from the U.S. are still relatively larger than other countries even if the U.S. has achieved absolute decoupling. The U.S. emitted 15.2 (metric tons/person) in 2018. In the same year, Qatar emitted 32.4, Australia 15.5, Korea, 12.2, Russia 11.1, Japan 8.7, Germany 8.6, China 7.4, United Kingdom 5.4, and India 1.8. Top five countries in terms of total emissions are China, U.S., India, Russia, and Japan (Word Bank CO_2 emissions database).

that the environmental degradation generated in the early development stages is expected to be mitigated following the economic growth (Kaika and Zervas 2016). In early 1990s, many researchers believed that the economic growth will eventually mitigate environmental problems following the EKC hypothesis (Kaika and Zervas 2016). Assuming the existence of absolute decoupling, we would expect many U.S. states should be on the downward sloping section of the EKC where emissions decrease with more income. However, the more important question is whether the inverted U-shaped EKC exists; what if many states are located on the negatively sloped portion of the U-shaped curve between emissions and income? In this case, although absolute decoupling may currently be occurring, emissions eventually start increasing as the economy grows. The novelty of this paper is to examine whether absolute decoupling is occurring on the U-shaped or the inverted U-shaped EKC. As alluded, mitigating CO_2 emission is important to keep the inverted U-shaped EKC. This paper presents evidence that U.S. is experiencing absolute decoupling with the U-shaped EKC and we should pay more attention to mitigate emissions with income growth.

The shape of EKC could change over time possibly due to different paces of economic growth among U.S. states and varying energy policies adopted by different U.S. administrations. For example, the U.S. administration had replaced the Clean Power Plan which aimed to reduce emissions from electricity generation during the Obama administration in 2014. The U.S. administration had relaxed bans on oil & gas extraction by changing important terms in the Endangered Species Act, and lessened the Coal Ash Rule, which controls and monitors the coal waste disposal (Baker 2020). The aforementioned changes in polices may have contributed to shifts in the EKC. Moreover, these changes might have increased emissions in recent years (Baker 2020; Sepeda-Miller 2020; EPA 2023), especially in 2018 after three years of decline (BBC 2019).

To answer research questions, that is, examining whether absolute decoupling is occurring on the U-shaped or the inverted U-shaped EKC in the U.S., rolling EKCs are estimated to capture how EKCs have evolved over time. As said, the novelty of this paper is to trace how the EKC curve has evolved over time using rolling approach to show the dynamic relationship between income and emissions. The idea behind rolling analysis is to construct new observations using samples of consecutive observations (Hällman, 2017). The parameters in EKC over the sub-samples should be similar if the parameters remain constant across the entire sample. If the parameters vary across the sub-samples, the shape of EKC could be different, potentially shifting from a U-shaped to an inverted U-shaped curve or vice versa.

Empirical results show that the EKCs appear to have evolved over time. Until 2012, EKCs have the inverted U-shapes, i.e. EKC hypothesis holds, with exception of few early sub-samples where the shape of EKCs are close to linear. Until early 2000, some states are located on the left side of inverted the U-shaped EKC which means that the relationship between economic growth and emissions is positive. Between 2010 and 2014, most of states have moved along the inverted U-shaped EKC and are located on the right side of the inverted U-shaped EKC where absolute decoupling is observed. However, after 2015, EKC has taken on the U-shaped form with many states located on the left side of the of the curve. While the relationship between emissions and income growth remains negative, indicating absolute decoupling, emissions may eventually begin to increase as the economy grows. The policy implication is straightforward; efforts should be made to transform the U-shaped EKC back to an inverted U-shaped EKC, even in cases where absolute decoupling is observed. An intriguing question that arises is how to shift the U-shaped EKC back towards an inverted U-shaped EKC in the near future.

The rest of this work is arranged as follows: Part 2 summarizes related studies and Part 3 discusses methodologies. Part 4 describes the data used in this study. Part 5 reports the results and Part 6 provides conclusion and policy implications.

2 Related studies

Climate change has become a major global concern (IPCC 2021). Suppressing CO_2 emissions is one of ways to address this problem (IPCC 2021). Economic growth and emissions are usually coupled implying that mitigating emissions may reduce income in a country or a region. Therefore, decoupling emissions and economic growth has been important to facilitate low-carbon economy (Shuai et al. 2019). There have been many studies to investigate the decoupling relationship, for example, Tapio (2005), Freitas and Kaneko (2011), Shuai et al. (2019), Wang and Su (2019) and Du et al. (2021), to name a few. As aforementioned in footnote 1, decoupling elasticity is defined $\epsilon = \frac{\Delta e/e}{\Delta m/m}$, where e stands for per capita emissions and e represents income per capita or per capita GDP. According to Tapio (2005), income and emissions can be coupled, decoupled or negatively decoupled. Coupling is defined when $0.8 < \epsilon < 1.2$, decoupling when $0 < \epsilon < 0.8$ and strong decoupling when $\epsilon < 0$. Tapio (2005) further defined various types of decoupling such as expansive decoupling and recessive decoupling based on the absolute decrease or increase of income and emissions.

Freitas and Kaneko (2011) showed that the strong decoupling occurred in Brazil in 2009 using OECD (2001, 2002) decoupling index by investigating relationship between income growth and CO_2 emissions from 2004 to 2009. Several relative decoupling were also detected in other periods before 2009 (Freitas and Kaneko 2011). Authors indicated that the main drivers of emissions reduction were energy mix and carbon intensity from 2004 to 2009. Wang and Yang (2015) computed decoupling elasticity for carbon emissions from industrial sector in Beijing–Tianjin–Hebei economic band in China from 1996 to 2010 using Logarithmic Mean Divisia Index (LMDI) method and Tapio index. They found that weak decoupling occurred during 1996–2000 which was followed by expansive coupling between 2001 and 2005. Both week decoulping and strong decoupling occurred from 2006 to 2010 (Wang and Yang 2015). Grand (2016) stated that considering which decoupling indicators to use is important. This is because the meaning of decoupling indicators from OECD (2002) and Tapio (2005) is different and more decoupling cases may exist (Grand 2016). Grand (2016) applied decoupling indicators to Argentina data, where its economy has not been stable between 1990 and 2012 and found that various coupling and decoupling relationships.

Loo and Banister (2016) investigated the decoupling relationships between CO_2 emissions in transportation sector and economic growth in 15 different countries. They found that the most of countries have already achieved decoupling (Loo and Banister 2016). Wu et al. (2018) estimated decoupling indices for developed and developing countries between 1965 and 2015. They showed that developed countries have stable and close to absolute decoupling relationship (Wu et al. 2018).

For the developing countries, decoupling indices lie inside the relative decoupling interval (Wu et al. 2018). Shuai et al. (2019) investigated the decoupling statuses for 133 countries from 2000 to 2014 between economic growth and three carbon emissions measures such as total emissions, emissions per capita, and carbon intensity with the Tapio (2005) index. Shuai et al. (2019) found that three-step decoupling exists, which

is a sequential order of decoupling; decoupling from carbon intensity followed by emissions per capita, and total emissions. Du et al. (2021) examined the decoupling for 289 cities in China with the Tapio (2005) decoupling indices. They found that decoupling in these cities have been intensified over the sample period (Tapio 2005).

Saha and Muro (2016) found that the U.S. has achieved decoupling of income growth and emissions by comparing changes in emissions to changes in income between 2000 and 2014 for all the U.S. states using the method similar to Tapio (2005). According to Saha and Muro (2016) delinking between carbon emissions and economic growth have already occurred in more than 30 U.S. states. Authors also found that decoupling has been sped up over the years as more states have delinked economic growth and emissions (Saha and Muro 2016). Following Heger and Vashold (2021), absolute decoupling is a process when emissions decrease steadily with economic growth which is similar to "strong decoupling" in Tapio (2005) and relative decoupling is a process when the economy grow faster than the growth rate of emissions A process called relative decoupling which is similar to "weak decoupling" in Tapio (2005).

Absolute decoupling indirectly indicates that many U.S. states are located on the downward sloped area of the U-shaped or the inverted U-shaped EKCs where emissions decrease along with more income. As such, it is more important to discuss the shape of EKC and identify where the U.S. states are located on the EKC. EKC hypothesis argues that an inverted U-shaped relationship exists between income and emissions. Grossman and Krueger (1991, 1995) introduced EKC hypothesis and suggested that the environmental degradation generated in the early development stages is expected to be mitigated following the economic growth. They found that the concentration of air pollutants increases with per capita GDP when the income is low but decreases at higher income. Since the studies of Grossman and Krueger (1991, 1995), there have been tremendous amount of similar literature. These studies have tested the validation of ECK hypothesis for different countries and for different time periods. It is practically difficult to summarize the previous EKC studies; refer to Stern et al. (1996) for early EKC studies and Shahbaz and Sinha (2018) for the comprehensive review of EKC literature where authors provided a survey of the empirical studies on EKC over the period of 1991–2017. The results of EKC for CO_2 emissions are inconclusive in nature. The reasons for the inconsistency can be the different explanatory variables included in the studies, methodological adaptations, and different time periods (Shahbaz and Sinha 2018).

The recent studies, such as Işik et al. (2017), Dogan et al. (2020), Işik et al. (2020), and Işik et al. (2021), have arrived inconclusive results as well. Işik et al. (2017) examined dynamic relationship between economic growth, financial development, international trade, tourism expenditure and CO_2 emissions in Greece, which are positively associated. Dogan et al. (2020) showed that EKC hypothesis may not hold when ecological footprint is used as a measure of the environmental degradation with Brazil, Russia, India, China, South Africa, Turkey from 1980 to 2014. Işik et al. (2020) investigated the tourism-induced EKC for G7 countries from 1995 to 2015 and found that only the tourism-induced EKC in France is valid. Işik et al. (2021) examined the EKC hypothesis for eight OECD countries between 1962 and 2015, but failed to confirm the EKC relationship using the decomposed model which isolates the effects of economic growth on the environment while controlling for the effects of economic downturns by decomposing the per capita GDP series into its increases and decreases, and considering only increases in the model. Ongan et al. (2022) combined the EKC model with a more general regression model to investigate the relationship between government spending and CO_2 emissions in Mexico and Canada. They found

that, contrary to the EKC hypothesis, there was no evidence of an inverted U-shaped relationship between economic growth and CO_2 emissions in either country.

There are many studies have tried to validate the EKC hypothesis in the U.S. which include tourism, trade, financial development, energy portfolio, and other quality determinants of related environmental (Alola and Ozturk 2021). Among others, Aldy (2005), Koirala and Mysami (2015), Atasoy (2017), Shahbaz et al. (2017), and Pata (2021) have supported the EKC hypothesis for the U.S. while Dogan and Turkekul (2016), Işik et al. (2019a), and Cary (2020) revealed the non- existence of the EKC hypothesis in the U.S.

Aldy (2005) investigated income-CO_2 relationship with U.S. data at state level and found an inverted-U EKC with the production-based emissions. For the consumption-based emissions, the shape of EKC takes plateaus at higher income after a peak. Note that consumption-based and production-based CO_2 emissions depend on how to measure emissions. Production-based covers the emissions from institutional units in a country which is similar to GDP and consumption-based includes emissions from domestic consumption which is production + imports − exports (Peter and Hertwich 2007). Koirala and Mysami (2015) confirmed that an inverted U-shaped EKC for the U.S state level data when investigating the effect of forest on CO_2 emissions. Atasoy (2017) applied panel data model to take into account the cross-sectional dependence and slope heterogeneity and validated the EKC hypothesis for 50 U.S. states between 1960 and 2010. Shahbaz et al. (2017) investigated the U.S. data between 1960 and 2016 and found the EKC by including trade openness and energy source. Pata (2021) stated that consumption of renewable energy and globalization are the main drivers of the decreasing environmental pollution, at the same time, consumption of non-renewable energy plays a dominant role in increasing environmental degradation.

There have been several studies which revealed that the EKC does not exist in the U.S. Dogan and Turkekul (2016) did not find evidence to validate the EKC hypothesis in the U.S. after control- ling energy consumption, financial development, urbanization, and trade openness. The empirical findings in Işik et al. (2019a) supported the the EKC hypothesis for five out of ten states such as Ohio, New York, Michigan, Illinois and Florida. These five states have the highest CO_2 emissions level. Cary (2020) found evidence for the EKC hypothesis in the U.S. is virtually nonexistent using a new data which contains sector level data on greenhouse gas emissions from the U.S. energy sector. Işik et al. (2019b) examined EKC hypothesis at the state level in the U.S. from 1980 to 2015 using augmented mean group (AMG) and common correlated effects estimation procedures. The results are mixed across different states. The AMG estimation confirmed the EKC hypothesis for 14 states. Anticipated positive effects of renewable energy consumption on CO_2 emissions were observed in only 13 states, and negative effects were observed in all states except Texas. Ongan et al. (2020) decomposed per-capita income series and used only the increase in per-capita income to test the EKC hypothesis in the U.S. between January 1990 and July 2019. The results showed that the EKC hypothesis is supported in the decomposed model, while the undecomposed model failed to confirm the EKC hypothesis. Işik et al. (2022) re-examined EKC hypothesis for the U.S. states between 1990 and 2017. Using the same method to Ongan et al. (2022), Işik et al. (2022) tested ECK hypothesis for U.S. states between 1990 and 2017 and the EKC hypothesis was confirmed for seven U.S. states.

Previous EKC studies assumed parameter stability, in other words, parameters in EKC are constant over the sample period. To understand the time-varying EKC, Aslan et al. (2018a), Aslan et al. (2018b), and Destek et al. (2020) have adopted rolling window models to obtain the parameters for sub-sample periods. Aslan et al. (2018a) examined the validity of the inverted U-shaped EKC between 1966 and 2013 for the U.S. and found the

changes of parameters and causal relationship between income and emissions over the sub-samples. Aslan et al. (2018b) also confirmed EKC hypothesis with the inverted U-shaped EKC in the U.S. from 1973 to 2015 for electrical industry and residential sectors. Destek et al. (2020) investigated the economic growth and emissions in G-7 countries between 1800s and 2010 with time-varying and rolling window approach. The results showed the W-shaped EKC for the U.S., Japan, and Italy and confirmed the inverted U-shaped EKC in France, Italy, and the U.S. before 1973.

This study contributes to the current literature by combining the EKC hypothesis and decoupling between income growth and emissions. To this end, next section explains how to proceed empirical analyses.

3 Theoretical background and methodology

3.1 Economic reasoning of EKC

Environmental Kuznets Curve (EKC) is a theoretical framework that suggests a relationship be- tween economic development and environmental degradation, e.g., pollution and other negative environmental impacts including CO_2 emissions. The EKC hypothesis states that as a country's economy grows, environmental degradation initially increase, but eventually decrease after reaching a certain level of economic development. This is because, as countries grow economically, they become better able to afford the cost of environmental protection and regulation, and that as a result, they will gradually reduce their negative environmental impacts. At the same time, economic growth may lead to greater investment in cleaner technologies, more efficient resource use, and more sustainable production practices, which can also help reduce environmental impacts. As such there exists an inverted U-shaped relationship between income and emissions (Grossman and Krueger 1991, 1995; Stern 1998). To empirically test the EKC hypothesis, researchers attempt to estimate the EKC equation, that is, environmental degradation is the quadratic functions of the levels of income (Stern 2004) which will be discussed in the next section. If the EKC hypothesis holds, the coefficient of the quadratic term would be negative and statistically significant. Unfortunately, as Stern (2004) pointed out, econometric criticisms of the EKC concern four main issues: heteroskedasticity, simultaneity, omitted variables bias, and cointegration issues. We will discuss these concerns in the following section as well.

3.2 Empirical strategy

This section introduces the methods we use to answer the research questions beginning with the panel model to estimate EKC. Then we discuss rolling window approach to trace the shapes of EKCs over the sub-samples. EKC with the panel data is given by:

$$\ln e_{it} = b_0 + b_1 \ln m_{it} + b_2 \left(\ln m_{it}\right)^2 + v_i + u_{it} \tag{1}$$

where $\ln e_{it}$ is logged CO_2 per capita for state i and year t, which is a function of logged income, $\ln m_{it}$, and squared logged income, $\left(\ln m_{it}\right)^2$. The parameters, b_0, b_1, and b_2 are the coefficients to be estimated. The term v_i is state-specific effects and u_{it} is the error term. We expect $b_1 > 0$ and $b_2 > 0$ to have an inverted U-shaped EKC. The marginal effect of income of emissions is:

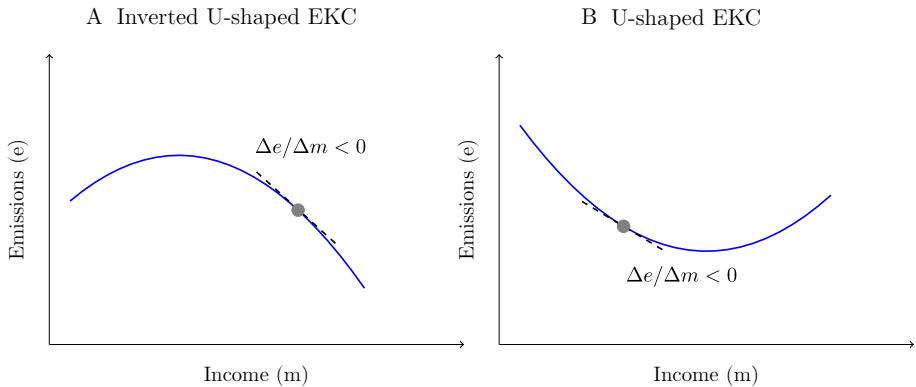A Inverted U-shaped EKC   B U-shaped EKC

Fig. 1 Strong Decoupling and Shapes of EKC. Note: A symbol e indicates emissions and m income thus $\Delta e/\Delta m$ is the slope of the EKC curves or marginal effect presented in Eq. (2)

$$\frac{\partial \ln e_{it}}{\partial \ln m_{it}} = b_1 + 2b_2 \ln m_{it} \tag{2}$$

The marginal effect in Eq. (2) can be considered to be the elasticity of emissions with respect to income since EKC in Eq. (1) takes a log–log form. Note that it is similar to "decoupling elasticity" in Tapio (2005). Following Tapio (2005), strong decoupling is happening when $\frac{\partial \ln e_{it}}{\partial \ln m_{it}} < 0$ and weak decoupling occurs when $0 < \frac{\partial \ln e_{it}}{\partial \ln m_{it}} < 0.8$. Refer to Fig. 1 on page 139 in Tapio (2005). It for other types of decoupling. One thing we emphasize is that the sign of marginal effect can be negative regardless of the shapes of EKC. Figure 1 illustrates strong decoupling and different shapes of EKC. The marginal effect is negative when states are located on negatively sloped area of EKCs.

Random or fixed effects models are popular choice to obtain Eq. (1) in previous studies Stern (2004). In the fixed effects model, the term vi is state-specific intercept that captures heterogeneities across states and treated as regression parameters (Stern 2004). As states are different in size, energy mix, climate policies etc., the fixed effects model could be a choice. In the random effects model, v_i is considered to be a random disturbance or unobserved effect which has zero mean (Stern 2004). The drawback of random effects model is omitted-variable bias, in other words, the random effects model requires that there is no correlation between income and v_i (Clark and Linzer 2015). Hausman test (Hausman 1978) is used to decide which model estimates Eq. (1) consistently.

As Stern (1998, 2004) and Lin and Liscow (2013) pointed out, Eq. (1) may be suffering from endogeneity problem due to i) reverse causality (simultaneity bias) and/or ii) omitted variables (or unobserved heterogeneity) bias, which cause the estimates to be biased. According to Kraft and Kraft (1978); Yu and Hwang (1978); Cheng and Lai (1997), the increase in the economic activity, especially more use of energy, would result in increasing in CO_2 emissions. At the same time, the decrease in CO_2 emissions from limiting energy use could result in negative effect on economic growth (Inglesi-Lotz 2016; Ouyang and Li 2018). Erol and Yu (1987) suggested the empirical evidence for the bidirectional causality between economic outputs (income) and energy usage (thus CO_2 emissions) (Shahbaz et al. 2015; Appiah 2018). The other source of endogeneity is omitted variables which make $\ln m_{it}$ to be possibly correlated with state-specific effects v_i, e.g., state tax policy, geographical location, amenities, energy policy, etc., which may cause a serious problem

(Baltagi 2005). Two stage least squares (2SLS) with instrumental variables (IV) technique might be the way to mitigate endogeneity (Wooldridge 2012). Lin and Liscow (2013) used instrumental variables, age dependency ratio and debt service, to address endogeneity in the water quality income relationship across countries.

The present paper identifies two IVs, unemployment rate and the trend variable, to mitigate the endogeneity problem. Both IVs are credible for income with the following reasons. First, according to Okun's law (Okun 1962), the unemployment rate is negatively correlated with GDP (Okun 1962; Cuaresma 2003). For every 1% increase in the unemployment rate, income will decrease roughly by 3% (Prachowny 1993). And unemployment rate is weakly associated with CO_2 emissions (Wang and Li 2021), which is one of requirements to be an ideal IV. According to Granados and Spash (2019), only six states out of 50 states have statistically significant correlation between unemployment rate and emissions (Granados and Spash 2019, Table 1, p.265). Second, the trend variable may serve as a proxy for variables that affect income which are not directly observable but may be correlated with time such as technological change and growth of work force (Stock and Watson 1988). We estimate Eq. (1) using 2SLS with unemployment rate and the trend as IVs.

When analyzing EKC, we assume that the parameters do not change over the sample period. But the environment of economy keeps changing frequently, for example, coal to gas switching, energy policies from different administrations, etc. As such, assuming the constant parameters is probably not reasonable (Zivot and Wang 2006). Estimating parameters over sub-samples or rolling windows of the sample period is a way to test the constancy of the parameters (Zivot and Wang 2006). Clark and McCracken (2009)

described the term rolling which refers to estimating the parameters based on a partial sample of the data. The idea behind rolling analysis is to construct new observations using samples of consecutive observations (H¨allman, 2017). The parameter estimates over the sub- samples won't change much if the true parameters are constant over the entire period of sample. The rolling approach will be able to trace the instability of the parameters if they change over the sub-samples, b_0, b_1 and b_2, in Eq. (1) are estimated using the following steps:

1. Decide a fixed rolling window size, w, which could be challenging. Size of the rolling window might be a concern as Rossi and Inoue (2012) suggest that different window size may lead to different results in practice. We use various window sizes for checking robustness.
2. The number of sub-samples is $N = T − w + 1$ with the fixed w. The first sub-sample includes observations from year 1 to w, the second sub-sample includes observations for year 2 through year $w + 1$, and so on.
3. Estimate Eq. (1) using each rolling window sub-samples from step 2 using 2SLS and collect estimates to plot.

4 Data

For this study, annual per capita personal income and CO_2 emissions per capita are collected for 50 states and Washington D.C. between 1980 and 2020 from Bureau of Economic Analysis (https://apps.bea.gov) and Energy Information Administration (https://www.eia.gov/environment/emissions/state/). Income is deflated using GDP deflator. Table 1 presents basic statistics and Fig. 2 plots the movements of income and emissions.

Table 1 Basic Statistics (2,091 observations)

Variable	Mean	Std. Dev	Min	Max
Real income ($ per person)	38,653	10,804	17,736	82,564
CO_2 emissions (metric tons per person)	23.52	18.25	3.48	38,653
Unemployment rate (%)	5.92	2.11	2.1	17.8

1. Income represents per capita personal income which is collected from Bureau of Economic Analysis (https://apps.bea.gov) and deflated using GDP deflator to make it real income,

2. CO_2 emissions from fossil fuel consumption (residential, commercial, industrial, transportation, and electric power sectors) are collected from Energy Information Administration (https://www.eia.gov/ environment/emissions/state/) and divided by state population,

3. Unemployed percentage of the labor force are collected from Local Area Unemployment Statistics,

U.S. Bureau of Labor Statistics (BLS) (https://www.bls.gov/lau/) and,

4. Number of observations = 51 states in the U.S. including Washington D.C. × 41 years from 1980 to 2020 = 2091

As indicated in Table 1, average personal income is \$38,653/person. Average emission is 24 metric tons/person. Panel A in Fig. 2 shows the movement of emissions with triangles representing the mean of emissions of all the states over the years. Panel A in Fig. 2 shows that the level of emissions varies substantially across states. Wyoming emitted more than 100 metric tons/person, while Washington D.C. emitted less than 10 metric tons/person. It indicates that there might exist heterogeneities among states. Panel A also shows that states with high emissions started decreasing emissions during 2005–2007. The average emissions is somewhat stable with decreasing trend after 2007.

Panel B in Fig. 2 shows the movements of personal income. Unlike emissions, personal income has increased steadily over time except during 2007–2008 due to the financial crisis. Between 1980 and 2020, average personal income has increased from \$24,528/person to \$53,448/person, which means 118% (2.8% per annum) changes. Because emissions are somewhat stable and have started decreasing since 2007 (Panel A), the relationship between income growth and emissions could be negative. As such, the U.S. has been experiencing decoupling between these two as Saha and Muro (2016) insisted.

Unemployment rate (unemployed percentage of the labor force) is also collected to use it as IV from Local Area Unemployment Statistics, U.S. Bureau of Labor Statistics (BLS) (https://www.bls.gov/lau/). As reported in Table 1, the mean of unemployment rate during the sample period is 5.92%. The highest rate is 17.8% and lowest is 2.1%. As shown in Panel C in Fig. 2, unemployment rate has cyclical movements as expected. Unemployment typically rises during recessions and declines during economic expansions (Cuaresma 2003). As discussed, unemployment rate might be a credible IV in 2SLS since it is negatively correlated with GDP (Okun 1962; Prachowny 1993; Cuaresma 2003) and it is weakly associated with CO_2 emissions (Granados and Spash 2019; Wang and Li 2021). Secondary IV is the trend variable. It is a proxy for variables that affect income which are not directly observable but may be correlated with time such as technological change and growth of work force (Stock and Watson 1988). The trend variable takes 1 for 1980 and 41 for 2020.
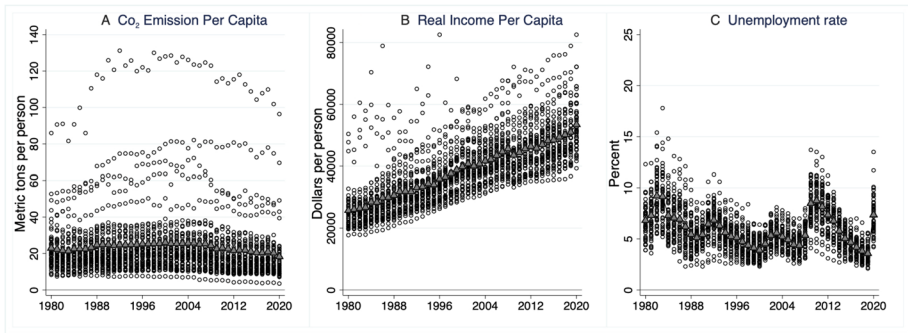
Fig. 2 Plots of CO_2 emissions and personal income. 1. CO_2 emissions from fossil fuel consumption (residential, commercial, industrial, transportation, and electric power sectors) are collected from Energy Information Administration (https://www.eia.gov/environment/emissions/state/) and divided by state population; Wyoming emitted more than 100 metric tons/person, while Washington D.C. emitted less than 10 metric tons/person, 2. Income represents per capita personal income which is collected from Bureau of Economic Analysis (https://apps.bea.gov) and deflated using GDP deflator to make it real income, and 3. Triangles represents annual average for each variable.

5 Results and Discussion

5.1 Rolling EKC Estimation with 2SLS

We estimate[4] Eq. (1) for 27 sub-samples. Each sub-sample contains 15 years (window size = 15) of data for 50 states and Washington D.C., for example, the first sub-sample includes data from 1980 to 1994 and the second sub-sample has data from 1981 to 1995 and so on. Subsequent sub-samples are created by adding one more year and removing the first year from the previous sub-samples. The last sub-sample contains the data from 2006 to 2020. The reason we choose the window size of 15 is twofold. First, there have been major events in energy markets and policy changes which may alter emissions with roughly every decade. For example, 1990 oil shock (Iraqi invasion to Kuwait), Kyoto Protocol in 1997, 2008–09 global financial crisis, and removing Clean Power Plan in 2017. Second, the first structural break in emissions in the sample is detected in the year of 1993 with the unit root test of Carrion-i-Silvestre et al. (2009).[5] As such, the first sub-sample contains the data from 1980 to 1994 (w = 15), which is the reasonable choice. We also build different window sizes to check the robustness of estimates.

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[4] To ensure that we do not have a spurious relationship between CO_2 emissions and personal income, we conducted a panel unit root test, Im–Pesaran–Shin (IPS) (Im et al. 2003) with demean for the entire sample. IPS test allow for a heterogeneous coefficient of lagged CO_2 emissions Baltagi (2005). We rejected the null hypothesis, all panels contain unit roots, indicating that some panels are stationary. The test statistics are not reported here but available upon request.

[5] The Bai-Perron test (Bai and Perron 1998, 2003) detects unknown structural break points in a time series data. The unit root test proposed in Carrion-i-Silvestre et al. (2009), the GLS-based test, may identify multiple structural breaks using the method similar to the Bai-Perron test for a non-stationary time series data. The GLS-based test reveals that there were structural breaks in 1993 & 2001 assuming two breaks, or 1993, 2001 and 2015 with three breaks. Results of the GLS-based test are not reported here and available upon request.

As discussed, first step of estimating EKC is to test endogeneity of income, i.e., ln (m) in Eq. (1). Following Wooldridge (2012), we collect the residuals from the first stage equation, regressing ln (m) on IVs, i.e., unemployment rate and the trend variable. Then Eq. (1) is estimated with the residuals from the first stage. If the coefficient of the residual from the first stage regression is statistically different from zero, we may conclude that ln (m) is endogenous (Wooldridge 2012, p.535). Empirical results reveal that ln (m) in Eq. (1) is indeed endogenous for the entire sample and 9 out of 27 sub-samples. All 9 sub-samples include later years from sub-sample 18 (1997–2011) to sub-sample 26 (2006–2019).

Second step is to test if all IVs are exogenous. If so, 2SLS residuals should be uncorrelated with the IVs (Wooldridge 2012, pp.536–537). To do this, Eq. (1) is estimated by 2SLS and residuals are collected and the residual is regressed on IVs. Under the null hypothesis that all IVs are uncorrelated with 2SLS residual $nR^2 \sim \chi_q^2$ where q is the number of IVs. i.e., unemployment rate and trend variable, are uncorrelated with 2SLS residuals for the entire sample $nR^2 = 0.026$ (P-value=0.99). Unfortunately, only 10 out of 27 sub-samples pass the test at 5% significance level from sub-sample 9 (1988–2002) to sub-sample 18 (1997–2011). Even so, we use both unemployment rate and the trend variable as IVs to estimate EKC because they have credible theoretical foundation. Unemployment rate is correlated with income (Okun 1962; Prachowny 1993; Cuaresma 2003) and not with emissions (Granados and Spash 2019; Wang and Li 2021). Also note that this test is only valid when the homoskedasticity assumption holds (Wooldridge 2012), which may not be the case here. Heteroskedasticities exist for all the sub- samples which are confirmed by the modified Wald test for group-wise heteroskedasticity in fixed effect regression (Baum 2000). All the EKCs are estimated using 2SLS with unemployment rate and the trend variable as IVs in the first stage.

Next step is to decide which model, fixed or random effects model, is used to estimate Eq. (1) consistently using the Hausman test (Hausman 1978). The null hypothesis is that the preferred model is random effects or v_i, is uncorrelated with the regressors (Greene 2000). If we fail to reject the null, random effects model is preferred. In our case, the null hypothesis is rejected ($\chi^2, = 7.5$ and P-value=0.02) for the entire sample which means the fixed effects model is preferred. The null is rejected for sub- samples 2 to 8 and sub-samples 24 to 27 while we fail to reject the null for other sub-samples. Deciding which model to use is challenging with the mixed result. We choose fixed effects model to estimate rolling EKCs with the following reasons. First, state-specific components, v_i, e.g., energy policies, industry structure, etc., may not be random and should be added to the model as regression parameters. Second, the drawback of random effects model is omitted-variable bias, in other words, the random effects requires that there is no correlation between income and v_i (Clark and Linzer 2015). As mentioned in the first step of estimating EKC, income is endogenous for the sub-samples 17 to 25.

5.2 Empirical Results

Figure 3 is developed using estimates from 2SLS panel fixed effects model and presents fitted EKCs on the scatters with actual observations for 12 selected sub-samples, 1984–1998 (sub-sample 5, Panel A in Fig. 3), 1986–2000 (sub-sample 7, Panel B in Fig. 3), and so on. Panel L in Fig. 3 presents the fitted EKC with the last sub-sample from 2006 to 2020 (sub-sample 27). The results for all 27 sub-samples are available upon request. As shown in Fig. 3, shapes of EKC for early sub-samples take an inverted-U, in other words, the sign of the coefficient
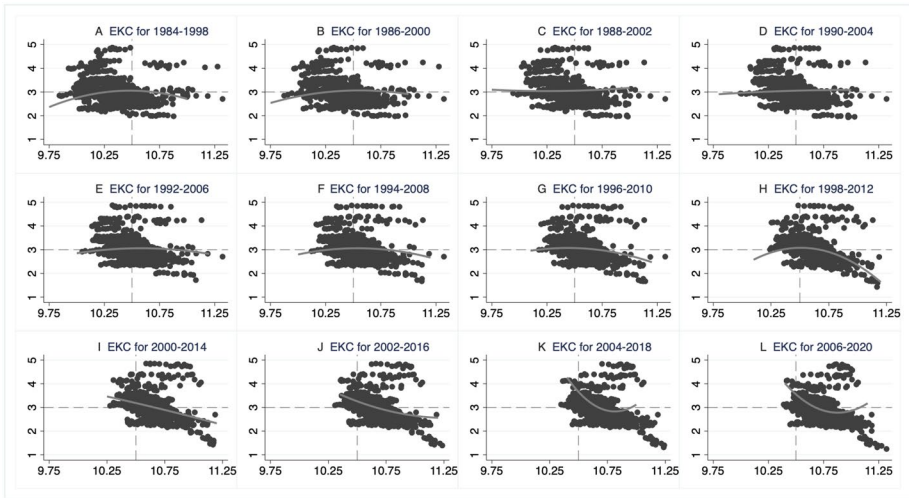
Fig. 3 Emissions, income, and fitted EKC. 1. Horizontal axis is logged income and vertical axis indicates logged emissions for all twelve panels. 2. Gray vertical and horizontal lines in each scatter diagram are the average of income and emission for the entire sample to indicate the relative position of the scatter, and 3. Fitted lines are $\ln e_{it} = \widehat{b}_0 + \widehat{b}_1 lnm_{it} + \widehat{b}_2 (lnm_{it})^2$; Coefficients are estimated using the 2SLS panel fixed effects model
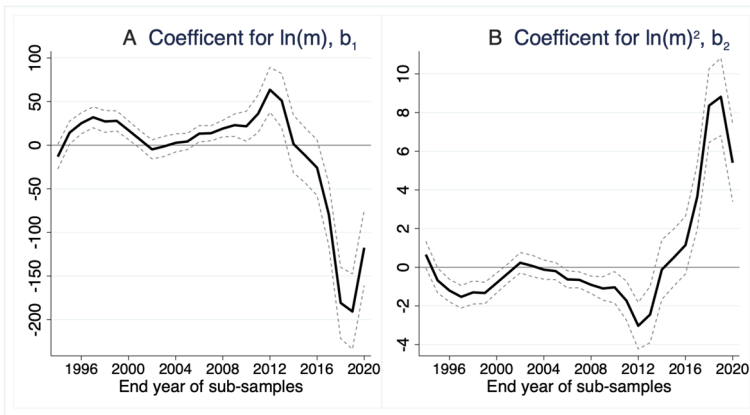
Fig. 4 Estimated coefficients of income. Notes: In Panels A and B, black solid lines are the coefficients of logged income and logged income squared in Eq. (1), respectively, and dotted lines indicate 95% confidence intervals. Note that b1 > 0 and b2 < 0 indicate inverted U-shaped EKC

for squared income, $\widehat{b}_2$, is negative. See Panel B in Fig. 4 which plots $\widehat{b}_2$ in Eq. (1) over the sub-samples. Panel B in Fig. 4 shows that most of $\widehat{b}_2$ over the early sub-samples take negative sign. From sub-samples 9 to 13 (Panels D, E, and F in Fig. 3, for example), $\widehat{b}_2$ are not

statistically significant and the shape of EKCs are linear. Over time, EKCs have been transformed towards inverted U-shape curves "again" like Panels H and I in Fig. 3.

The EKC curve becomes a negative sloped line (Panel J) and has been changed to U-shaped curve as shown in Panels K and L in Fig. 3. We can observe these changes in Panels A and B in Fig. 4 as well. As indicated, when EKCs are inverted U-shaped, $\hat{b}_1 > 0$ and $\hat{b}_2 < 0$. Most of $\hat{b}_1$, is positive in the early sub-samples as shown in Panel A in Fig. 4 and negative in some of the later sub-samples. Panel B shows that $\hat{b}_2$ is negative for many of the early sub-samples but become positive in the later sub-samples. Note that the last five sub-samples have positive $\hat{b}_2$ and the last two, that is, from sub-samples 24 to 27, have statistically significant positive $\hat{b}_2$, which make the EKCs to be U-shaped (Panel B in Fig. 4).

As illustrated in Fig. 1, strong decoupling (negative decoupling elasticity) between income growth and emissions can be observed when most of states are located on the negatively sloped area of the.

EKCs regardless of their shapes. And indeed it is happening in the U.S. as shown in Panels J, K and L in Fig. 3. Strong decoupling with inverted U-shaped EKC or negatively sloped linear EKC is desirable as emissions decrease with economic growth, for example, Panels H and I in Fig. 3. Strong decoupling with U-shaped EKC is not desirable. Emissions decrease with economic growth initially, however, emissions start increasing at some point when most of states move to positively sloped area of the U-shaped EKC, for example, Panels K and L in Fig. 3. As shown in Fig. 3, there are some of outliers in the Northeast and Southeast corners especially in later sub-samples, e.g., Alaska and Wyoming (high income and high emissions sates) and Washington DC (high income and low emissions state).[6]

We dropped these states and re-estimated Eq. (1). We obtain similar results as reported in Fig. 5. For the additional robustness checking, Eqs. (1) is re-estimated with different window sizes such as w = 13, w = 14, w = 16, w = 17, and w = 18. Estimated coefficients are slightly different in magnitude but do not change much.

Figure 6 presents marginal effects of income on emissions in Eq. (2) over the sub-samples. As discussed, marginal effects of income depend on the level of income. Figure 6 reports marginal effects of income with different income levels such as 25th percentile (Panel A), median (Panel B), and 75th

percentile levels of income (Panel C). Marginal effects can be interpreted as percentage changes in emissions with respect to one percent change in income since we use the log–log model. Figure 6 shows that initially marginal effects are positive and magnitudes are less than 0.8 with a decreasing trend. It implies that income growth outpaces emission changes or weak decoupling (Tapio 2005). Also it implies that many states are located on positively sloped area of inverted U-shaped EKC like Panel B or C in Fig. 3.

Marginal effects become negative from sub-sample 17 for 25th level of income (Panel A in Fig. 6), sub-sample 15 for median income level (Panel B in Fig. 6), and sub-sample 13 for 75th levels of income (Panel C in Fig. 6). Marginal effects keep decreasing except for 75th level of income. It indicates that the U.S. is experiencing strong decoupling as described in Saha and Muro (2016). As shown in Panel C in Fig. 6, marginal effects of high-income states started rising in the later sub-samples, which is because rich states are located on the right hand side of the U-shaped EKC like Panel L in Fig. 3.

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[6] Studentized residuals for these states are larger than $+2.5$ (Alaska and Wyoming) or smaller than -2.5, which may be considered as the outliers.
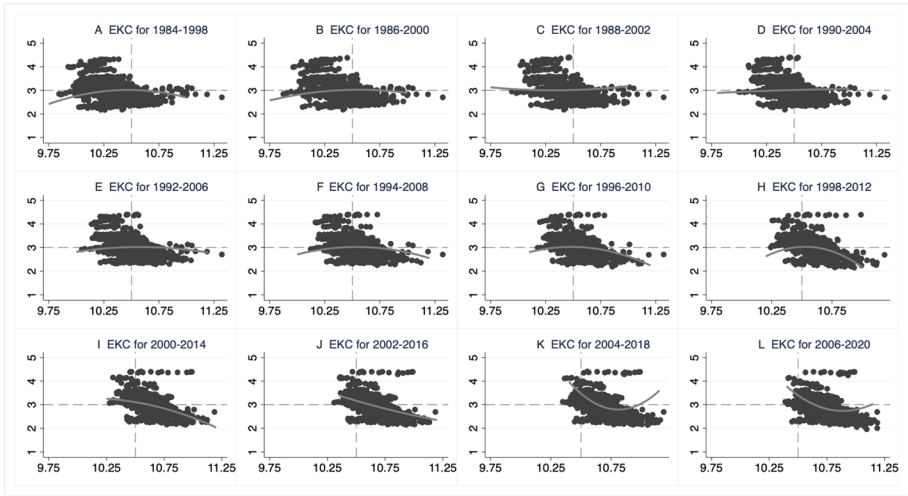
Fig. 5 Emissions, income, and fitted EKC after dropping AK, WY, and DC. 1. Horizontal axis is logged income and vertical axis indicates logged emissions for all twelve panels, 2. Gray vertical and horizontal lines in each scatter diagram are the average of income and emission for the entire sample to indicate the relative position of the scatter, and 3. Fitted lines are $\ln e_{it} = \hat{b}_0 + \hat{b}_1 lnm_{it} + \hat{b}_2 \left(lnm_{it} \right)^2$; Coefficients are estimated using the 2SLS panel fixed effects model
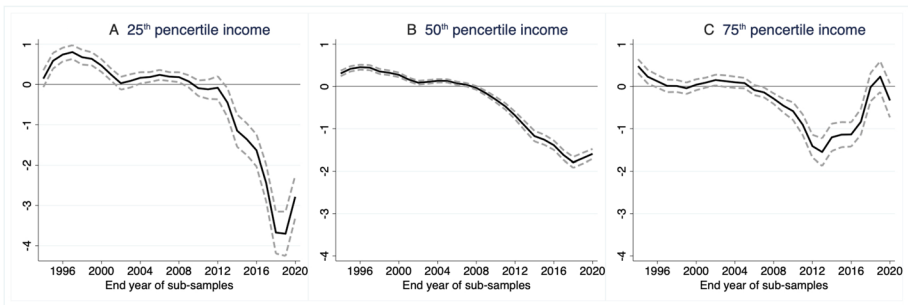
Fig. 6 Marginal effect of income. Dotted lines indicate 95% confidence interval of marginal effect; marginal effect can be interpreted as percentage change in emissions with respect to one percent change in income since we use the log–log model

6 Conclusion and Policy implications

The primary contribution of this study is to show that the recent decoupling of income growth and emission might be illusionary. This paper demonstrates that the U.S. has the U-shaped EKC with recent changes in emissions in transportation sector, strong electricity demand, reversals of eco-friendly energy policies, and the recent manufacturers' onshoring. Rolling EKCs for panel fixed effects model with data for 50 states and Washington D.C. from 1980 to 2020 are used to trace the shapes of EKCs over time. We find that the shapes of EKCs have changed over time from positive linear to inverted U and from inverted U to U. After 2015, EKC has taken on the U-shaped form with many states located

on the negatively sloped portion of the U-shaped EKC like Panels K and L in Fig. 3. While the relationship between emissions and income growth remain negative indicating strong decoupling, emissions may eventually begin to increase as the economy grows.

The question is why EKCs have changed to U-shaped from inverted U-shaped. The reason is, for example, that relatively more observations in Panel I in Fig. 3 (sub-sample 21, EKC for 2000–2014) had moved to northeast, i.e., high income and high emissions area, in Panel L in Fig. 3 (sub-sample 27, EKC for 2006–2020). The high income and high emissions states in sub-sample 25 may cause the change in EKC shape. These states are Alaska, Indiana, Iowa, Kansas, Louisiana, Missouri, Montana, North Dakota, Pennsylvania, Texas, Utah, and Wyoming. As shown in Fig. 3, especially the later sub-samples, income and emissions scatters have moved to the northeast not moved to southeast. The potential reasons of our finding, i.e., transforming the inverted U shaped EKC to the U shaped EKC after 2015, could be:

- A significant increase in emissions from the transportation sector (Irfan 2019), which currently is the largest emitter in the U.S. Power sector fall below the transportation sector from 2016 (EIA 2017).
- Strong electricity demand in recent years when the U.S. has experienced some of the hottest summers and coldest winters leading to use air condition and heating (EIA 2019). Shift towards electric vehicles might be another reason for the strong electricity demand.
- Reversals of eco-friendly energy policies rollback of environmental regulations by the U.S. administration. Under the Trump administration, several environmental regulations were rolled back or weakened, including the Clean Power Plan, which aimed to reduce emissions from power plants. In addition, revised important terms in the Endangered Species Act, relaxed bans on oil & natural gas extraction, and lessened the Coal Ash Rule, which controls and monitors the coal waste disposal (BBC 2019; Baker 2020; Sepeda-Miller 2020).
- Direct industrial greenhouse gas emissions has increased (EPA 2023). due to reshoring or onshoring of the U.S. manufacturing industry, bringing operations back to the U.S. from offshoring for cost saving, government incentive and quality control (Baschuk 2022; Carr et al. 2022).

The policy implication is clear; efforts should be made to transform the U-shaped EKC back to an inverted U-shaped EKC, even in cases where absolute decoupling is observed. This can be achieved through policy changes in energy shifts, such as implementing and reinforcing energy efficiency standards for appliances, buildings, and industrial processes, establishing a carbon pricing mechanism to incentivize emission reduction, and allocating increased funding for public transportation systems to promote cleaner modes of transportation and decrease individual car usage. By adopting these policy measures, we can reshape the EKC and move towards the desired inverted U-shaped curve.

Note that the EKCs in this study include only income and income squared as explanatory variables. We believe that the fixed effects panel model controls most of heterogeneities across states but adding other variables such as energy mix or industrial structure might improve estimating EKCs, which could be future research agenda. Also, in-depth investigations of the impact of the potential reasons of our findings listed above are necessary as well as to identify additional factor may contribute the U-shaped EKC with absolute decoupling. Therefore, it is clear that further research is warranted to explore these aspects thoroughly.

Data availability The data used in this study are available from the public domains, for example, U.S. Bureau of Economic Analysis, U.S. Energy Information Administration, and U.S. Bureau of Labor Statistics.

Declarations

Competing of interest We declare that we have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

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