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Does income growth affect renewable energy or carbon emissions first? A Fourier-based analysis for renewable and fossil energies

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ABSTRACT

Environmental issues and global warming continue to drive researchers to investigate the validity of hypotheses regarding the environment. The environmental Kuznets curve (EKC) is the most popular hypothesis in the environmental economics, prompting researchers to propose a new hypothesis based on it. In this framework, the renewable energy Kuznets curve (RKC) hypothesis was proposed as a prerequisite for the EKC. According to the RKC, at the beginning of the economic growth process, an economy tends to use fossil fuels and reduce the use of renewable energy (RE) because fossil fuels are cheap. Then, as economic growth process continues and income reaches a threshold/turning point, the economy begins to rely more on RE sources. Such RE use indicates a U-shaped association between income and RE (the RKC hypothesis). Based on this information, the study compares the validity of EKC and RKC for the United States (USA) and aims to answer the question of whether the increase in per capita income initially increases RE or decreases carbon emissions. To test and compare the EKC and the RKC simultaneously and to capture smooth structural shifts, this paper uses time series techniques based on the Fourier method from 1973 to 2022. This paper presents results that support the validity of RKC and EKC. The outcomes also illustrate that the turning point of income is lower for the RKC hypothesis than for the EKC model. This suggests that the RKC hypothesis is a prerequisite for the EKC hypothesis. In other words, a higher income first helps in the deployment of renewable energies and then in the reduction of carbon emissions.

Nomenclature

Abbreviations		Symbols	
ARDL	Autoregressive Distributed Lag	cos	Cosine
CO_2	Carbon Dioxide	d	First Difference
EKC	Environmental Kuznets Curve	ε_t	Error Term
EF	Ecological Footprint	k	Frequency
EIA	Energy Information Administration	ln	Logarithm
FEC	Fossil Energy Consumption	sin	Sine
FMOLS	Fully Modified Ordinary Least Squares	T	Time Period
GDP	Gross Domestic Product	t	Time Trend
LCC	Load Capacity Curve	π	Pi-Value
OECD	Organisation For Economic Co-Operation And Development		
RE	Renewable Energy		
REC	Renewable Energy Consumption		
RKC	Renewable Energy Kuznets Curve		
URB	Urbanization		
USA	United States of America		

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1. Introduction

Many models and hypotheses have been propounded by researchers for the income-energy–environment links. The energy ladder hypothesis postulates that households seeking to maximize their utility under neoclassical economic theory begin to use more demanding fuels as their income increases [1–3].

The *green paradox hypothesis* posits that an increasing tax on CO_2 emissions can lead to further depletion of current fossil sources, which in turn destroys the environment [4,5]. The rebound effect hypothesis focuses on the results of energy conservation policies and the potential energy savings ([6]; Chakravatary et al., 2013). Accordingly, this hypothesis states that an upsurge in energy productivity can reduce energy prices and a decrease in energy prices can increase energy consumption [7]. The "pollution haven" hypothesis stresses that relatively weak ecological policies and regulations in some economies may induce multinational companies to relocate their polluting and dirty activities to these countries [8–10]. Therefore, these transfers may reduce environmental quality in host countries [11]. However, the pollution halo hypothesis argues that the eco-friendly and relatively modern technologies used by multinational firms can improve ecological quality in host countries as they transfer these technologies to the host countries [10,12].

The stochastic impacts by regression on population, affluence, and technology *(STIRPAT) model* focuses on the influences of population, economic development, and technological development on environmental deterioration [13–15]. The STIRPAT model assumes that population and technological progress increase or decrease environmental degradation, while the influences of the economic growth process on the environment are complex [14].

The *EKC* postulates an inverted U-shaped relation between income and ecological deterioration. As the economy expands, environmental quality initially decreases and then increases again as soon as income reaches a turning point [16,17]. The EKC hypothesis explains such a relationship: in the initial phase of economic growth, mainly fossil fuels are used. As the economy continues to grow and economic growth leads to an increasing demand for better environmental quality, fossil energy sources are replaced by relatively new and clean RE sources [18]. Annexes 1-6 show the number of publications in the Web of Science (WoS) database on these hypotheses/models from 2000 to 2023. Based on these figures, it can be seen that researchers have paid attention to these hypotheses, especially in recent years. It can also be observed that the EKC has been tested more than all the other five hypotheses combined. This means that the EKC is by far the most popular hypothesis in the environmental economics literature, leading to new research and implications regarding this hypothesis.

Yao et al. [19], who focused on the EKC, propounded a new model in relation to this hypothesis, which implies a U-shaped link between RE use and income. According to this model, a decline in ecological quality at the beginning of economic progress may be due to a decrease in RE use. Thereafter, in the later phases, there may be an increase in ecological quality due to the continued use of RE sources. This argument refers to a U-shaped link between RE and income and is referred to as the *RKC*.

Based on the EKC, researchers have proposed various hypotheses over time, such as the RKC [19] and the load capacity curve (LCC) [20]. Since the RKC and LCC hypotheses include ecological quality proxies such as RE and load capacity factor (LCF) as the explained variables, the relationship between these indicators and GDP is expected to be U-shaped. Analyzing the RKC hypothesis is a new research topic and there are only a few studies.

Studies have explored the validity of the RKC for various countries. However, no study has yet tested the RKC for the USA. The studies have generally used linear econometric methods and neglected structural breaks. Therefore, this study aims to expand the existing knowledge by comparatively analyzing RKC and EKC for the USA using Fourier-based methods.

As can be seen from the Energy Information Agency (EIA) data in Fig. 1, the USA continues to consume a large amount of energy from fossil fuels. However, this share has tended to decrease, and the share of RE has increased over the period observed. Due to the dominant role of fossil fuels, the level of CO_2 in the USA has not reached the desired levels, although it has fallen in recent years as shown in Fig. 2.

The level of CO_2 emissions in 2022 was very close to the 1988 level, but above the 1990 level. Considering that the Kyoto Protocol aims to reduce emissions by 5 % compared to the 1990 level, it becomes clear why the USA has not yet signed the Protocol. This study inspects the influences of fossil and RE sources on ecological quality in the USA under the EKC and RKC.

The USA is a suitable sample country for the comparison of RKC and EKC due to its high CO_2 emissions and RE use. The high level of environmental pollution, RE consumption, and income in the USA are the main motivations for this study. The reason why the study focuses on the USA is because it is the largest economy in the world, and the second largest country that using the most RE and emits the most CO_2. It is well known that there is a close relationship between the size of the economy and the use of RE and CO_2 emissions. Against this background, the study analyzes whether economic size primarily increases CO_2 emissions or promotes the use of RE.

The motivation for the study is to examine whether the US directs its increased per capita income first to promote RE utilization or to reduce CO_2 emissions. Based on this motivation, the study seeks answers to three main research questions. 1) Is RKC valid for the USA? 2) Does the income turning point of RKC precede EKC? 3) Is urbanization a factor influencing RE in the USA? The study aims to provide recommendations for policymakers by answering these research questions and the nonlinear link between RE and income in carbon neutrality policies of the USA.

The study makes multiple contributions to the existing literature. First, the RKC theory has never before been tested in the USA. Therefore, one of the greatest strengths of this paper is that it is the first to examine the RKC for the USA. Second, this study contributes to existing knowledge by comparing the turning points of the RKC and EKC for the USA with Fourier transforms. Third, the paper applies Fourier-based methods to account for breaks in the USA in recent decades. Considering the oil crisis of 1973–1974, the high inflation rates in the USA in the early 1980s, the war between the USA and Iraq, the financial crisis of 2008, the sharp expansion of the FED balance sheet in times of crisis, and the coronavirus-19 pandemic, time series techniques based on the Fourier transform can provide more reliable and efficient output.

Section 2 presents the literature review, while Section 3 shows the mathematical background of the EKC and RKC hypotheses. The model

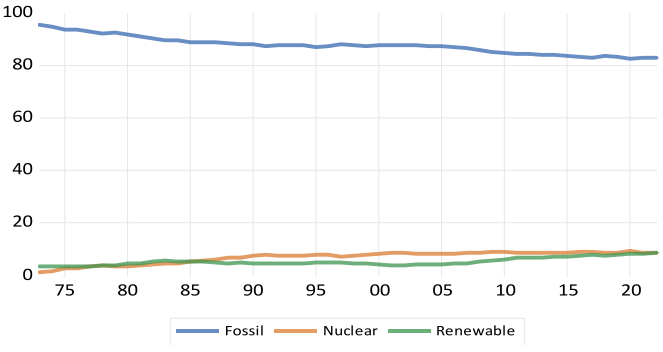

Fig. 1. Share of energy sources in energy consumption mix in the USA (%, 1973–2022).
Source: EIA [77].

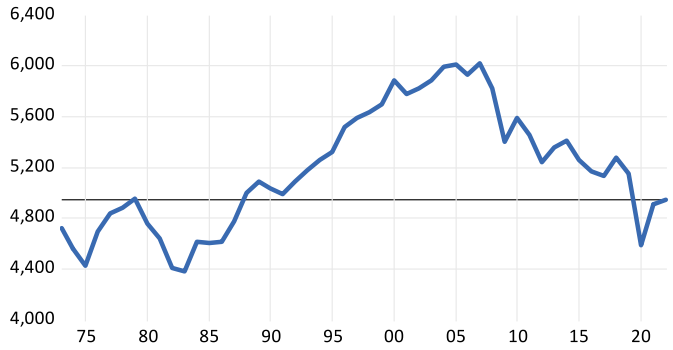

Fig. 2. CO_2 emissions in the USA (million metric tons, 1973–2022).
Source: EIA [77].

and the dataset are presented in Section 3. The methodology is defined in Section 4. Section 5 reports the results, while Section 6 concludes the paper.

1.1. literature review

Researchers have investigated environmental issues using various indicator models. Asghar et al. [21] analyzed the determinants of energy consumption, Zhang et al. [22] explored the factors affecting the conservation of natural resources, Zhao et al. [23] and Pata and Karlilar [24] investigated the macroeconomic regressors of LCF. In the current literature, various studies continue to analyze and discuss environmental issues in detail.

Environmental issues are one of the components of the development goals in the policy agenda of many countries, and the USA is one of the most important of these countries. As the USA, together with China, is the country that produces the most CO_2 emissions worldwide, the determinants its pollution indicators have been and continue to be studied empirically by researchers.

The environmental impacts of the urban population are an important topic of discussion for the USA, as more than 80 % of the US population lives in urban areas. Dogan and Turkekul [25] used ARDL and reported that urbanization is driving up CO_2. Khan et al. [26] noted that urbanization upsurges CO_2 emissions. Tawfeeq [27] concluded that urbanization mitigates CO_2 emissions in 48 US states.

Researchers have extensively investigated the effects of income and energy use on CO_2 emissions in the USA in detail. Aslan et al. [28] performed the dynamic ARDL and noted that the EKC is not valid. Alola and Ozturk [29] employed ARDL and verified the EKC. Sun et al. [30] utilized quantile ARDL and supported the EKC. Pata [31] used the Bayer-Hanck cointegration test and confirmed the validity of the EKC. In contrast, Wang and Kim [32] noted that the EKC took on a U-shaped form after 2015. The studies have generally looked at CO_2 emissions for the USA and found that there is a non-linear relationship between income and CO_2. In addition, most of these studies have determined that energy consumption, which is dominated by fossil fuels, is a factor that increases CO_2 emissions.

There is a huge literature on EKC, and this literature has lost none of its popularity to date [33,34]. Many papers to date have tested the EKC in the USA. Some papers have supported the EKC (see, e.g., Ref. [17,31,35,36]), but others have provided evidence that the EKC hypothesis is not valid (see e.g., Ref. [37–39]). Some studies have analyzed the EKC for the USA based on the ecological footprint (EF). Zafar et al. [40] employed ARDL and supported the EKC for the EF. Usman et al. [41] employed ARDL and concluded that renewable energy and income mitigate the EF. Usman et al. [42] utilized ARDL and found that EKC is valid for EF, but not for CO_2 emissions. Saqib et al. [43] employed quantile ARDL and noted that EKC is valid for the EF. Joof et al. (2024) utilized ARDL and reported the validity of the EKC.

In the literature, there is no consensus among researchers on the ecological impacts of urbanization and the validity of EKC for the USA. Many studies have found that fossil fuels trigger environmental degradation in the USA, and researchers agree on this point (see, e.g., Ref. [44,45]). In contrast, various studies have emphasized renewable energy as the driving force for CO_2 reduction in the USA (see e.g., Ref. [46–48]). However, previous studies have examined RE as a linear determinant of CO_2 for the USA. According to Yao et al. [19], RE can be influenced by economic growth and this interaction can be non-linear (quadratic). In this context, Yao et al. [19] proposed the RKC hypothesis and compared this hypothesis with EKC. If the income turning point of RKC is earlier than that of EKC, the increase in income in the country under study first promotes renewable energy and then reduces ecological degradation. Comparing the RKC and the EKC is critical to environmental policy making, but no researcher has yet analyzed the validity of the RKC for the USA. In their seminal study, Yao et al. [19] supported the RKC hypothesis by using panel estimators for 17 countries. Wang et al. [49] employed panel data estimators and noted that the RKC is valid for 67 countries. Nabaweesi et al. [50] employed a pooled mean group estimator and supported the RKC in five East African nations.

So far, studies have used the ARDL and its derivatives (bootstrapped, dynamic, etc.) to analyze ecological degradation in the USA. This is the first research gap in the literature, as the corresponding approaches neglect structural breaks. This study minimizes potential estimation biases by including structural breaks in the modeling with Fourier transforms. The second research gap in the literature is that there is no study that analyzes the RKC for the USA. This study aims to fill the second research gap by comparatively analyzing the validity of RKC and EKC for the USA.

2. Mathematical background of the EKC and RKC hypotheses

A quadratic function that can be written as $y = f(x) = ax^2 + bx + c$. For this quadratic function, an extreme point is usually maximized or minimized [51]. The first derivative $f'(x)$ plays a key role in exploring the extreme values of the function [52]. The first derivative must be equal to zero for a maximum or minimum point, which is called the first-order condition [51]. The first-order derivative of y concerning x, which is equal to zero, can be expressed as in Eq. (1):

$$\frac{dy}{dx} = f'(x) = 2ax + b = 0 \tag{1}$$

where x is computed as in Eq. (2):

$$x = -\frac{b}{2a} \tag{2}$$

As Baldani et al. [51] and Chiang and Wainwright [52] clearly express, the first-order condition is necessary but not sufficient to determine whether an extreme point implies a maximum or a minimum. Such an investigation requires the investigation of the second-order condition. For the above function, the second-order derivative can be expressed as in Eq. (3):

$$\frac{d^2y}{dx^2} = f''(x) = 2a \tag{3}$$

If $2a > 0$, the extreme point indicates a minimum, while the extreme point implies a maximum if $2a < 0$.

Next, the study considers the mathematical formulations of the EKC and RKC hypotheses. The EKC model can be illustrated as in Eq. (4):

$$ED = a_1 y + a_2 y^2 \tag{4}$$

The RKC model can be depicted as in Eq. (5):

$$RE = b_1 y + b_2 y^2 \tag{5}$$

ED, y, y^2, and RE represent environmental deterioration, income, income squared, and RE use, respectively. For the EKC and RKC models,

the first-order conditions can be shown as in Eqs. (6) and (7), respectively:

$$\frac{dED}{dY} = a_1 + 2a_2 y = 0 \quad (6)$$

$$\frac{dRE}{dY} = b_1 + 2b_2 y = 0 \quad (7)$$

For the EKC model, y is calculated as $-\frac{a_1}{2a_2}$, while y is calculated as $-\frac{b_1}{2b_2}$ for the RKC model. In addition, the second-order condition for the EKC model is represented as in Eq. (8):

$$\frac{d^2ED}{dY^2} = 2a_2 \quad (8)$$

If a_2 is lower than 0, $2a_2$ is lower than 0, and the extreme point indicates a maximum. In addition, for the RKC model, the second-order condition is demonstrated as in Eq. (9):

$$\frac{d^2RE}{dY^2} = 2b_2 \quad (9)$$

If b_2 is higher than 0, $2b_2$ is higher than 0, and the extreme point indicates a minimum. These explanations indicate that the possible extreme/turning points of the EKC and RKC models can be computed. Furthermore, whether the extreme points indicate a maximum or minimum can be easily detected through the coefficient of y^2. The EKC and RKC hypotheses are graphically shown in Fig. 3.

In Fig. 3, ED depicts the ecological deterioration. An important conclusion is that the turning point of the RKC model occurs before that of the EKC model, which is consistent with the explanations discussed earlier. According to this, an upsurge in income provides a rise in RE use after income reaches y1. Thereafter, as income heightens and reaches the level of y2, the ecological quality will increase.

3. Empirical models and data

To investigate whether the EKC and RKC hypotheses dominate in the USA, this paper sets up the empirical models in Eq. (10) and Eq. (11):

$$\ln CO_{2t} = \delta_0 + \delta_1 \ln Y_t + \delta_2 (\ln Y)_t^2 + \delta_3 \ln FEC_t + \delta_4 \ln REC_t + \varepsilon_t \quad (10)$$

$$\ln REC_t = \lambda_0 + \lambda_1 \ln Y_t + \lambda_2 (\ln Y)_t^2 + \lambda_3 URB_t + \varepsilon_t \quad (11)$$

Theoretically, the EKC model is shown in Eq. (10), while the RKC model is shown in Eq. (11). The theoretical basis of these equations is established by considering the technique effect proposed by Grossman and Krueger [53]. When per capita income exceeds a certain threshold, countries can allocate funds to projects that can support the development of clean technologies with technique effect. In addition, policymakers may find the opportunity to promote the use of RE through improved financial opportunities. In this context, the study bases the theoretical foundation of Eqs. (10) and (11) on the EKC and RKC hypotheses, respectively.

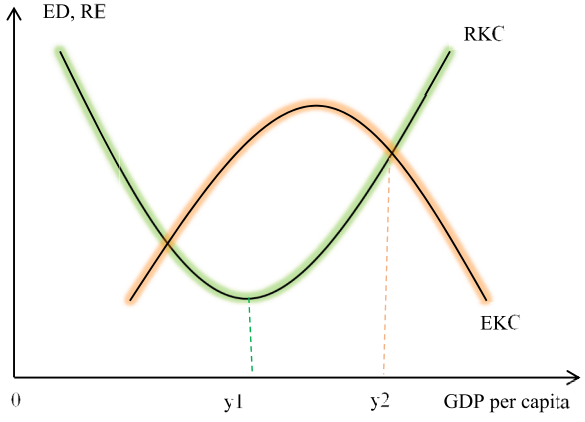

Fig. 3. Graphical representations of the RKC and EKC hypotheses.
Source: Yao et al. [19].

The EKC hypothesis illustrates that income growth first increases and then decreases environmental degradation. In other words, economic expansion can help to limit the environmental damage a country has caused in the past in the future. Switching from fossil fuels to renewable fuels is a crucial option to minimize environmental damage. In this context, a country's economic progress can help finance investment in RE, and there may be a non-linear association between income and RE. The RKC explains this non-linear relationship by noting that at a certain turning point, a country's economic expansion can theoretically accelerate RE investment in that country.

CO_2 is one of the most important causes of global warming and many researchers use CO_2 as environmental pollution [54–56]. Income and the squared form of income are used in this study following Grossman and Krueger [53]. The established quadratic model implies that there may be an inverted U-shaped association between income and pollution. Fossil fuels are one of the most important causes of CO_2 emissions [57] and are therefore included in the model due to their high explanatory power. In many recent studies, REC has been found to be one of the best options for CO_2 reduction [58,59]. In view of this, the study includes REC as an explanatory variable along with FEC in the model.

Some works have explored the determinants of REC. Yang et al. [60] found that URB hinders the development of REC in China. In contrast, Han et al. [61] reported that URB has no effect on REC in China. Islam et al. [62] noted that URB reduces REC in Bangladesh. Su et al. [63] emphasized that URB is a supporting factor for REC in 116 countries. Intensive energy consumption in urban areas can affect FEC and REC in various ways, and therefore, the study analyzes the impact of URB on REC in the USA. The study considers REC as the dependent variable in Eq. (2) under the RKC hypothesis. The RKC hypothesis shows that income is a factor that increases REC beyond a certain income level, and theoretically, renewable energy indicators are considered as dependent variables in RKC models. Table 1 reports the variables under consideration.

If δ_1 is proves to be significant and positive and δ_2 proves to be significant and negative, the EKC hypothesis prevails. In addition, if λ_1 is found to be significant and negative and λ_2 is found to be significant and positive, the RKC hypothesis dominates. If the empirical findings indicate that both hypotheses prevail, then the turning point of income should be lower for the RKC model than for the EKC model. The turning point for GDP per capita is computed as $-\delta_1/2\delta_2$ for the EKC model, while it is computed as $-\lambda_1/2\lambda_2$ for the RKC model.

RE sources are clean and eco-friendly, while fossil fuels are pollute and are bad for the environment. Hence, the coefficients of δ_3 and δ_4 are expected to be positive and negative, respectively, as many previous papers find similar outputs (see, e.g., Ref. [17,64,65], among others). In contrast to Sun et al. [66], Danish et al. (2020) stress that urbanization

Table 1
Variables in the models.

Variable	Symbol	Definition	Source
Environmental destruction	CO_2	CO_2 emissions (million metric tons)	EIA [77]
Income	Y	GDP per capita (constant 2015 USD)	World Bank [80]
Fossil energy consumption	FEC	Quadrillion Btu	EIA [77]
Renewable energy consumption	REC	Quadrillion Btu	EIA [77]
Urbanization	URB	Urbanization (% of total population)	World Bank [80]

results in an increasing demand for energy. Therefore, the coefficient of urbanization (λ_3) can be either positive or negative, depending on how the energy need stemming from the urbanization process is met.

4. Methodology

In this section, the procedures for testing for unit roots and cointegrationare presented. As mentioned earlier, unit root and techniques based on the Fourier method are used in this study. The four-stage empirical strategy of the study is shown in Fig. 4.

As part of the empirical strategy, the study first conducts a unit root analysis. In this stage, the study uses the Fourier-Lagrange multiplier (Fourier LM) unit root test by Enders and Lee [67]. This test takes into account sudden changes in the series (possible structural breaks due to shocks such as war, pandemic, economic crisis, etc.) with Fourier transformations and thus helps to correctly determine the stationarity of the series. In the second stage, the study analyzes the validity of the EKC using the Fourier-Shin cointegration test of Tsong et al. [68] and the long-run estimator. In this stage, the study calculates the effects of Y, FEC and REC on CO_2 in terms of elasticity by adding Fourier terms to the FMOLS. In the third stage, these processes are repeated for the RKC hypothesis and the study calculates the effects of Y and URB on REC in terms of elasticities. In the final step, the study compares the results of the EKC and RKC hypotheses and discusses whether income initially incentivizes REC or CO_2 reduction in the USA economy.

4.1. Fourier LM unit root test

To check the unit root, Enders and Lee [67] proposed a Fourier-based approach and the first step can be shown as in Eq. (12):

$$y_t = \alpha(t) + \rho y_{t-1} + \gamma t + z_t \tag{12}$$

where $\alpha(t)$ is the deterministic function for t. ρ denotes the coefficient of the lagged variable to prevent autocorrelation, γ illustrates the coefficient of the time trend, and z_t shows error term. The Fourier approximation can be used to define $\alpha(t)$. This model can be described as in Eq. (13):

$$\alpha(t) = \alpha_0 + \sum_{k=1}^{n} \mu_k \sin(2\pi kt/T) + \sum_{k=1}^{n} \vartheta_k \cos(2\pi kt/T) \tag{13}$$

where α_0 represents the constant term, k denotes the particular frequency, μ_k and ϑ_k illustrate the coefficients of the trigonometric terms, and and π is the pi value, . Under a single frequency, Enders and Lee [67] used Eq. (14) for unit root testing:

$$\Delta y_t = w y_{t-1} + a_1 + a_2 t + a_3 \sin(2\pi kt/T) + a_4 \cos(2\pi kt/T) + u_t \tag{14}$$

where Δ is the diffirence indicator, and u_t is the error term. To test the H_0 of a unit root described by $w = 0$, Enders and Lee [67] compared the test statistic with the critical values.

4.2. Fourier-Shin cointegration test

To check the cointegration, Tsong et al. [68] first considered the following regression model in Eq. (15):

$$y_t = d_t + x_t'\beta + \eta_t, d_t = \delta_0 + f_t, \eta_t = \gamma_t + z_{1t}, \tag{15}$$

In Eq. (15), f_t is the Fourier approximations, and d_t includes a constant term and Fourier transformations. In the second step, Eq. (16) can be investigated to test the null hypothesis of cointegration:

$$y_t = \sum_{i=0}^{m} \delta_i t^i + \alpha_k \sin\left(\frac{2k\pi t}{T}\right) + \beta_k \cos\left(\frac{2k\pi t}{T}\right) + x_t'\beta + \upsilon_{1t} \tag{16}$$

If the test statistic is lower than the critical values, then there is cointegration in the model. Also, if the calculated F-statistic is higher than the critical values, the Fourier terms should be used in the model.

5. Findings

The results of the unit root test are depicted in Table 2. Accordingly, the LM unit root test provides evidence that all variables under consideration have a unit root in their levels, but no unit root in their first differences.

In this paper, the FMOLS developed by Phillips and Hansen (1990) is performed for the parameter estimates. Panel A in Table 3 depicts the results for the EKC model. As can be seen in Panel A1, the null hypothesis cannot be rejected, and the F-statistic indicates that the Fourier approximations should be used, which means that the FMOLS estimator with Fourier terms can be employed for the parameter estimates. As shown in Panel A2, the FMOLS method indicates that lnY, $(lnY)^2$, lnFEC, and lnREC have estimates of 5.657, −0.267, 1.166, and −0.058, respectively. Panel B shows the results for the RKC model. As seen in Panel B1, the null of the cointegration cannot be rejected, and the F-statistics support the use of a Fourier-based approach. As shown in Panel B2, the coefficients of lnY, $(lnY)^2$, and URB are −85.698, 4.239, and −0.261, respectively. In addition, cos is significant in both the EKC and RKC models.

Based on these results, the paper finds: (i) the EKC and RKC hypotheses dominate, (ii) fossil energy reduces ecological quality, (iii) RE raises environmental quality as expected, and (iv) the urbanization process leads to fewer RE consumption for the USA economy. Considering the findings in favor of the EKC hypothesis, the findings of the paper concur with those of Roach [35], Pao et al. [36], Atasoy [69], Bulut [17], Pata [31], and contradict with the findings explored by Baek [37], Bilgili et al. [38], Sarkodie and Strezov [70], and Ongan et al. [39]. The validity of the EKC implies that the United States can minimize its ecological problems with increasing income.

The findings of the paper about RE are compatible with those of Bilgili et al. [38], Bulut [17], Pata [71], Pata et al. [72]. The USA is the second largest RE user in the world and has a high share of RE investment and R&D spending. RE sources can have a direct impact on CO_2 mitigation as their carbon density is low. In this context, the USA can help achieve net-zero targets by increasing the use of modern RE resources.

The adverse effect of urbanization on RE consumption indicates that fossil energy sources can meet the energy needs arising from the urbanization process. In contrast to Yang et al. [60] and Su et al. [63], the RE hindering role of urbanization is in line with Salim and Shafiei [73], Islam et al. [62], Dingru et al. [74], Pata et al. [75], and Asghar et al. [21]. Urban areas consume large amounts of fossil fuels to meet their energy needs. Much of the road transportation, especially in urban areas, is fueled by heating oil, which increases the demand for oil. At the same time, USA society is the third largest consumer of coal in the world [76]. Industrialization and mass production in urban areas increase the demand for coal, and the increase in demand for fossil fuels hinders the development of RE. Urbanization is therefore a hindering factor for RE deployment.

As clearly explained above, it is to be expected that the turning point implied by the RKC model must be lower than that of the EKC model. Accordingly, the turning point of the EKC model is 10.593 (=-5.657/2*-0.267), and that of the RKC model is 10.108 (=85.698/2*4.239)[1]. These findings indicate that, as expected, the turning point of income is higher for the EKC model than for the RKC model. Therefore, rising income starts to enhance RE consumption. Afterwards, as GDP per capita grows and reaches a higher threshold, ecological degradation decreases due to the increased use of RE.

The main findings are summarized in Fig. 5. The turning point

[1] It can be seen from the parameter estimations (the coefficients of $(lnY)^2$) that the second-order condition is also met.

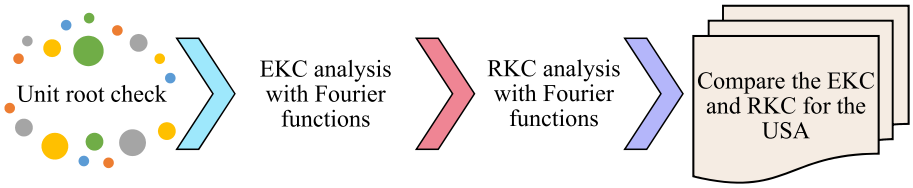

Fig. 4. Empirical flowchart.

Table 2
Fourier LM results.

Variable		k	Test stat.
$lnCO_2$	I(0)	1	−2.815
	I(1)	1	−6.043*
lnY	I(0)	1	−3.749
	I(1)	5	−5.247*
$(lnY)^2$	I(0)	1	−3.712
	I(1)	5	−5.467*
lnFEC	I(0)	1	−2.119
	I(1)	1	−5.966*
lnREC	I(0)	1	−1.985
	I(1)	3	−7.245*
URB	I(0)	1	−2.761
	I(1)	1	−5.222*

Note: * illustrates 1 % statistical significance.

Table 3
Tsong et al. [68] cointegration test.

Panel A: The EKC model			
Panel A_1: Cointegration			
Optimal frequency	Min. SSR	Test stat.	F stat.
2	0.003	0.093	351.929*
Panel A_2: Parameter estimation			
Variable	Coefficient	Std. error	t-stat.
lnY	5.657*	0.911	6.209
$(lnY)^2$	−0.267*	0.042	−6.226
lnFEC	1.166*	0.057	20.241
lnREC	−0.058*	0.020	−2.844
cos	−0.019*	0.003	−6.746
sin	0.001	0.003	0.425
Panel B: The RKC model			
Panel B_1: Cointegration			
Optimal frequency	Min. SSR	Test stat.	F stat.
1	0.271	0.044	14.604*
Panel B_2: Parameter estimation			
Variable	Coefficient	Std. error	t-stat.
lnY	−85.698*	26.520	−3.231
$(lnY)^2$	4.239*	1.302	3.253
URB	−0.261**	0.108	−2.413
cos	−0.141**	0.053	−2.617
sin	0.065	0.054	1.216

Notes: * and ** illustrate 1 % and 5 % statistical significance, respectively.

income of RKC occurs earlier than that of EKC and that RE is an effective tool to achieve carbon neutrality targets. Urbanization prevents the deployment of RE. Since the RKC turning point is earlier than the EKC, the USA should increase the transfer of funds to RE investments and accelerate its carbon reduction targets. In addition, the US government should minimize the negative impact of urbanization on RE through green urbanization plans.

The USA is the world's second largest CO_2 emitting country and carbon neutrality is important to its global sustainability goals. REC deployment is a leading policy option for CO_2 reduction. The findings of the study suggest that the urbanization of the USA is preventing the development of RECs. To minimize this, the government should disseminate urban plans that take into account environmental concerns in the states. It is important to promote the use of green transportation and green energy sources for heating.

As far as the validity of the EKC and RKC hypotheses is concerned, the turning point of the RKC precedes the EKC. This situation indicates that the economic expansion in the USA first expands the penetration of REC and then contributes to CO_2 reduction. Therefore, the USA should encourage REC for CO_2 reduction, increase financial investment in wind turbines and solar panels, and expand research and development activities related to clean energies. The validity and pioneering work of RKC shows that the "renewables first, carbon reduction second" strategy can guide environmental policies in the USA.

6. Conclusion and policy implication

6.1. Conclusion

According to the EKC, ecological degradation rises with economic expansion until income reaches a threshold or a turning point. It begins to decline because economies have become wealthy enough to care about the environment. The RKC hypothesis postulates a U-shaped relationship between RE uptake and economic growth. As soon as per capita income reaches a certain level, the use of RE will increase (RKC hypothesis). The EKC hypothesis implies a higher income threshold than the RKC hypothesis.

This study examined the RKC and EKC hypotheses for the USA. To account for both abrupt and gradual breaks, the study used the Fourier approximation in time series analyzes. The findings illustrated that the

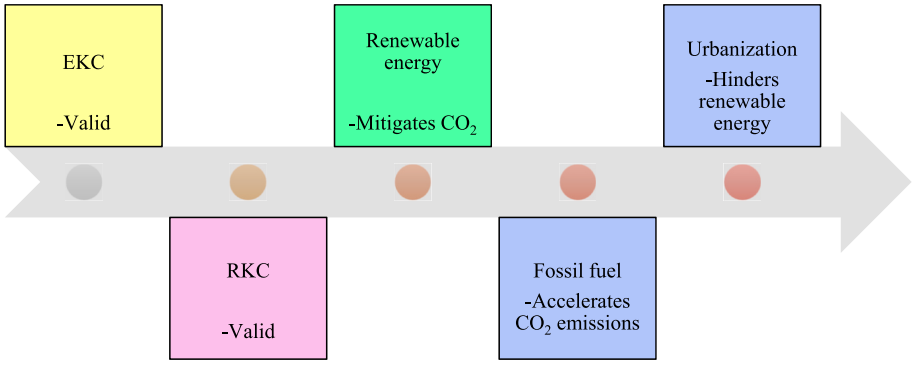

Fig. 5. Summary of the main results.

turning point of the RKC model occurred before the turning point of the EKC model and that both the RKC and EKC hypotheses are valid for the USA. The findings also indicated that fossil fuels and RE decreased and increased environmental quality in the USA, respectively. The models' thresholds for per capita income not only provide empirical evidence for the dominance of these hypotheses, but also have significant economic ramifications for the USA economy. The turning points indicated by the RKC and EKC models should be calculated in monetary terms (and in USD currency, since the variables are expressed in that currency), since the study uses the natural logarithmic values of the variables under consideration. Accordingly, the estimator showed that the turning point for the RKC model was USD 24512.8 (=2.71810.108), and the turning point for the EKC model was USD 39811.1 (=2.71810.593).

6.2. Policy implications

Considering that the per capita GDP of the US economy was about 40000 USD in 1993 and reached almost 63000 thousand USD in 2022, the per capita income in the USA is highly sufficient to further utilize RE sources and improve the ecological quality. Although CO_2 emissions in the USA have been trending downward in recent years, they are still above the level set by the Kyoto Protocol. This is due to two interrelated factors. First, fossil fuels lead the US energy mix. According to EIA [77] data, the share of RE in total primary energy consumption in the USA was 4.23 % in 2000 and doubled to 8.53 % in 2022. However, the share of FEC in energy mix was 82.8 % in 2022. Second, environmental policies in the USA appears to be very loose. OECD [78] data shows that USA ranks last among the G7 countries in terms of the ratio of environmental taxes to GDP in 2021. Moreover, in 2020, the USA ranked 18th out of 27 OECD countries in terms of environmental policy stringency. These figures therefore explain the reasons for the high CO_2 emissions in the USA. Although the US government is currently introducing many policies and programs in favor of RE, such as the Energy Independence and Security Act of 2007, loan guarantee programs, and Renewable Portfolio Standards, production tax credits, the share of RE in energy production and consumption is not at the desired level, and the high share of fossil fuels is leading to ecological destruction in the USA.

Based on the totality of empirical evidence and energy and environmental data, this paper argues that the US government should tighten environmental policies and provide more support and incentives for RE. There is no doubt that the potentially contractionary effect of stricter environmental policies on economic performance and the negative impact of incentives on the fiscal balance should not be ignored in the USA. Fossil fuels massively increase CO_2 emissions in the USA and RE is not sufficient to reduce CO_2. Although, according to the RKC hypothesis, the USA has exceeded the GDP per capita threshold for both RE promotion and CO_2 reduction since 1993, it is still far behind in achieving carbon neutrality targets. In this context, the USA government should allocate a larger share of the financial resources that its economic development brings to RE investments, RE research and development activities, and subsidizing RE producing companies. In this way, promoting RE can help the USA achieve its CO_2 reduction and carbon neutrality goals.

6.3. Limitations and future research

The study has some research limitations. First, it examines the RKC hypothesis by considering only total RE. Future studies can analyze the validity of the RKC hypothesis separately for disaggregated RE types such as wind, solar and biomass. The second research limitation of the study is related to the fact that only the US was analyzed. The USA is responsible for about 15 % of global CO_2 emissions. In future studies, a comparative analysis of the EKC and RKC hypotheses in broader groups of countries could provide greater scope and perspective for sustainability discussions. The third point is that the study only considers the time-domain characteristics of the series when analyzing the RKC. Researchers can provide more comprehensive information by testing the validity of the RKC with wavelet transforms in new studies. The fourth research limitation is that the study does not account for technological progress. Future studies can analyze the impact of RE-related R&D expenditures on RE and CO_2 under the EKC and RKC. Another research possibility is that this study can be replicated for the USA at the state or company level. Future studies that focus on these five research opportunities can add to the body of knowledge on the RKC and EKC.

CRediT authorship contribution statement

Ugur Korkut Pata: Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Umit Bulut:** Data curation, Conceptualization, Writing – original draft, Writing – review & editing. **Daniel Balsalobre-Lorente:** Investigation, Software, Writing – original draft, Writing – review & editing. **Jana Chovancová:** Formal analysis, Methodology, Writing – review & editing.

Consent for participate

Not applicable.

Ethics approval

Not applicable.

Consent for publication

Not applicable.

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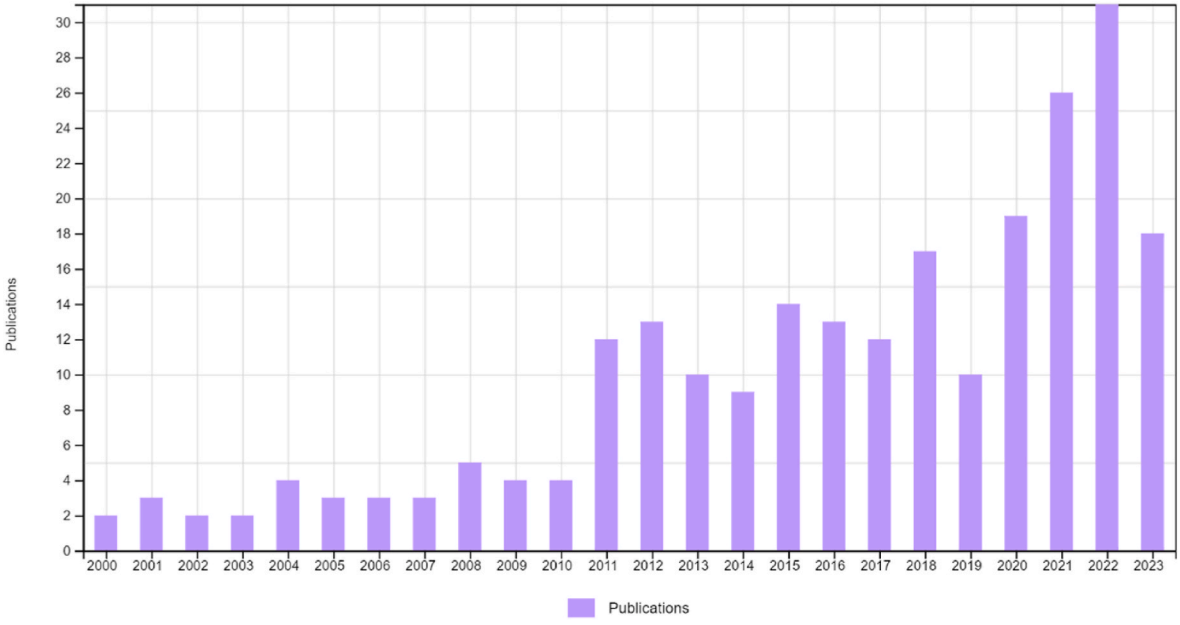
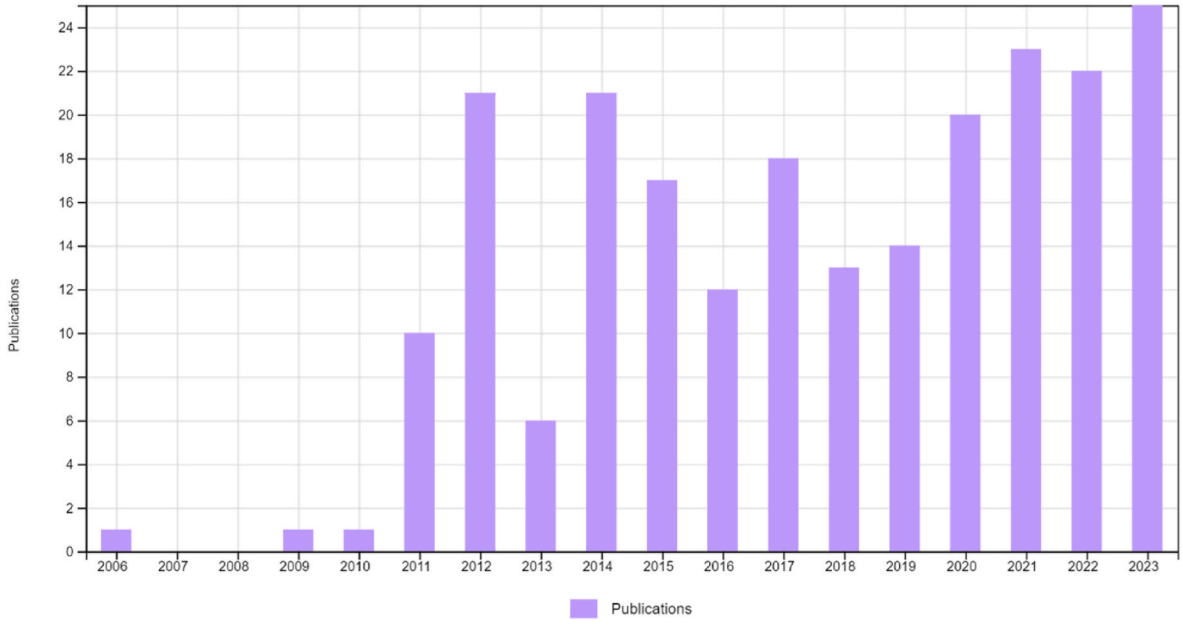
Declaration of competing interest

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.

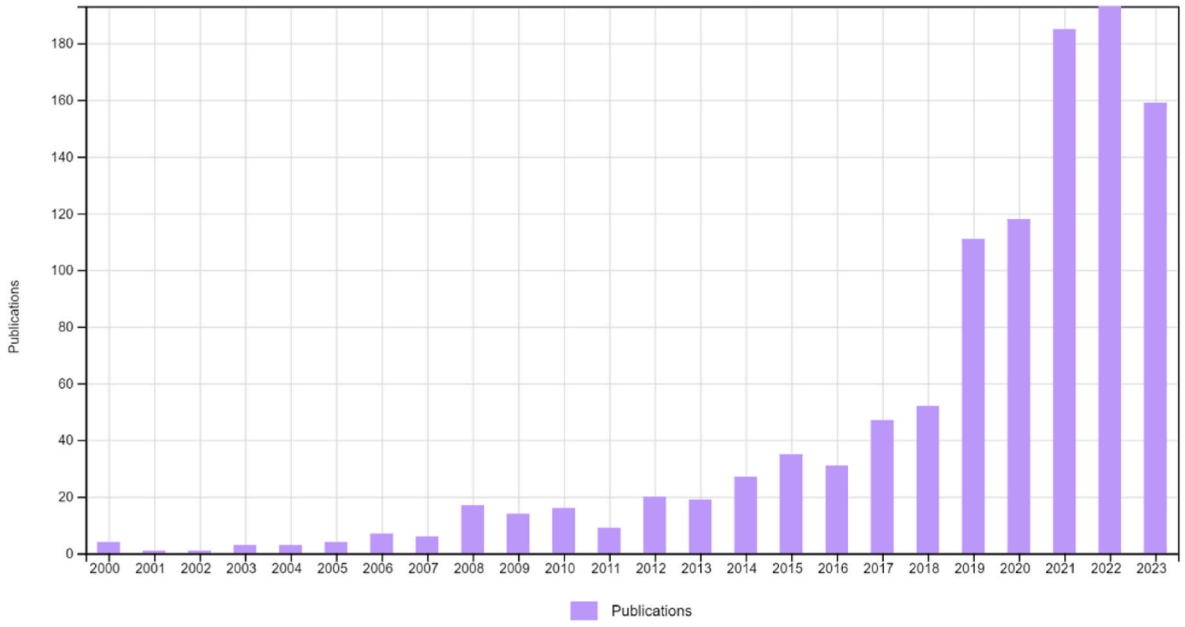
Appendix. The number of publications for the aforementioned hypotheses over the period 2000–2023



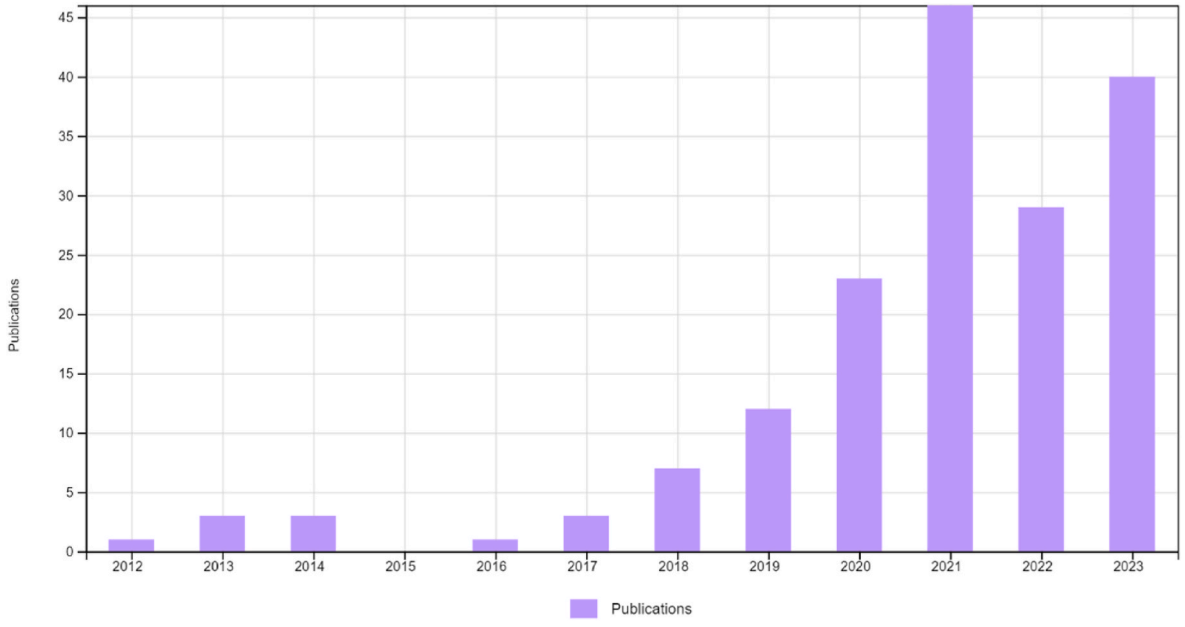
Annex 1. The number of publications on the energy ladder hypothesis
Source: WoS Database [79].



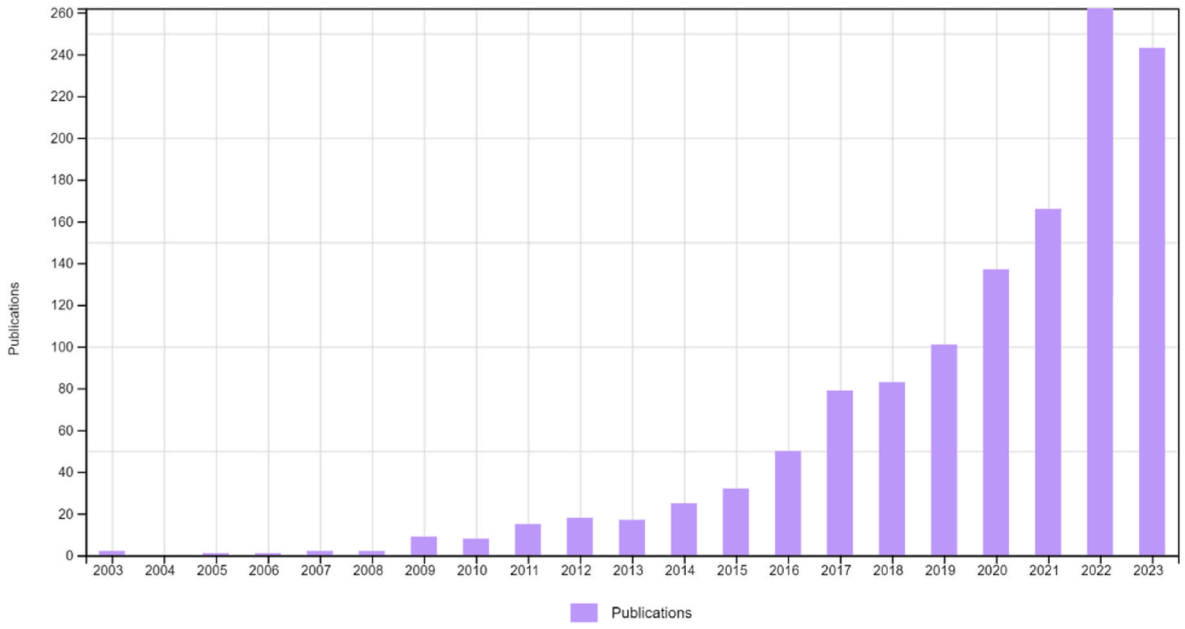
Annex 2. The number of publications on the green paradox hypothesis
Source: WoS Database [79].



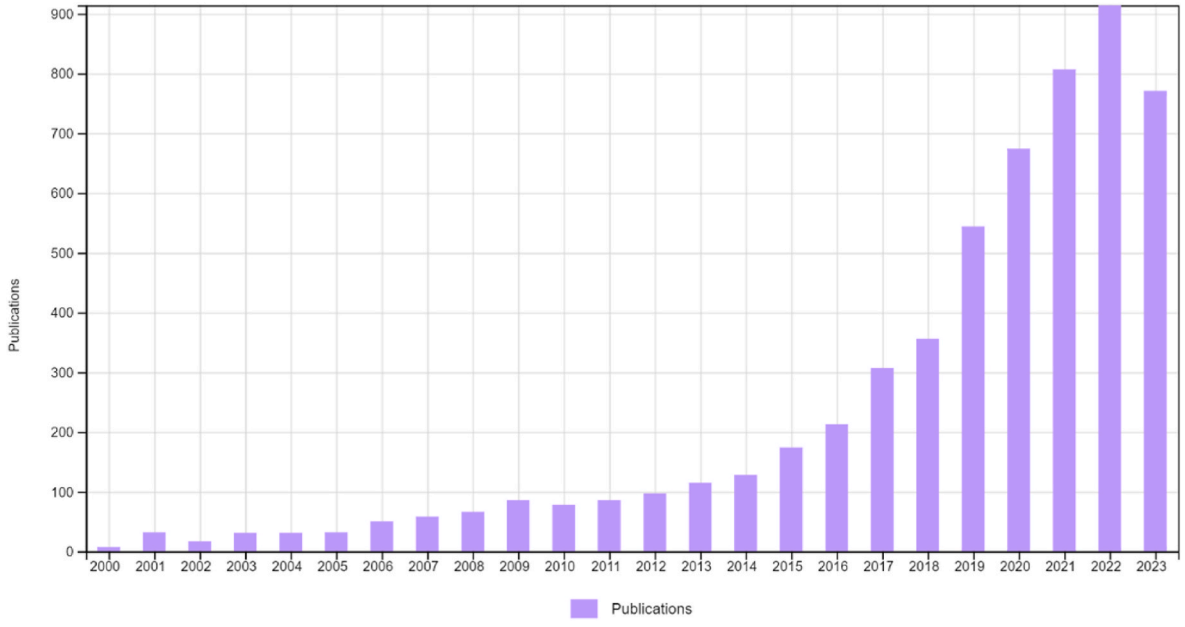
Annex 3. The number of publications on the pollution haven hypothesis
Source: WoS Database [79].



Annex 4. The number of publications on the pollution halo hypothesis
Source: WoS Database [79].



Annex 5. The number of publications on the STIRPAT model
Source: WoS Database [79].



Annex 6. The number of Publications on the EKC hypothesis
Notes: The name of the hypothesis/model is searched in inverted commas in the WoS database. For instance, publications associated with the energy ladder hypothesis are searched using the statement "energy ladder". When a researcher tests the pollution haven hypothesis, he/she also tests the pollution halo hypothesis. Therefore, the publications for these hypotheses can be considered under the pollution haven hypothesis, which is more popular than the pollution halo hypothesis.
Source: WoS Database [79].

Data availability

Data will be made available on request.

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