

Historical Environmental Kuznets Curve for the USA and the UK: Cyclical Environmental Kuznets Curve Evidence¹

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Abstract

Human activities, including population growth, industrialization, and urbanization, have increasingly impacted the environment. Despite the benefits of economic growth to individual welfare, its negative environmental consequences necessitate a thorough assessment. The environmental Kuznets curve (EKC), positing an inverted U-shaped relationship between income per capita and environmental degradation, has been extensively studied since its proposition by Grossman and Krueger (1991). However, empirical evidence on the validity and shape of the EKC varies due to methodological differences, country-specific dynamics, and other factors. **Examining the historical growth paths of individual countries helps explain the mixed findings in empirical EKC research. Long-term data allow researchers to determine the EKC's shape and turning points, aiding policymakers in devising appropriate environmental policies for each economic growth cycle within the framework of global environmental governance. Accordingly, this study contributes to the literature by taking a historical perspective on the EKC, focusing specifically on the United States and the United Kingdom. Drawing on data spanning from 1850, we employ advanced econometric techniques, including Fractional Frequency Flexible Fourier Form (FFFFF) Dickey-Fuller (DF)-type unit root tests and structural breaks unit root tests (SOR), to overcome limitations of traditional linearized EKC estimations. Moreover, the classical polynomial regression approach is employed to model the long-term cycles based on the scatterplot inspection of per capita CO₂ and per capita GNP series.**

Contrary to conventional expectations, our empirical findings do not support the existence of a clear inverted U-shaped EKC relationship between carbon dioxide (CO₂) emissions and economic growth for either country. Instead, our analysis reveals the presence of multiple regimes, indicating a cyclical pattern where economic growth affects environmental quality with varying severity over time. Furthermore, we demonstrate proper modeling techniques for the EKC, highlighting the importance of identification and misspecification tests. Our study identifies cyclical EKC patterns for both the UK and the USA, with the UK exhibiting two cycles and the USA exhibiting three, shaped by varying economic, social, and technological contexts. By revealing the nuances of the economic growth-environmental degradation nexus for these early developer countries, our study provides valuable insights for policymakers seeking to devise evidence-based and environmentally sustainable growth policies within the framework of global environmental governance. These findings underscore the importance of considering historical context and structural changes when analyzing the EKC, providing valuable insights for policymakers aiming to design adaptive and sustainable economic growth strategies.

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1. Introduction

It has been well documented that human activities have been exerting an increasing impact on the environment through population growth, agriculture, transportation, the industrial revolution, and urbanization, among other factors. Although economic growth enhances the welfare of individuals, it also may have a negative impact on the environment. Thus assessing the economic growth-environmental degradation relation enables policymakers to formulate evidence-based strategies and environmentally friendly growth policies. The environmental impacts of economic growth have generally been examined in the framework of an environmental Kuznets Curve (EKC) proposed by Grossman and Krueger (1991), which posits an inverted U-shaped relation between income per capita and various indicators of environmental degradation. Since the pioneering work of Grossman and Krueger (1991), the economic growth-environmental degradation nexus has been examined extensively. The existing empirical literature provides mixed evidence regarding the existence and the shape of the EKC, depending on the methodology used, countries and time period covered, or additional explanatory factors controlled.

This study aims to contribute significantly to the existing literature by taking a novel historical perspective on the EKC, focusing specifically on the United States and the United Kingdom. While previous research predominantly examines cross-country EKC patterns, our study provides a detailed analysis of the economic growth-environmental degradation nexus within the context of these early developer countries. By delving into historical data spanning from 1850, our research offers a unique opportunity to explore long-term trends and dynamics, shedding light on the evolution of environmental quality alongside economic growth in two pivotal nations.

Resorting to examine the historical growth paths of individual countries may explain the mixed findings of empirical research (Dinda, 2004). The availability of a long span of data relating to income and environmental quality indicators enable researchers to determine the proper shape of the EKC as well as the turning points so that policymaker may devise and adopt proper environmental policy measures for each cycle of economic growth in the

framework of global environmental governance. This paper assesses the environmental impact of economic growth for two early developer countries, the USA and the UK, employing data spanning from 1850. The paper utilizes Fractional Frequency Flexible Fourier Form (FFFFF) Dickey-Fuller (DF)-type unit root tests and structural breaks unit root test (SOR) as well as Fourier filter to overcome the myopic forecast of the scant linearized version of the Kuznets curve estimation. The empirical results indicate that traditional EKC relation regarding the CO₂ emissions can be affirmed for neither the USA nor the UK, but there exist multiple regimes where economic growth hampers environmental quality at different severities by using the polynomial regression. Moreover, we have shown the proper way of modeling the Environmental Kuznets curve in this paper by using identification and misspecification tests. Therefore, the previous mixed results may come from these miss-modeling strategies.

The empirical findings reveal distinct cycles in the economic growth-environmental degradation nexus for both countries, influenced by major historical events such as World Wars I & II, the Great Depression, oil price shocks, and financial crises. Notably, policy responses to these events, such as energy-saving measures and technological innovations, have shaped the trajectory of environmental degradation. Overall, this study contributes to the literature by offering a nuanced understanding of the economic growth-environmental degradation relationship, highlighting the importance of historical data and advanced econometric techniques in improving EKC estimations and informing evidence-based policy decisions in the realm of environmental governance. In summary, this study's unique historical perspective, methodological innovations, and intriguing findings make a substantial contribution to the existing literature on the EKC. By elucidating the complexities of the economic growth-environmental degradation relationship for the USA and the UK, our research contributes to a more comprehensive understanding of this critical issue and provides actionable insights for policymakers seeking to promote sustainable development within the framework of global environmental governance. **The rest of the paper is structured as follows: Section two provides a brief literature review. Section three details the methodology, including the FFFFF and SOR unit root tests, and describes the data used in the study. Section four presents the empirical results. Section five discusses the findings. Finally, section six offers the conclusion of our analysis.**

2. Literature Review

Existing literature generally evaluates the validity of the EKC hypothesis in a cross-country setting which implicitly assumes a standard structure for all countries. Empirical results suggest that countries may differ concerning their economic growth dynamics, as well as their social, political, and biophysical factors which could render different EKC structures for different countries (Dinda, 2004). Consequently, another strand of literature is comprised of single-country studies. Some studies provide empirical evidence supporting the validity of the EKC hypothesis (Apergis and Ozturk, 2015; Churchill et al., 2018; Hanif, 2017; Holtz-Ekain et al., 1995; Jayanthakumaran et al., 2012; Kasman and Duman, 2015); while there are others that cannot justify the existence of an EKC curve or report the existence of U-shaped or N-shaped environmental Kuznets Curves (Destek and Sinha, 2020; Dogan and Turkekul, 2016; Moutinho et al., 2020).

EKC is analyzed for different countries around the globe. In this paper, we specifically focus on the EKC literature that takes a historical perspective. The broad characteristics of these studies are summarized in Table 1. Empirical evidence from these studies exhibits significant differences across countries, including some conflicting results for the same country. These studies generally emphasize the evolution of energy intensity over time, particularly the shifts in the energy mix and conversion efficiency. An important driver for this is the oil crisis in the 1970s which resulted in improved energy efficiency with the adoption of energy-saving technologies. Doms and Dunne (1995) provided empirical evidence indicating that factories' built-in high energy price era (1973-1983) were more energy efficient.

Table 1. Summary of historical EKC literature

Reference	Time period	Country	Method	Findings
Balaguer and Cantavella (2016)	1874-2011	Spain	Autoregressive Distributive Lag (ARDL) Bounds Test	Inverted U shaped
Churchill et al. (2018)	1870-2014	20 OECD countries	Panel Cointegration	EKC for Panel ; Inverted U shaped for five countries
Esteve and Tamarit (2012a)	1857 - 2007	Spain	Linear Cointegration	3 regimes
Esteve and Tamarit (2012b)	1857 - 2007	Spain	Vector Error-Correction Model (VECM) Threshold Cointegration	Inverted U shaped

Fosten et al. (2012)	1830-2003	UK	Nonlinear Threshold Cointegration / TAR And M-TAR Models	N shaped
He and Richard (2009)	1948-2004	Canada	Semiparametric and Flexible Nonlinear Parametric Modeling	No EKC
Kander and Lindmark (2004)	1800 - 2000	Sweden	Environmental Accounting- Decomposition	Inverted U shaped
Lindmark (2002)	1870-1997	Sweden	Structural Time Series Models Using Kalman Filter(STRM)	No EKC
Lindmark and Acar (2014)	1850–2000	Sweden	OLS/ TSLS	A Right Tilted-S Form Dynamic Relationship
Lipford and Yandle (2010)	1950 - 2004	G8 + 5 countries	OLS	N shaped
Moomaw and Unruh (1997)	1950 - 1992	16 countries	Panel Data Analysis	N Shaped
Sephton and Mann (2016)	1830–2003	UK	Nonlinear Cointegration	Monotonically increasing Inverted U shape
Shahbaz et al. (2017)	1820 - 2015	G7	The Cross-Validated Local Linear Nonparametric Regression Technique	Inverted U-shaped (except Japan)
Yilanci et al. (2023)	1850–2018	UK	The Time-Varying Cointegration- The Time-Varying Causality Test	Inverted U shaped

3.

Although there is a significant body of research for Sweden (Kander and Lindmark, 2004; Lindmark, 2002; Lindmark and Acar, 2014; Shahbaz et al., 2020); for Spain (Balaguer and Cantavella, 2016; Esteve and Tamarit, 2012a, 2012b; Sephton and Mann, 2016); for Canada (Unruh and Moomaw, 1998; Moomaw and Unruh, 1997; He and Richard, 2009), empirical evidence regarding EKC hypothesis for the USA and the UK are scant. Lanne and Liski (2004) investigated the existence of structural breaks in historical per capita CO₂ data for 16 early developed countries, including the USA and the UK, employing data belonging to the 1870-1998 period using a multiple-break time series method. They provided evidence for a two-phase pattern for the USA, the initial fast growth followed by an early downturn to a period of lower growth, and a three-phase pattern for the UK where declining per-capita emissions characterized the third phase. The turning points were 1908 for the USA; 1901 and 1974 for the UK. Similarly, Huntington (2005) used a single break procedure to assess carbon

emissions-GDP relationship for the USA using data belonging to 1870–1998. His findings were in line with that of Lanne and Liski (2004) in that they found a break in 1913. Congregado et al. (2016) explored the validity of EKC for the USA, employing quarterly data for the time period 1973-2015. Their cointegration analysis supported the existence of an inverted U-shaped EKC only when structural breaks were accounted for. They reported that the income and pollutant relationship was not stable and was characterized by three structural breaks and four periods. For the UK, Fosten et al. (2012) employed a nonlinear threshold cointegration method to assess the income-pollution nexus for 1830-2003. For CO₂ emissions, their empirical results showed the existence of a N-shaped EKC, providing evidence of an asymmetric environmental degradation-economic growth relation, while long-run results supported the EKC hypothesis. Sephton and Mann (2016) showed that economic development and emissions were non-linearly cointegrated for the same time period. They verified an inverted U-shaped EKC with a turning point in 1966, which may reflect the introduction of the Clean Air Act in the UK in the summer of 1956. Yilanci et al. (2023) investigated the validity of Environmental Kuznets Curve (EKC) hypothesis for the United Kingdom from 1850 to 2018, using innovative time-varying estimation techniques alongside traditional time-series methods. These techniques allowed for changes in cointegration parameters over time. Findings suggested that initially, as the economy develops, pollution levels rise with income. However, around the 1920s, there was a turning point where environmental quality begins to improve alongside economic growth. While different shapes (such as U-shaped, inverted U-shaped, N-shaped) were observed in sub-samples, the overall analysis confirmed the presence of the EKC hypothesis in the UK. The variations in shapes across sub-samples were attributed to the non-linear nature of the EKC hypothesis, influenced by external and internal shocks such as oil price shocks, economic recessions, and changes in energy and environmental policies.

3. Methods

This section outlines the methodologies employed to investigate the stationarity properties of the variables used in this study. Subsequently, an overview of the historical data utilized, including the definitions of the variables and their sources is also provided.

3.1 Unit Root Tests

One of the most fundamental assumptions in estimating smooth transition autoregressive (STAR) models is stationarity. This assumption is valid for other nonlinear models as well. Among the models we consider in this study, the stationary assumption remains valid. This is

one of the most common mistakes made in previous Kuznets curve studies. In order to make a nonlinear model estimation, the stationarity properties of the data were determined with linear unit root tests. However, the nonlinear stationary series in the nonlinear model estimation will mean that they are taken as levels within the nonlinear model, and therefore the correct model specification will be made in terms of variables. It was decided to perform a cointegration analysis due to the series with $I(1)$ as a result of the linear unit root test. Unfortunately, due to this decision, nonlinear features that should be investigated at the level were investigated in the context of a long-term relationship in the difference series and gave rise to mixed results in the literature. Two very flexible unit root tests are used to investigate both the presence of stationarity and the statistical identification of the CO_2 and GNP data in nonlinear framework. This statistical identification will act as a preliminary test in the EKC models in due course. In some cases, the use of simple nonlinear models gives more effective results than the use of complex nonlinear models. For example, multiple regime STR model, TAR, or Markov regime-switching could be estimated here, but the polynomial model we discussed is well proxied enough to these models and uses simple OLS as the estimation method. In this sense, we will be able to determine the exact structure of Kuznets behavior with a simple nonlinear model away from model complexity. Accurate estimation of other nonlinear models may not be possible when multiple regimes are involved. As a result, we will be far from such handicaps. In addition, when these complex nonlinear models are estimated, a better fit to the data and more accurate threshold values can be obtained. Since our fundamental goal here is to show the Kuznets curve cycles rather than U-shape or N-shape, the polynomial regression estimation is the most optimal model for us. In this sense, we will be able to show the cycle relationship without leaving any doubt about complex nonlinear models. The most crucial point to be emphasized here is the choice of order in polynomial models. By performing both a priori identification test and a misspecification test after estimating the model in the polynomial order, we are in a position to give exact numbers in terms of cycle numbers. Primarily, Omay (2015) multiple smooth break unit root tests will be used. The estimation of the frequency shed light on the cycle numbers in the Kuznets curve when we obtained the stationarity. In addition to the FFFFF DF-type test of Omay (2015), this paper also employs the sharp and smooth structural breaks unit root test (SOR) developed by Shahbaz et al. (2018). As a nonlinear unit root test, the SOR test efficiently captures the cycles as it can account for both smooth and sharp breaks in the series. ²

² The technical details of these tests are given in supplementary material as technical annex.

Following Leybourne et al. (1998) the test statistics proposed here are calculated with a two-step procedure:

Step 1. Using constrained nonlinear optimization algorithm via Genetic³, we estimate only the deterministic component of the preferred model and compute its residuals.

$$\text{Model A: } \hat{\varepsilon}_t = y_t - \hat{\alpha}_1 - \hat{\alpha}_2 F_t(\hat{\gamma}, \hat{\tau}) \quad (1)$$

$$\text{Model B: } \hat{\varepsilon}_t = y_t - \hat{\alpha}_1 + \hat{\beta}_1 t - \hat{\alpha}_2 F_t(\hat{\gamma}, \hat{\tau}) \quad (2)$$

$$\text{Model C: } \hat{\varepsilon}_t = y_t - \hat{\alpha}_1 - \hat{\beta}_1 t - \hat{\alpha}_2 F_t(\hat{\gamma}, \hat{\tau}) - \hat{\beta}_2 F_t(\hat{\gamma}, \hat{\tau}) t \quad (3)$$

$$F_t(\gamma, \tau) = 1 / (1 + \exp[-\gamma(t - \tau T)]), \quad \gamma > 0 \quad (4)$$

Step 2. Compute the Enders and Lee (2012) to this de-trended series.

The testing equation is finally as follows:

$$\Delta \hat{\varepsilon}_t = \alpha_0 + \sum_{k=1}^n \alpha_k \sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^n \beta_k \cos\left(\frac{2\pi kt}{T}\right) + \phi_1 \hat{\varepsilon}_{t-1} + \sum_{i=1}^p \phi_k \Delta \hat{\varepsilon}_{t-i} + \nu_t \quad (5)$$

For Omay (2015) FFFFF-ADF test, the non-de-trended series with LSTR model will be used in equation 5, hence the equation will be as follows:

$$\Delta y_t = \alpha_0 + \sum_{k=1}^n \alpha_k \sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^n \beta_k \cos\left(\frac{2\pi kt}{T}\right) + \phi_1 y_{t-1} + \sum_{i=1}^p \phi_k \Delta y_{t-i} + \nu_t \quad (6)$$

3.2 Data

This study employs annual historical data belonging to the USA and the UK, covering 1875–2010 for the USA, and 1851–2010 for the UK, respectively, with the start and end dates being purely driven by data availability. Historically, Europe and North America were the primary contributors to global carbon emissions. However, by the end of 2009, Asia began to surpass them, accounting for half of the world's carbon emissions. Europe and North America showed strong decoupling of economic growth from environmental impacts during 2000–2017 (Sanyé-Mengual et al., 2019; Song et al., 2019; Yang et al., 2021). Moreover, China is the

³We use the genetic algorithm in our estimation process of the smooth transition trend since it is shown to be the best performing algorithm in estimating LST types of equations. For details, see Omay et al. (2018).

world's largest emitter of CO₂, and a significant portion of the growth in global carbon emissions between 2010 and 2012 can be attributed to China, accounting for nearly 75% of the increase resulting from the burning of fossil fuels and cement production (Wei, 2024). Furthermore, the COVID-19 pandemic further accelerated this trend, albeit temporarily (Liu et al., 2020). Carbon dioxide and other greenhouse gas emissions experienced a sharp decline in 2020 due to lockdown measures implemented during the first half of the year, which constrained global mobility and hindered economic activity (Bhanumati et al., 2022; Ray et al., 2022). The selected time periods for both countries were chosen to capture the historical evolution of global carbon emissions patterns and their associated environmental impacts.

The income indicator is real GNP, and the environmental degradation indicator is CO₂ emissions in tones. Population variable has also been included in the estimations. Data used in this study comes from various sources. The UK GNP data is obtained from the Bank of England, which contains five multi-century annual output series⁴. This paper employs real UK GNP at factor cost (1700-2016), a geographically-consistent estimate based on post-1922 borders, millions of British pounds, chained volume measure, 2013 prices as income indicators for the UK. The USA nominal GNP and the GNP deflator data are obtained from multiple sources. The GNP deflator is used to deflate the nominal GNP to obtain the real GNP. The data belonging to the pre-1947 period comes from the National Bureau of Economic Research⁵, the actual sources of which are the tables of quarterly data corresponding to Appendix B of Gordon (1986). The post-1947 data is from the Federal Reserve Bank of St. Louis. Gordon (1986)'s database runs until 1983:4, where the base year of the GNP deflator is 1972. Although National Income and Product Account (NIPA) quarterly data series were nonexistent before 1947, nominal GNP and GNP deflator data based on the NIPA are available from 1947. In order to have a consistent series with that of the GNP series of NIPA, Omay et al. (2017) updated the base year of the GNP deflator for the pre-1947 period from 1972 to 2009, thus obtaining a real GNP in constant 2009 prices. The data on fossil-fuel CO₂ emissions, estimated from historical energy statistics, are obtained from the Carbon Dioxide Information Analysis Centre (CDIAC)⁶. The population statistics are acquired from Office for National Statistics for the UK and Office for National Statistics for the US, respectively (Table 2).

Table 2. Data definitions and sources

⁴ Please see <https://www.bankofengland.co.uk/statistics/research-datasets> for detailed information about the historical sources of the data.

⁵ <http://www.nber.org/data/abc/>.

⁶ <http://cdiac.ornl.gov/>.

Variable	Definition / Source	Time Period
GDP		
UK	Real GNP 1851-2010	A Millennium of Macroeconomic Data maintained at https://www.bankofengland.co.uk/statistics/research-data-sets
USA	Nominal GNP /GNP Deflator pre-1947	National Bureau of Economic Research http://www.nber.org/data/abc/
	Nominal GNP/ GNP Deflator Post – 1947	FRED database of the Federal Reserve Bank of St. Louis
CO₂ emissions (metric tons)		
UK		Carbon Dioxide Information Analysis Centre (CDIAC)
USA		
Population		
UK		Office for National Statistics (https://www.ons.gov.uk/)
USA		Census of Population and Housing (https://www.census.gov/prod/www/decennial.html)

4. Empirical Results

In this section, the empirical findings are presented. The first subsection discusses the outcomes of the unit root tests, which are crucial for understanding the stationarity properties of the variables of interest. Following this, the polynomial regression models used to identify the cyclical patterns in the Environmental Kuznets Curve (EKC) for both countries are presented. **4.1 Unit Root Test Result**

The FFFFF and SOR unit root test results for GNP and CO₂ series for the USA and the UK are shown in Table 3 and Table 4, respectively.

Table 3. FFFFF test intercept and trend

Y	-5.104* (0.1)	-5.487* (0.1)
CO ₂	3.794 (1)	-4.787** (0.1)
Pop	-3.992 (0.8)	-4.024** (0.1)
Y/pop	-4.943 (0.6)	-3.148 (0.1)
CO ₂ /pop	-2.726 (2.3)	-2.693 (1.9)

Note: The unit root tests are done to intercept and trend of the FFFFF test. *, ** and *** are % 1 and %5 and %10 significance levels.

Table 4. SOR Test: Model C

	USA	UK
Y	-4.004 (2)	-4.124 (3)
CO ₂	-4.771*** (5)	-4.593 (2)
Pop	-5.857* (3)	-5.839* (2)
Y/pop	-5.893* (2)	-4.990** (2)

Note: The unit root tests are done to intercept and trend of the FFFFF test. *, ** and *** are %1 and %5 and %10 significance levels.

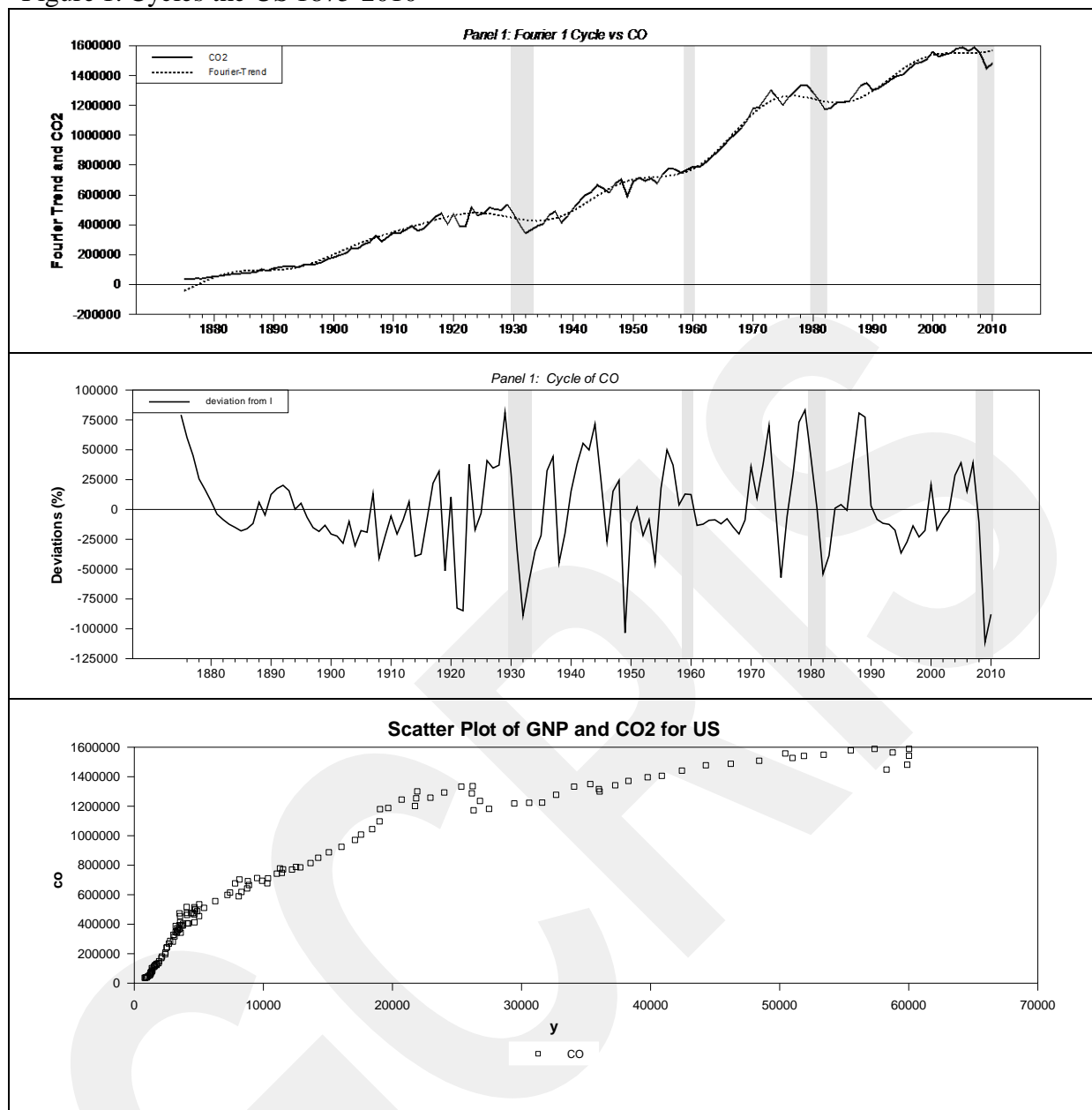
Figures 1 and 2 present in panels (a), (b), (c), and (d); (a) the historical CO₂ series along with estimated nonlinear trend functions; (b) deviations from trend; (c) scatterplots of CO₂ and GNP; (d) scatterplots of per capita CO₂ and per capita GNP for the USA and the UK, respectively. The structural shifts in the trend of the data can be clearly seen, suggesting that the structural breaks should be taken into account while testing for stationarity or non-stationarity, supporting the findings of Cheng et al. (2014). Moreover, the Fourier approximations seem reasonable and support the notion of long swings in both carbon emissions and GNP series for both the USA and the UK. While the FFFFF test is successful for the UK data, the SOR test performs better for the US data in assessing the stationarity properties of the series. These findings indicate that the UK series are less volatile than the US series, while the US series encompasses more complex and cyclical movements. The results of the stationarity tests direct us to employ two methods that assess the nature and complexity of the cyclical movements of the series. While Enders and Li (2015) employ a Fourier filter to model the cyclical movements.

The trend-cycle decomposition proposed by Enders and Li (2015) employed the same set-up as Morley et al. (2003), except that the FFF (trigonometric terms) are included in the trend:

$$\begin{aligned}
 y_t &= \tau_t + c_t \\
 \tau_t &= \mu + FFF + \tau_{t-1} + \eta_t \\
 FFF &\equiv \sum_{k=1}^n a_k \sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^n b_k \cos\left(\frac{2\pi kt}{T}\right) \\
 (1 - \phi_1 L - \phi_2 L^2)c_t &= e_t \\
 \begin{pmatrix} \eta_t \\ e_t \end{pmatrix} &\sim i. i. d. N\left(\begin{pmatrix} 0 \\ 0 \end{pmatrix}, \begin{pmatrix} \sigma_\eta^2 & \sigma_{\eta e} \\ \sigma_{\eta e} & \sigma_e^2 \end{pmatrix}\right)
 \end{aligned}$$

Where y_t is 100 times the quarterly value of log real GDP, τ_t is the unobserved trend, and c_t is the cycle. Following Enders and Li (2015) we let the cyclical component to take the AR(2) form.

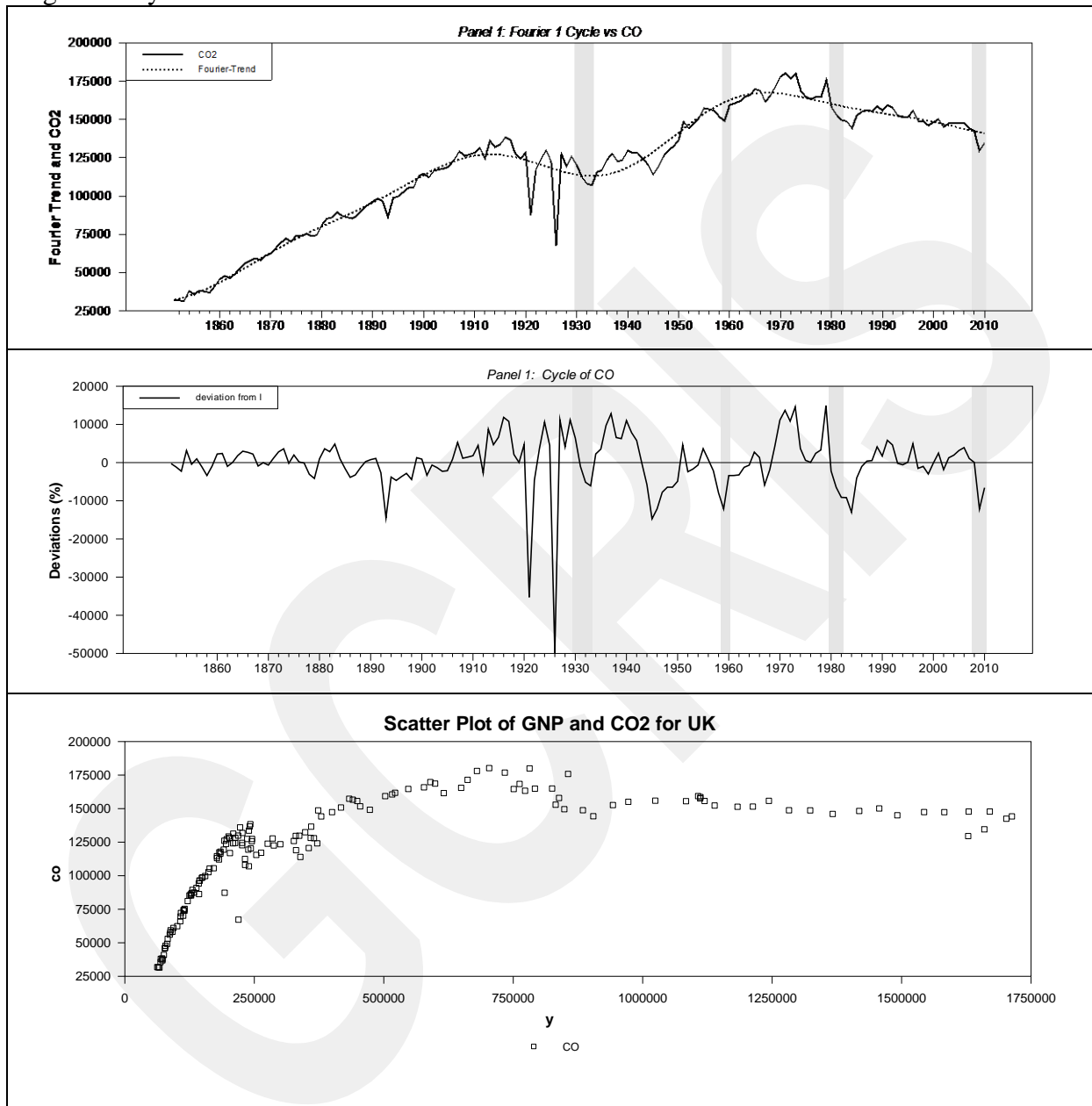
Figure 1. Cycles the US 1875-2010



Next, trend shifts in the data series in levels have been investigated by employing Flexible Fourier Transforms proposed by Enders and Li (2015). The inspection of the level CO_2 – level GNP series scatterplots indicates the existence of four cycles in the USA and two cycles in the UK, respectively. These findings are in line with the results of Enders and Li's (2015) approach. However, the scatterplots of per capita CO_2 – per capita GNP in Figures 1 and 2 suggest that the EKC relation is characterized by three cycles for the USA and two cycles for the UK, respectively. It emerges that the breaks are associated with significant events such as the Great Depression, the two-time oil price shocks that occurred during the periods between 1974–76 and 1979–1981, and the financial crisis of 2008. Moreover, the

impact of the Clean Air Act in the UK introduced in the summer of 1956 can be traced as well.

Figure 2. Cycles the UK 1851-2010



4.2 Cyclical Kuznets Curve Estimation via Polynomial Regression

In the Environmental Kuznets Curve (EKC) framework, long-term shifts in technology may introduce cycles that influence pollution levels. These cycles often coincide with periods of economic growth, during which countries may experience significant technological advancements across various sectors. For example, technological innovations in energy efficiency, pollution control, waste management, transportation, and information and communication technologies (ICT) can lead to fluctuations in pollution levels over time. These shifts in technology enable the adoption of cleaner and more sustainable practices, contributing to the observed cycles in pollution levels within the EKC framework. As researchers, we aim to model these long-term cycles to better understand the dynamic relationship between technological development, economic growth, and environmental degradation within the EKC paradigm.

The study so far showed that the CO₂ series for both countries have more than one cycle by using different methods. The inspection of the scatterplots of per capita CO₂ – per capita GNP series, on the other hand, suggests that there are two cycles in the UK and three cycles in the US environmental degradation –economic growth relations, respectively. Accordingly, a 4th-degree polynomial and a 6th-degree polynomial EKC models are estimated for the UK and the US, respectively.

Accordingly, the empirical model for the UK and the US can be written as follows:

$$CO_{2t}\beta_0 + \beta_1 GNP_t + \beta_2 GNP_t^2 + \beta_3 GNP_t^3 + \beta_4 GNP_t^4 + u_t$$

for the UK where t= 1851-2010.

$$CO_{2t} = \beta_0 + \beta_1 GNP_t + \beta_2 GNP_t^2 + \beta_3 GNP_t^3 + \beta_4 GNP_t^4 + \beta_5 GNP_t^5 + \beta_6 GNP_t^6 + u_t$$

for the US t=1875–2010.

In these models, the environmental deterioration indicator is CO₂ per capita, and the income indicator is GNP per capita. The results obtained here will be used to model the structure of large cycles, regardless of the significance of t statistics. Therefore, the preliminary methods give us the identification of the polynomial EKC model. Criteria such as SSR, AIC, or SIC cannot determine the degree of the polynomial because the more degrees of

polynomials are increased in polynomial-style models, these criteria are decreasing to select the higher-order polynomials. Thus, we have determined the polynomial degree accurately with the methods we have used for identification purposes. These models are Fourier filter and Fourier type unit root tests. Hence, the fundamental problem determination of polynomial orders is solved with alternative methods. The models estimated in this regard are presented in Table 6 for the USA and in Table 7 for the UK, respectively. The estimation results, together with model identification criteria shown in Table 8, indicate that impact of GDP per capita variables alternates in sign, suggesting that there are two turning points for the UK EKC and three turning points for the US EKC curves. These findings are in line with the findings of Fourier filter and Fourier type unit root tests presented in the previous section.

Table 6. Polynomial Model Estimates for the USA

USA		
$\frac{CO_t^2}{Pop_t} = -18838.841 + 1630.078 \left(\frac{GNP_t}{Pop_t} \right) - 45.314 \left(\frac{GNP_t}{Pop_t} \right)^2 + 0.632 \left(\frac{GNP_t}{Pop_t} \right)^3$ $- 0.004 \left(\frac{GNP_t}{Pop_t} \right)^4 + 0.001 \left(\frac{GNP_t}{Pop_t} \right)^5 - 0.001 \left(\frac{GNP_t}{Pop_t} \right)^6$		
$R^2 = 0.951$, F-test=441.587(0.000), Log Likelihood = -971.988		
<i>Roots of the polynomial regression</i>		
[1] 12.41290+ 5.06644i	[2] -15.77412+11.96721i	[3] 3.86121-15.88801i
[4] 12.41290- 5.06644i	[5] 3.86121+15.88801i -	[6] 15.77412-11.96721i

From Figure 3, we see the estimation from the polynomial model placed on the scatter plot of CO₂ and income. In Figure 3, the polynomial sixth degree (blue line) and the linear (red line) or first-degree polynomial models are given together. We have visually given how well the predictions we made from the 6th-degree polynomial model we built predict the Kuznets relationship. Here, it is clearly seen from the USA data that the Kuznets relationship makes three cycles.

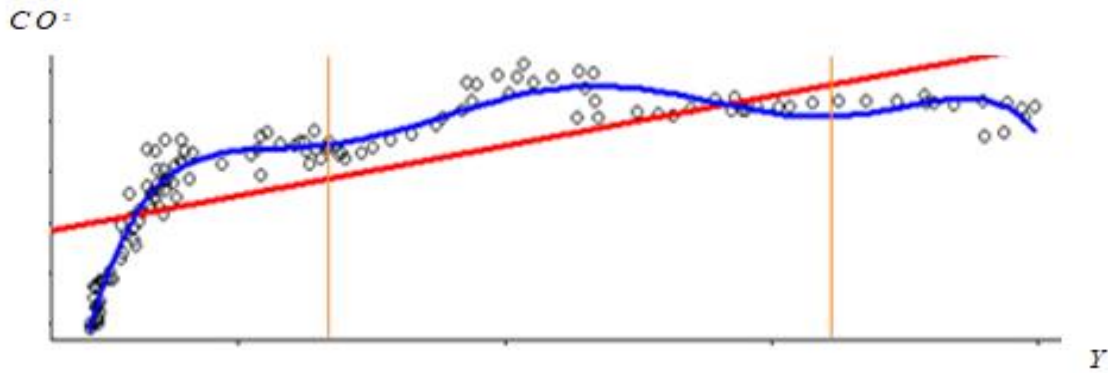


Figure 3. Cyclical Kuznets Curve for the US data

As shown in Table 6 above, the sixth-order polynomial estimation, equal to 3 cycles, is made for US data. Likewise, the estimation of the 4th degree polynomial corresponding to two cycles was estimated for the UK data. From the estimation results, the t statistics of the parameter coefficients of all polynomials were significant. More importantly, the signs of all parameters confirm the Kuznets curve relationship. Therefore, we provide the evidence of cyclical Kuznets Curve for UK and USA.

Table 7. Polynomial Model Estimates for the UK

		UK
$\frac{CO_2^2}{Pop_t} = -0.0002 + 0.994 \left(\frac{GNP_t}{Pop_t} \right) - 103.083 \left(\frac{GNP_t}{Pop_t} \right)^2 + 4299.978 \left(\frac{GNP_t}{Pop_t} \right)^3 - 63581.671 \left(\frac{GNP_t}{Pop_t} \right)^4$		
	<small>(-1.063) (10.879) (-8.311) (6.664) (-5.666)</small>	
$R^2 = 0.912, F\text{-test}=88.157 (0.000), \text{Log Likelihood} = -1720.555$		
<i>Roots of the polynomial regression</i>		
[1] 0.0002055515-0.000000000i	[2] 0.0175254497+0.01286726i	
[3] 0.0175254497-0.01286726i	[4] 0.0323734700+0.000000000i	

From Figure 4, we see the estimation from the polynomial model placed on the scatter plot of CO₂ and income for UK data. In Figure 4, the polynomial fourth degree (blue line) and the linear (red line) or first-degree polynomial models are given together. We have visually given how well the predictions we made from the 4th-degree polynomial model we built predict the Kuznets relationship for UK. Here, it is clearly seen from the UK data that the Kuznets relationship makes two cycles.

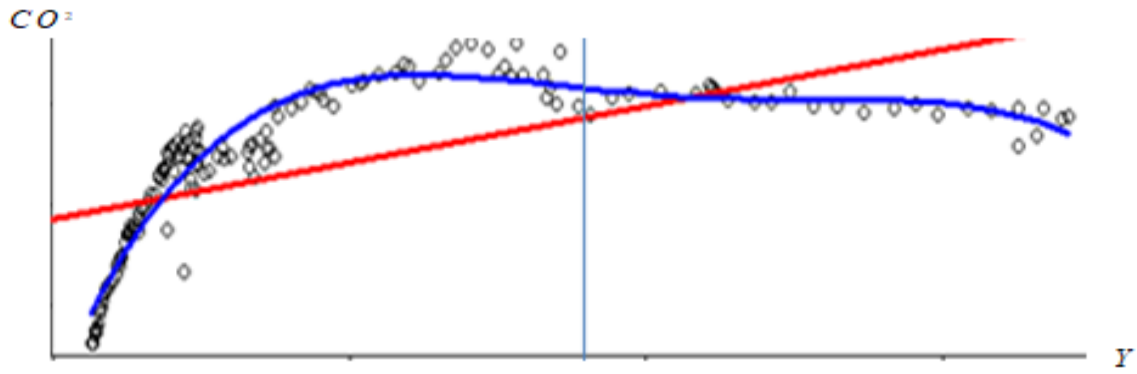


Figure 4. Cyclical Kuznets Curve for the UK data

The UK Kuznet relationship appears to be U-shaped as if there is only one Kuznets relationship. However, it is clearly seen from Figure 4 that it fits better when the fourth-order polynomial is taken instead of second order. In addition, the F test method was used to strengthen the confirmation of this situation. The fourth-degree polynomial got the highest F-test value according to the F-test result. In this sense, the F test has also confirmed that the UK Kuznets relationship has made two cycles. These obtained results are the same as those obtained with the Fourier filter.

Table 8. Model Misspecification: F-test

	USA	UK
$\beta_1 + \sum_{i=1}^1 \beta_{1+i} (GNP_t / Pop_t)^{1+i}$	161.158	9.695
$\beta_1 + \sum_{i=1}^2 \beta_{1+i} (GNP_t / Pop_t)^{1+i}$	259.811	67.679
$\beta_1 + \sum_{i=1}^3 \beta_{1+i} (GNP_t / Pop_t)^{1+i}$	266.454	88.079
$\beta_1 + \sum_{i=1}^4 \beta_{1+i} (GNP_t / Pop_t)^{1+i}$	264.647	88.157
$\beta_1 + \sum_{i=1}^5 \beta_{1+i} (GNP_t / Pop_t)^{1+i}$	315.728	86.303
$\beta_1 + \sum_{i=1}^6 \beta_{1+i} (GNP_t / Pop_t)^{1+i}$	441.587	86.530
$\beta_1 + \sum_{i=1}^7 \beta_{1+i} (GNP_t / Pop_t)^{1+i}$	406.919	
$\beta_1 + \sum_{i=1}^8 \beta_{1+i} (GNP_t / Pop_t)^{1+i}$	291.590	

Note : The dependent variable is $\frac{CO_t^2}{pop_t}$ and the explanatory variable is $y_t = \frac{GNP_t}{pop_t}$

Identification tests (namely Fourier Filter and Fourier type unit root tests) and estimated polynomial regression showed us that the fourth-order for the UK and the sixth-order for the USA were appropriate polynomials. We will perform a diagnostic check of the 4th and 6th-degree polynomials we estimated in Table 7 and Table 6 with the F test method. If the obtained F test values reach the highest value at the 4th degree for the UK and the sixth degree for the USA, the models we have designed do not contain a model specification problem. As shown from Table 7, we can see that the 6th-degree polynomial is the most significant model for the USA, with a test value of 441.587. Likewise, the F test value in the UK was found to be the highest, 88.157, that is, the most significant, for the model containing the 4th-degree polynomial.

5. Discussion

This section delves into the detailed discussion of the empirical findings for the USA and the UK. We analyze the nature of the cycles, comment on possible turning points, and explore the significant historical events that have shaped the economic growth-environmental degradation nexus in both countries. Specifically, we examine how major occurrences such as World Wars I & II, the Great Depression, oil price shocks, and financial crises have influenced the cyclical patterns observed in the Environmental Kuznets Curve (EKC).

5.1 The USA

The empirical findings of this paper show that the EKC for the USA is characterized by 3 cycles. Empirical evidence supports the validity of an inverted U-shaped EKC in the early phase of economic growth in the USA (1875-1932). Economic growth initially has a negative impact on environment, which was then reversed. The CO₂ emissions were at the lowest level in this cycle in 1932. The USA has experienced a rapid economic growth following the Civil War which ended in 1865. Campbell (1999) points out that the Gilded Age (1877-1895) was characterized by dual paths of growth. On the one hand, large immigration flows from Europe after 1865, the Western movement, resulted in the expansion of agricultural areas, coupled with an increase in demand for labor. On the other hand, industrialization efforts have gained momentum with the introduction of railroads. Hence the USA experienced a unique growth trajectory of undergoing extensive agricultural settlement at the time of their industrial transitions, resulting in the doubling of the US GNP per capita between 1870-1900

(Campbell, 1999). Although the carbon emission levels of early industrialized countries, the UK, the USA and Germany were very close to each other until the early 1890s, with the Gilded Age the USA emerged as the top CO₂ emitter in the world. However there had been a sharp decline in growth rate to around 2.8 per cent in 1910 -1929 period, as there were three recessions (Harrison and Weder, 2009). Yet the Roaring Twenties experienced the widespread effects of innovations in manufacturing and technology. The Great Depression marked the beginning of a recession, leading to a fall in economic growth that was accompanied by a fall in CO₂ emissions. The findings for the first cycle of EKC is consistent with the earlier empirical evidence provided by Tol et al. (2009) who showed that CO₂ intensity rose until 1917 because of the transition from wood to coal, but technological and behavioral changes led to a fall in CO₂ afterwards.

During Great Depression there was a decrease in GNP by 25%, resulting in economy hitting its trough in 1933. The economic recovery started in the spring of 1933, achieving a real GDP growth rate of 9% per year between 1933 and 1937. With the start of the World War II in 1939, the USA took steps to enlarge its military and to convert its industrial base to produce armaments and other war materiel rather than civilian goods. Within this framework the US manufacturing sector thrived. Besides Lend Lease program initiated in 1941 ensured that the USA provided American goods to its European allies, leading to an increase in US exports, mostly composed of military equipment. Klausen (1998) stated that the civilian war economy that developed from 1939 to 1945 paved the path for the postwar welfare state. The collaboration between government, private sector and organized labor ensured a continued economic growth following the WWII until 1960. The USA experienced an uninterrupted period of continuous economic growth between July 1938 -February 1945⁷. The second cycle in the EKC for the USA took place in 1932-1960 period. The rapid growth in industrial production, and hence in energy demand, to meet the demands of European Allies brought carbon intensity to a new level in the initial phases of 1932-1960 cycle, leading to a deterioration in environmental quality. So WWI and WWII seem to have differential impact on US carbon intensity. Mikayilov et al. (2018) showed that World Wars had recessionary effects for all countries bringing a fall in their emission levels. Although this was the case for the WWI for the USA, our empirical evidence suggests the reverse for the WWII.

⁷ <https://www.nber.org/cycles.html>.

The 1960s witnessed one of the longest uninterrupted period of economic expansion in history of the USA. Until 1972 carbon emissions continued to grow with increases in production. However, an external event, oil price shock, led to a structural change in carbon emissions–economic growth relationship. Moomaw and Unruh (1997) pointed out that oil shock and the 1973 oil embargo stabilized or decreased the fossil fuel energy intensity of economic activity in many OECD countries, leading to a decoupling of economic growth and environmental pollution relationship. Following the first oil shock in 1973-1974, President Nixon launched Project Independence, to achieve US energy self-sufficiency by 1980, in addition to diversifying energy mix, whereby increasing the share of natural gas and nuclear power. Energy Policy and Conservation Act has been signed in 1975 establishing automobile fuel efficiency standards and extending price controls on oil. An increase in energy prices enhanced the efforts for designing energy saving and energy efficient technologies, leading to emergence of renewable energy technologies since 1980s.⁸

The US economy experienced recessions in 1979 and 1981, which were characterized by low productivity, leading to a drop in CO₂ emissions which lasted about 4 years. After oil prices returned to their normal levels, the demand for real investment increased substantially, leading to an increase in output and employment. Larson (2012) noted that growing population and wealth were the main factors driving CO₂ emissions from 1985 to 2005. During this period the US economy experienced three long cycles of economic expansion in 1991, 2001 and 2009 which lasted at least 120 months. In 1990 the legislation of the Clean Air Act has been adopted which aimed to reduce environmental pollution. In 1997 the Kyoto Protocol was adopted by the USA and 121 other nations, but not ratified by the US Congress, which entered into force in 2005. The US CO₂ emissions, in the last cycle, reached its peak in 2005. Although recessions are considered to lower the environmental impact, the falling CO₂ levels since 2005 may indicate that the recession could not be the only cause of the environmental improvement. Becoming more energy efficient and less carbon-intensive, compared to previous decades, may also have contributed to the improvement in environment (Shahbaz et al., 2017). The findings for the third cycle are consistent with the findings of Congregado et al. (2016).

⁸ Please see Mittlefehldt (2018) for a review of development of renewable technologies in the USA since the energy crises of the 1970s.

5.2 The UK

The empirical results of this paper show that EKC for the UK is characterized by two cycles. The first turning point almost coincide with that of Yilanci et al. (2023) around the 1920s while the second turning point is very close to the turning point reported by Lanne and Liski (2004). The first cycle 1851-1919 witnessed a rapid economic and social change. Following the Industrial Revolution, which was central to world history, the UK economy has expanded more rapidly and real incomes have risen at a faster pace, in the post-1850 period than in the two centuries which preceded it (Wrigley, 2013). The invention of steam engine increased productivity by promoting economies of scale in manufacturing; transformed transportation, which in turn enhanced the pace of industrialization. By 1899 the relative importance of steam power increased and it accounted for over four-fifths of total primary power. Wrigley (2013) reported that annual energy consumption in England and Wales increased from 65,130 terajoules in 1561-1570 period to 1,835,300 terajoules in 1850-1859 period. Additionally, the composition of energy mix has also changed. While the primary energy source was draught animals (32.4%) and firewood (33.0%) in 1561-1570 period, coal accounted 92% of energy source in 1850-1859 period. As production has heavily relied on coal, environmental impacts were inevitable⁹. Starting from 1870s, coal was also used for manufacturing of synthetic gas to be used for illumination and later for cooking (Arapostathis et al., 2013). The CO₂ emissions increased from 143 megatonnes (Mt) in 1858 to 535 Mt in 1916. The smoke problem was considered to be the major cause of health problems and social unrest, especially in Midwest England (Stradling and Thorsheim, 1999). There had been a continuous rise in carbon emissions through the Victorian age. Hence the transformation of traditional economy to a mass producer industrial economy had negative environmental effects. The empirical finding of this paper indicate that the first EKC cycle covers the period 1851-1919 which almost coincide with the cycle reported by Ball and Wood (1996).

The WWI had drastic impacts on the UK economy. Although GDP per capita increased during the war, it fell back to the pre-war level in 1919 (Broadberry and Howlett, 2005). In addition to having far reaching economic and social effects, the WWI has shifted the balance of economic power from the Old World to the New World, as the USA emerged as the world's major economic power (Schenk, 2005). The adverse effects of WWI in the 1920s include higher unemployment, lower trade, and a reduction in GDP. Following the WWI the

⁹<https://www.carbonbrief.org/analysis-uk-carbon-emissions-in-2017-fell-to-levels-last-seen-in-1890>

UK economy was depressed throughout 1920s, unemployment reaching 12% in 1921. Alford (1981) argued that there had been productivity falls because of industrial conflict. The coal miners' strike in 1921 and general strike of 1926 caused disruptions to the supply of coal and hence production, leading to a fall in CO₂ emissions. The fall in productivity relative to 1912 was estimated to be 25% and 38% in 1921 and 1926, respectively (Churchill et al., 2018). The Great Depression originated in the USA but quickly spread to Europe and hit the UK as the American demand for British goods has declined, leading to a fall in the UK exports. Carbon emissions fell further until mid-1930s. Humphrey and Stanislaw (1979) noted the depression in the economy might have increased efforts to conserve fuel in industry and in households, causing energy saving in the 1930s. The smoke abatement policies of late 19th century banning industrial activities from urban areas in addition to migration of households away from the city centre, contributed to a fall in smoke and sulphur dioxide concentrations in London from 125 $\mu\text{g}/\text{m}^3$ and 170 $\mu\text{g}/\text{m}^3$ in 1890 to about 70 $\mu\text{g}/\text{m}^3$ and 80 $\mu\text{g}/\text{m}^3$ by 1935 (Brimblecombe, 1977). Yet, the sentimental attachment of English public to use coal for heating and cooking at homes, practical difficulties of replacing it by a fuel that could be used in an open grate and the challenges in enforcing laws against smoke which was hard to define and measure at the time were key barriers for the abatement of coal (Ashby and Anderson, 1977). The coupling of anticyclone and windless conditions with an extremely cold winter in 1952 resulted in forming of a thick layer. The effects of smoke from domestic coal use were exacerbated further from the presence of a number of coal-fired power stations within Greater London. Consequently, 'The Great Smog of London' has resulted in severe impacts, ranging from reducing visibility to respiratory illnesses and 13,500 more deaths than normal between December 1952 and March 1953 (Bell et al., 2004), creating a momentum for the introduction of air pollution measures in Britain. It is against this background that the government passed the Clean Air Act of 1956.

The WWII had an adverse impact on the UK economy compared to the US economy. According to Harrison (1998) there had been a 84% increase in real GDP of the USA, whereas the UK has achieved a GDP growth of 16.5% between 1938 and 1945. The pressures of war demanded mass production of military equipment, which necessitated shifting from civilian production to military production, which was more energy intensive (Coombs, 2013). UK exports in 1940 declined one third compared to 1935. Following the WWII the UK experienced a long period of stability without a major recession between 1945-1973, marked by a rapid economic growth in 1950s and 1960s, which was seen as a "Golden Age" (Schenk,

2005). However, the oil crisis of 1973, and 1973-74 stock market crashes resulted in a recession, with double digit inflation and rising unemployment levels. The nationalization of private and municipal gas companies via the Gas Act of 1948 formed British Gas, a vertically integrated monopoly for the sale and distribution of town gas to consumers. Yet, high costs of carbonization of coking-coal and variation in heating value and low pressure of town gas have led the UK to become the first country in Europe to import liquefied natural gas. The gas industry in the UK has changed significantly with the discovery of natural gas in the UK Continental Shelf by driving a national policy to switch from town gas to natural gas (Arapostathis et al., 2013). A period of neo-liberal economics has begun in 1979 including the privatization of gas and electricity sectors. In 1980s inflation was successfully reduced at a cost of higher unemployment. Following the economic expansion of 1988-1989, in 1993 there was another slump with negative economic growth rates. The post WWII period witnessed an improvement in energy efficiency and hence environmental pollution. The main reason for this improvement was the substitution of oil for coal between 1950-1970, and substitution of gas for coal afterwards (Fouquet and Pearson, 1998; Humphrey and Stanislaw, 1979). The Royal Commission on Environmental Pollution published a report on 'Energy - The Changing Climate', calling for 60% reductions in UK CO₂ emissions from 2000 levels by 2050 to enable limiting global emissions to 550 ppm. This target was subsequently adopted by the Energy White Paper in 2003¹⁰. In 2008, the UK Government legislated the Climate Change Act to reduce its greenhouse gas emissions by 80% from 1990 levels by 2050. In response to IPCC Special Report in 2018 and following the advice from the independent advisory body, the Committee on Climate Change (CCC), the UK Government has legally committed to reduce its greenhouse gas emissions to net-zero in June 2019. These legislative changes culminated a push for the decarbonization of power sector through the utilization of renewable energy and use of this clean power in industry, transport and residential (mainly to replace the use of natural gas for heating) sectors. Consequently, mean carbon intensity of the UK power grid was reduced by 53%, from 529g CO₂/kWh in 2013 to 215g CO₂/kWh in 2019 (National Grid, 2020). The CCC expects the carbon intensity to reach 2 g CO₂/kWh in 2050 (CCC, 2020).

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https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/272061/5761.pdf (Accessed on 20/02/2021)

Although output has been increasing, there has been a continuous decrease in CO₂ emissions since the early 1990s, with the level of emissions in 2017 as low as they were in the year 1890. There may be a couple of factors at play leading to an improvement in environmental indicators. In addition to achieving energy efficient production, shifting production of pollutive sectors to other countries may have also contributed to this fall in CO₂ emissions. The empirical findings of Mulatu (2017) support the pollution haven hypothesis for both the USA and the UK.

The findings of this study closely corroborate prior research, particularly the work of Yilanci et al. (2023), further reinforcing its conclusions. The empirical analysis reveals a distinct pattern within the Environmental Kuznets Curve (EKC) for the United Kingdom, marked by two discernible cycles. Initially, the analysis indicated a U-shaped relationship resembling a singular Kuznets curve; however, a more nuanced understanding emerged upon employing a fourth-order polynomial. These results align with the insights of Yilanci et al. (2023), who similarly observed various shapes of EKCs (including U-shaped, inverted U-shaped, and N-shaped) within sub-samples. This underscores the intricate relationship between economic development and environmental quality across historical periods.

The cyclical patterns identified in this study have significant policy implications, not only for the UK and the USA but also for countries globally. The presence of multiple cycles in the Environmental Kuznets Curve (EKC) highlights that economic growth and environmental degradation are not linear processes suggesting that environmental impacts vary over different phases of economic growth, influenced by technological advancements, policy measures, and socio-economic changes. This understanding is crucial for designing flexible policies that can respond effectively to the dynamic nature of the growth-environment relationship.

For countries at different stages of economic development, it is important to consider the historical context and structural changes that have shaped their current environmental and economic conditions. Policymakers should use long-term data to identify the turning points in their EKC and implement targeted interventions that address the specific needs of each phase. Moreover, empirical results suggest that global environmental governance frameworks must be flexible enough to accommodate the diverse trajectories of individual countries. International cooperation and knowledge-sharing may help countries learn from each other's experiences and adopt best practices. Policies should also emphasize the importance of technological transfers and financial support to developing countries, enabling them to leapfrog to cleaner technologies without compromising economic growth. Countries can achieve sustainable development goals while mitigating the adverse effects of economic activities on the environment, by integrating these insights into policy design. Hence

recognizing the cyclical nature of the EKC and the influence of various economic, technological, and policy contexts can help policymakers design more effective and adaptive strategies.

6. Conclusions

The existing literature investigating economic growth-environmental degradation nexus generally employs cross-country panel data, implicitly assuming a standard structure for all countries at different stages of development. However, countries may be at different levels of economic growth, which necessitates single country investigation of the EKC hypothesis. Moreover, economic growth may impact the environment differently during economic expansions and recessions, which calls for a historical perspective to capture the dynamic nature of the EKC relationship. Further, having a long span of data enables researchers to evaluate the differential impact of growth cycles. In fact, this approach may result in defining more cycles of economic growth-environmental degradation nexus compared to the standard inverse U-shaped EKC. In this line of reasoning, this paper assesses the association of economic growth-environmental degradation for two early developer countries, the USA and the UK, employing historical data, which may offer further insights into the long-run association of income growth and environmental deterioration.

For this purpose, this paper employs the FFFFF DF-type unit root test of Omay (2015) and the sharp and smooth structural breaks unit root test (SOR) developed by Shahbaz et al. (2018). Moreover, Enders and Li (2015) Fourier filter is used to identify the polynomial order of the regression. Polynomial EKC models are estimated for both countries. The empirical findings show that the EKC for the USA is characterized by three cycles; the EKC for the UK is characterized by two cycles. Our results show that major events such as World Wars I & II, Great Depression, oil price shocks, and financial crises have impacted the economic growth-environmental degradation nexus. For both countries, the initial phases of economic growth are characterized by an inverted U-shaped EKC, with industrialization efforts contributing to carbon emissions. The recessionary effects of World War I led to a decrease in the carbon emission levels in the USA and the UK. In the first phase of the second cycle, both countries have achieved rapid economic growth at the expense of environmental degradation. The Great Depression affected both countries similarly, resulting in a decrease in economic growth coupled with an improvement in environmental indicators. World War II had a similar effect

on carbon emissions in the UK, but for the USA, it resulted in an increase in CO₂ as production as the USA emerged as the new major world power. The scientific and technological innovations and increases in productivity led to an improvement in environmental degradation for both countries after the 1930s. Both countries experienced rapid economic growth in the 1960s, accompanied by an increase in CO₂ emissions, which was reversed by the oil price shocks of the 1970s. Following the oil price shock, policymakers in both countries adopted energy-saving policies aiming at energy efficiency and energy self-sufficiency. The end-use energy efficiency policy actions, energy efficiency improvements in the buildings sector were also important in explaining the fall in greenhouse gas emissions (Nelson et al., 2016). According to the International Energy Agency's 2019 report on Global CO₂ Emissions, although global CO₂ emissions show an increasing trend, global energy-related CO₂ emissions stayed constant at around 33 gigatonnes (Gt).¹¹ This may be due to a decrease in CO₂ emissions in advanced economies due to utilizing renewable energy resources, such as wind and solar PV, and using more natural gas instead of coal.

It is important to note that CO₂ emissions are influenced by a multitude of factors beyond economic growth. Our polynomial model primarily focuses on the relationship between economic growth and CO₂ emissions, which may not fully capture the impact of technological advancements, policy measures, and socio-economic variables. Although this approach aligns with many existing studies, it also underscores the need for further research that incorporates a broader range of variables. Future studies could explore the interactions between economic growth and other determinants of CO₂ emissions, such as energy consumption patterns, technological innovations, and regulatory frameworks. Additionally, the globalization of the economy has led to significant transfers of CO₂ emissions to countries where industrial production is relocated. The relocation of pollutive production from developed countries like the USA and the UK to middle and low-income countries with less stringent environmental regulations, such as China, India, sub-Saharan countries, ASEAN countries, and MENA countries has significant implications (Nasir et al., 2019; Berry et al., 2021). This issue, referred to as the pollution haven effect, shifts the burden of environmental degradation to developing countries, complicating global efforts to reduce emissions. This critical aspect of the evolution of the EKC needs further exploration. As industries move to

¹¹ <https://www.iea.org/articles/global-co2-emissions-in-2019>

countries with less stringent environmental regulations, CO₂ emissions are effectively outsourced, potentially leading to an underestimation of emissions in developed countries and an overestimation in developing ones. Investigating how globalization and industrial relocation influence the EKC may provide a better understanding of the global environmental impacts of economic activities. The increasing trend of industrial relocalization should also be monitored, as it may contribute to rising CO₂ emissions in the future, thereby affecting EKC patterns.

Our empirical results show that resorting to historical data and employing advanced unit–root tests with Fourier filter, which enable researchers to identify multiple cycles, improved the EKC estimations, and provided a better understanding of economic growth–environmental degradation relation for both countries. For future research more empirical research is needed that examines the changes in emission composition, distinguishing the trends in emissions from solid and non-solid fuels burning (Lanne and Liski, 2004). This may also shed light to the differential impact of oil shocks on environmental degradation.

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