Reinvestigation of the validity of the EKC hypothesis extended with energy: A time-varying analysis for the United Kingdom

Abstract

The Environmental Kuznets Curve (EKC) hypothesis has been extensively analyzed as a long-term relationship between the economic development stages and related environmental impacts. Most of the existing literature has however produced unreliable results as extensive databases have been used without considering the length of the time span. In this study, the EKC hypothesis is re-investigated for the United Kingdom for the time period 1850-2018. The objective is to conduct an innovative methodological approach that, contrary to the conventional estimation methods, uses time-varying techniques—the time-varying cointegration test of Bierens and Martins (2010) and the time-varying causality test of Shi et al. (2018, 2020)—to account for the incidence of unexpected historical events, such as socio-economic and policy crises. Results show that, for the considered years, the EKC hypothesis is valid for the UK. In addition, by including income, carbon dioxide emissions, and energy consumption data, the present study also analyses the environmental impacts of energy use and the environmental quality changes that have taken place during the considered period of time. This result proves that energy consumption pollutes the environment significantly; however, the magnitude of its impact can be affected by many shocks. According to the empirical findings, policymakers could adhere to current policies because environmental quality has started to increase for several decades in the United Kingdom. The employed methodology, and the related results, can support the definition of policies and the development of additional research initiatives.

Keywords: EKC hypothesis, energy consumption, Granger causality, time-varying coefficients, United Kingdom

1. Introduction

The extensive fossil fuel dependency and the increasing consumption of developed and developing areas are largely contributing to the increase in the quantity of GHG emissions generated by countries. Over the decades, a wide range of analyses has been performed to investigate the relationships existing between economic growth and environmental impacts, and related sustainability policies have been defined. Within this context, the Environmental Kuznets Curve (EKC), is a well-known hypothesis used to investigate the possible trade-offs existing between development trends of countries and related environmental impacts. The EKC was firstly proposed by Grossman and Krueger in 1991 (Grossman and Krueger, 1991) and has acquired significant popularity thanks to the work conducted by the World Bank (1992). By predicting an inverted U-shaped relationship between pollutants and per capita income, the EKC expects the environmental quality to deteriorate as GDP increases. However, after reaching a certain point, the relationship starts to turn, and environmental quality improves as income rises (Frankel and Rose, 2005; Tsurumi and Managi, 2010) (see Figures 1 and 2).

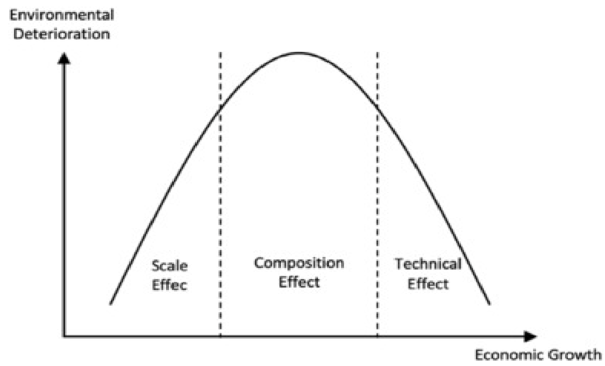


Figure 1

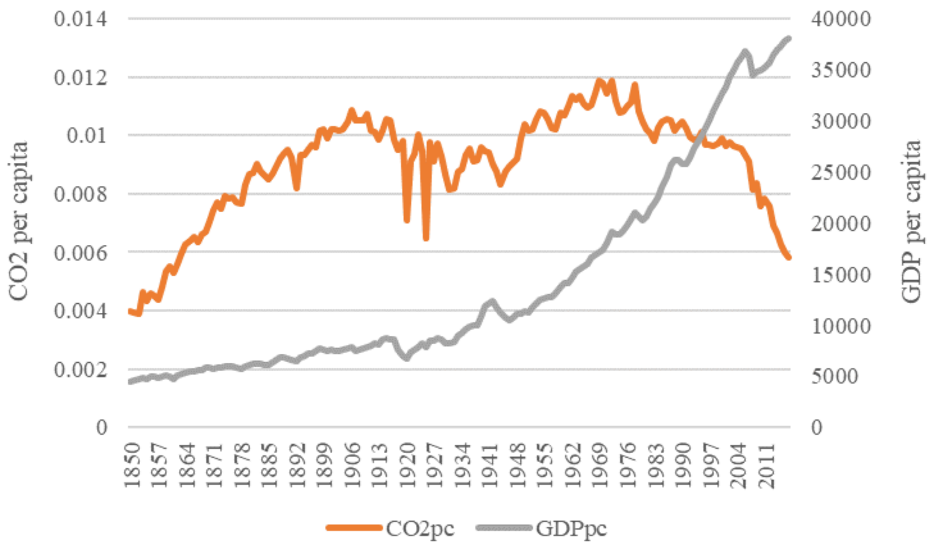


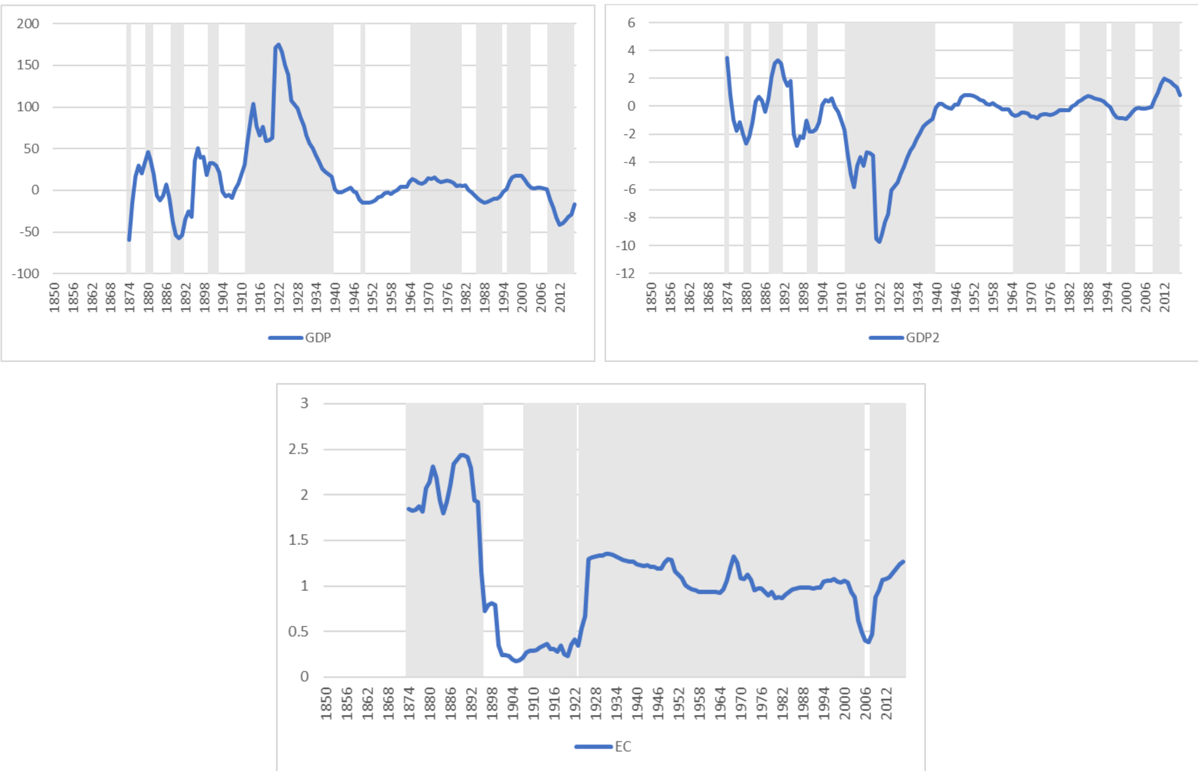
Figure 2

By highlighting the potential contributions of structural changes and technological advancements, the EKC hypothesis has been a core factor for the definition of the sustainable development approach and for the promotion of green growth strategies (Panayotou, 1993; Andreoni and Levinson, 2001; Stern, 2004; Brock and Taylor, 2010). Despite being an essentially empirical phenomenon, the EKC analyses have however produced a wide range of contradictory results. N-shaped, monotonic, and no relationship at all have for example being identified by studies focusing on different types of pollutants, model specifications, and econometric approaches (Thomson, 2012; Pham et al., 2020; Uddin, 2020; Mrabet et al., 2021, Magazzino et al., 2023a). In addition, the geographical focus of the analyses has also been largely advocated to question the role of structural changes and international trade in relation to the Carbon-Leakage and the Pollution Heaven Hypothesis (Stern et al., 1996; Liddle, 2018; Khan et al., 2020).

Given the ambiguity of the obtained results and the potential impacts on policy and approaches, further analysis should be devoted to question the existing methodological techniques. Within this context, the present paper aims to address an important issue related to the use of extensive datasets, that are fundamental for the analysis of the EKC as a long-term phenomenon. On the one side, the trends of countries need to be tracked over various development stages. On the other side, the use of extensive datasets can include unexpected historical events, such as socio-economic and policy crises, which can impact the overall EKC trend. To be able to account for these time-varying effects, a novel methodological approach is employed in this paper. The aim is to capture episodic movements in the cointegration and causality relationships and to track the possible effects of economic, financial, and policy shocks, together with disasters and wars. Results can provide a more comprehensive historical overview and support the definition of policies designed in line with an extensive range of possible events. While the tests that consider structural breaks in the cointegration tests can be used to test the long-run relationship between the variables by allowing changes. However, the presence of a relationship can change over time, and employing a technique that considers structural breaks does not capture this change, and so has low power in the case of episodic relationships. This approach will help us comprehend the evolving relationship between economic growth and environmental degradation.

Since the EKC hypothesis is a long term-phenomenon, an extensive time-period needs to be considered. For this reason, the United Kingdom has been selected as a case study for this paper. Covering the period 1850-2018, for which consistent data are available, the ECK analysis for UK includes a range of economic development stages such as the pre-industrial, the industrial and the post-industrial stages. During this period the British economy experienced extensive socio-economic changes with related impacts on energy production and uses. As previously highlighted by Fouquet and Pearson (1998), by 1870 the use of steam completely overtook the water as a source of industrial power and at the beginning of the nineteenth century the use of coals for residential purpose largely increased. The rising disposable income and the relatively low prices of coal contributed to increase the residential consumption from 19 million tons is

1869 to 35 million tons in 1913. The economic expansion and the related technological innovations also supported the rapid development of alternative energy sources, such as the transformation of coal into gas and the use of petroleum products. However, during the last few decades, the introduction of the nuclear power plants and the rising share of renewable energy sources largely contributed to the reduction of coal. The European commitments toward the coal phase-out and the increasing climate concerns also accelerated the transition to more sustainable energy sources. As reported in Figure 3, the rising level of GDP, characterizing the British development during the entire period considered in this paper, has been closely matched with a carbon dioxide emission increase. Since the 1960s, however, the progressive introduction of nuclear power, liquid fuels and renewable energy sources contributed to the reduction of the CO_2 per capita generated.



Note: Grey-shaded areas show the periods when the relevant variable is statistically significant.

Figure 3

Since the adoption of the Climate Change Act of 2008, the British government is also legally obliged to mitigate the national emissions of greenhouse gas and is aiming to reach the carbon neutrality by the year 2050 (UK Gov, 2021). Given the importance that energy use is playing in the existing relationships between emissions and growth, energy consumption data are used in this paper as a control variable, as defined as one of the main drivers of environmental impacts. As previously highlighted by Inglesi-Lotz (2019) energy consumption is a significant factor affecting the environmental quality of the countries. In addition, being a fundamental input of production, energy use is closely related to economic and environmental changes (Jobert et al., 2014). Therefore, considering the literature on this specific topic, and the important role that energy use had in the economic development of UK, in this study the traditional EKC model is extended with the incorporation of an energy consumption variable. To the best of our knowledge, this is the first study that tests the EKC hypothesis using such a large dataset for the United Kingdom, employing methods that allow the cointegration parameters to change over time.

The main limitation of this study is that the model cannot take into account significant control variables because of the unavailability of the data beginning from the 1850s. These main variables can be listed as follows: globalization, trade openness, foreign direct investment, urbanization, and so on.

The paper is organized in the following manner: Section 2 offers a summary of the literature on the EKC analysis conducted for the UK. Section 3 describes the data and methodological approach. Section 4 contains the empirical findings and discussion, while Section 5 brings the paper to a close.

2. Literature Survey

Grossman and Krueger (1991) conducted the first study to examine the nonlinear link between per capita income and environmental pollution. They argued that there was an inverted U-shaped nexus between these variables. This type of relationship was named as the Environmental Kuznets Curve (EKC). Over the past few decades, the EKC hypothesis has become popular among practitioners and the empirical literature has extended significantly. In this section, a review of the main existing studies focusing on United Kingdom is provided. The objective is to discuss existing methodologies, together with the main benefits and gaps.

Only a few studies have examined the validity of the EKC hypothesis for the United Kingdom in a time-series setting, despite the extensive literature devoted to it. Among those, Acaravci and Ozturk's (2010) investigated 19 European countries and employed the Autoregressive Distributed Lag (ARDL) bounds testing method for the period 1960-2005. The empirical results showed no long-run relationship between per capita income and CO_2 emissions in the UK. Similarly, Ubaidillah (2011) analyzed the link between per capita income and carbon monoxide emitted by the UK's transport sector between 1970 and 2008. The findings, derived from the Johansen cointegration test, highlighted that the considered variables moved together in the long-run and supported the EKC hypothesis for the road transport sector of the UK. One of the most seminal papers using long-span data for the UK was conducted by Fosten et al. (2012). The study used CO_2 and SO_2 emissions data for the time period 1830-2003 and 1850-2002, respectively. The empirical evidence provided by nonlinear threshold cointegration tests suggested that the EKC hypothesis holds for this country. Similarly, Sephton and Mann (2016) used the same ecological indicators of environmental pollution in the United Kingdom. The authors argued that their findings, based on nonlinear cointegration, confirm the EKC hypothesis. Finally, Shahbaz et al. (2017) conducted the cross-validated Local Linear nonparametric regression technique considering the period between 1820 and 2015. Their empirical results support the EKC hypothesis for the UK.

With the recent introduction of novel methodologies, considering, for example, sharp structural shifts, smooth structural breaks, asymmetric relationships, or differences across quantiles, and parametric versus semi-parametric models (e.g., Yilanci and Ozgur, 2019; Gorus and Karagol, 2022; Magazzino et al., 2023b), practitioners have been eager to re-investigate the nexus between per capita income and ecological pollutants in (or including) the United Kingdom economy. Researchers have used these superior techniques to obtain more reliable and unbiased results. Among them, Ben Amar (2021) utilized the dynamic correlation measure and bivariate cross-wavelet coherency covering, and his paper covered the dataset from 1751 to 2016. Beşe and Kalayci (2021) conducted various time-series analyses to test the validity of the EKC hypothesis for Denmark, Spain, and the United Kingdom during the period 1960-2014. Recently, Caglar (2023) carried out a nonlinear ARDL method to determine the impact of per capita income on carbon emissions in the UK for 1974-2020. Besides, Vanli (2023) conducted a similar analysis through the ARDL bounds test for the United Kingdom for 1948-2018. The empirical results of both Ben Amar (2021), Caglar (2023), and Vanli (2023) supported the validity of the EKC hypothesis for the United Kingdom, while Beşe and Kalayci (2021)'s findings did not.

In panel setting analysis, plenty of empirical investigations include the UK in the sample. Among these studies, Churchill et al. (2018) employed various panel data techniques for 20 OECD countries covering 1870-2014. Their findings supported the validity of the EKC hypothesis for the UK for the considered period. Yilanci and Ozgur (2019) used the ecological footprint per capita as an ecological indicator and examined the relationship with per capita income in G7 countries from 1970 to 2014. To this purpose, they conducted rolling panel window causality, and the empirical findings indicated that there was no inverted U-shaped relationship between these variables for the UK economy. In addition, Destek and Sinha (2020) employed the first-generation panel cointegration tests to determine the long-run relationship between per capita income and emissions levels for 24 OECD countries from 1980 to 2014. The empirical results based on the FMOLS estimation show that the EKC hypothesis holds for the United Kingdom. Leal and Marques (2020) used the panel ARDL method, considering 20 OECD countries from 1990 to 2016. They suggest that the EKC is valid only for highly globalized countries. Recently, Gorus and Karagol (2022) employed the random forest method to test the validity of the EKC for 27 OECD countries covering 1971-2016. Their findings partly confirmed this hypothesis in a panel setting.

Aydin et al. (2023) tested the validity of the EKC hypothesis for G7 countries for the period 1990-2018. The authors found that the EKC hypothesis is valid for the whole panel, while it is not supported considering only the United Kingdom. Duran et al. (2023) found that there is an inverted U-shaped relationship between per capita income and per capita ecological footprint in 10 nuclear energy-producing countries during the period 1990-2020. In addition, Jahanger et al.'s (2023) findings supported the presence of the EKC hypothesis for nine countries across different quantiles for the period 1990-2017. Besides, Magazzino et al. (2023b) conducted both parametric and semi-parametric models for 9 developed countries (including the UK). They found that the EKC hypothesis is valid for the UK, according to the semi-parametric estimation results. Recently, Ullah et al. (2023) found that there is a N-shaped relationship between per capita income per capita carbon emissions for G-10 countries for 1994-2020.

The wide range of analyses conducted so far, together with the different methodological approaches, does not allow a full consensus on the validity of the EKC hypothesis for the UK. In addition, most of the existing studies have ignored the time-varying nature of the relationship which is particularly important as it allows to track the possible effects of economic, financial, and policy shocks, together with disasters and wars. Incorrect conclusions can be drawn by ignoring this variation. To address this problem, and to capture episodic movements in the cointegration and causality relationships, time-varying techniques are used in this study. A set of novel time-series methods are then used to determine the presence of the EKC hypothesis, extended with energy data, for the UK economy during the period 1850-2018. These approaches will enable us to better understand and account for the dynamic nature of the relationship between economic growth and environmental degradation.

3. Data, Model, and Method[1]

3.1. Data and Model

This investigation looks at the EKC theory for the UK in the time frame of 1850 to 2018. The data period was selected based on the data availability for the chosen variables. To this end, the following equation has been constructed:

$$CO_2 = f(GDP, GDP^2, EC)$$

where CO_2 denotes the per capita carbon emissions measured in kilotons, GDP indicates the per capita gross domestic product measured in 2011 US dollars, and EC shows the per capita energy consumption (including coal, natural gas, nuclear, petroleum, and renewables) at the aggregate level measured in megawatt hours. CO_2 series is obtained from the website of the Community Emissions Data System[2], while the GDP series is gathered from the website Maddison Project Database[3], and EC is obtained from the website of the National Infrastructure Commission[4]. We used all data in natural logarithms.

To gain insight into the data, we first presented the descriptive statistics in Table 1.

[1] The data and code are available from the corresponding author upon a reasonable request. In this study, we employed Easyreg, Gauss, and Eviews to conduct the analyses.
[2] https://zenodo.org/record/4509372
[3] https://www.rug.nl/ggdc/historicaldevelopment/maddison/
[4] https://nic.org.uk/data/all-data/historic-energy/#tab-primary-energy-consumption

Table 1. Descriptive statistics

Variables	Mean	Median	Maximum	Minimum	Std. Dev.	Skewness	Kurtosis	Jarque-Bera
CO_2	-4.736	-4.652	-4.434	-5.549	0.249	-1.583	4.974	98.026*
EC	3.371	3.362	3.841	2.611	0.318	-0.314	2.181	7.502**
GDP	9.333	9.098	10.547	8.374	0.643	0.501	1.962	14.669*
GDP^2	87.513	82.777	111.236	70.120	12.221	0.573	2.029	15.889*

Note: * and ** show the significance at the 1% and 5% levels, respectively.

The results in Table 1 reveal that GDP^2 possesses the highest mean and standard deviation, which indicates that the values of the GDP^2 series are more spread out than those of the other series. The skewness coefficients of the CO_2 and EC shows that they are left-skewed, indicating a larger proportion of lower values compared to higher values. The skewness statistics of the remaining series show that their distribution shifts to the right of the mean value. The kurtosis statistics of CO_2 and GDP and GDP^2 are lower than 3, which suggests that the distribution of these series has a short tail compared to the normal distribution, whereas the distribution of the EC is heavy-tailed compared to the normal distribution. The p-values of the Jarque-Bera test statistics reveal that all series have non-normal distributions.

3.2. Methodology

The dataset utilized in this study spans over 150 years, encompassing various crises, natural disasters, wars, pandemics, and other events that may have had a lasting or temporary impact on the analyzed relationship. Therefore, we have incorporated time-varying methods in this study, in addition to traditional tests, to explore the possible influence of these events over time on the Environmental Kuznets Curve (EKC). This approach will enable us to better understand and account for the dynamic nature of the relationship between economic growth and environmental degradation.

3.2.1. Cointegration Tests

To test the long-run relationship between the considered variables, we employed Johansen's (1991, 1995) cointegration test, which is less susceptible to small sample bias than the Engle-

Granger cointegration test, thus making it more reliable for small sample sizes. Johansen cointegration test is based on a vector autoregressive (VAR) model as:

$$Y_t = \mu + A_1 Y_{t-1} + A_2 Y_{t-2} + \cdots + A_p Y_{t-p} + e_t \tag{1}$$

where Y_t denotes the k-vector of the integrated (I(1)) endogenous variables in Eq. 1, that is, $[CO_{2t}, GDP_t, GDP_t^2, EC_t]'$. μ shows a vector of deterministic variables, e_t is an nx1 vector of innovations, and p shows the lag order of the VAR model. This VAR model can be rewritten in a compact form as

$$\Delta Y_t = \mu + \Pi Y_{t-1} + \sum_{i=1}^{p-1} \Gamma_i \Delta Y_{t-i} + e_t \tag{2}$$

where $\Pi = \sum_{i=1}^{p} A_i - I$ and $\Gamma_i = -\sum_{j=i+1}^{p} A_j$. While the estimates of Π contain long-run adjustments, those of Γ_i contain short-run adjustments in Y_t's changes. We can conclude that there is a long-run relationship when Π has a reduced rank $r < k$, therefore there are $k \times r$ matrices α and β such that $\Pi = \alpha\beta'$ and $\beta' Y_t \sim I(0)$. We employ the following trace and maximum eigenvalue test statistics to check the rank of Π:

$$\lambda_{\text{trace}}(r) = -T \sum_{i=r+1}^{g} ln(1 - \hat{\lambda}_i)$$

$$\lambda_{\max} = -T\, ln(1 - \hat{\lambda}_{r+1})$$

where T is the sample size, $\hat{\lambda}_i$ shows the i^{th} largest estimated canonical correlation, and r is the number of co-integrating vectors under the null.

Bierens and Martins (2010) introduced a new cointegration test to assess the null hypothesis of a steady long-run relationship against the alternative of time-varying cointegration, by extending Johansen's approach as

$$\Delta Y_t = \mu + \Pi_t Y_{t-1} + \sum_{i=1}^{p-1} \Gamma_i \Delta Y_{t-i} + e_t \tag{3}$$

The main difference between Eq. 3 and Eq. 2 is the subscript of Π in Eq. 3, which shows that Eq. 3 has a time-varying coefficient matrix. We analyze the null hypothesis of a steady cointegration $\Pi_t = \alpha\beta'$ against the alternative of $\Pi_t = \alpha\beta_t'$.

Bierens and Martins (2010) showed that the time-varying cointegrating vector, β_t, could be represented by a finite sum of Chebyshev polynomials, $P_{i,T}(t)$, of decreasing smoothness:

$$\beta_t = \beta_m\left(\frac{t}{T}\right) = \sum_{i=0}^{m} \xi_i P_{i,T}(t), \quad P_{0,T}(t) = 1, \; P_{i,T}(t) = \sqrt{2\,cos[\,i\pi(t-0.5)/T]} \tag{4}$$

$i \geq 0; t = 1, \ldots, T,$

P and i represent a polynomial vector, and a scalar, respectively. m is the degree of the Chebyshev time polynomial.

The following model is obtained by substituting Eq. 4 in Eq. 3:

$$\Delta Z_{jt} = \gamma_0 + \alpha\left(\sum_{i=0}^{m} \xi_i P_{i,T}(t)\right)' Z_{j(t-1)} + \sum_{k=1}^{p-1} \Gamma_k \Delta Z_{j(t-k)} + \varepsilon_{jt}. \tag{5}$$

when $m = 0$, Eq. 5 becomes the usual vector error correction model (VECM) as in Johansen (1991), the null hypothesis of time-invariant cointegration becomes $m = 0$, against the alternative of $m > 0$. The null hypothesis can be examined using the following test statistic:

$$LR_T^{tvc} = -2\left[\hat{l}_T(r, m = 0) - \hat{l}_T(r, m > 0)\right] \tag{6}$$

where r is the cointegration rank, and $\hat{l}_T(r,.)$ shows the log-likelihoods computed in the estimated values of the VECM parameters. LR_T^{tvc} follows a chi-squared distribution with $r \times m \times k$ degrees of freedom.

3.2.2. Time-Varying Causality Test

Toda and Yamamoto (1995) suggest testing for the existence of a causality relationship by estimating a VAR model with extra lags. Therefore, the following VAR model should be estimated to test the null hypothesis of no-causality:

$$Y_t = \mu + \sum_{i=1}^{k+d_{max}} \alpha_i Y_{t-i} + u_t \qquad t = 1, 2, 3, \ldots, T$$

where Y_t shows a k-vector of endogenous variables, $d_{\max}$ denotes the maximum integration level of the variables, and k indicates the optimal lag length. The null hypothesis of non-causality for a right-hand side variable to the left-hand side variable can be examined by testing the first k coefficients of the right-hand variable using a standard Wald statistic.

Shi et al. (2018, 2020) suggest a time-varying causality test that uses supremum Wald statistic sequences derived from sub-samples of the data. The sup-Wald statistics can be written as

$$SW_f(f_0) = \sup_{f_2=f, f_1\in[0, f_2-f_0]} W_{f_1}^{f_2}$$

where f_1 and f_2 are the beginning and end points of regression, respectively. $W_{f_1}^{f_2}$ is the Wald statistic obtained for each sub-sample regression over [f1, f2] with a sample size fraction of $f_w = f_2 - f_1$. Following the suggestion of Phillips et al. (2015) we determine the window length (f_w) as:

$$f_w = \left\{T\left(0.01 + 1.8\big/\sqrt{T}\right)\right\} \tag{7}$$

As Shi et al. (2018, 2020) demonstrated, the recursive evolving window (REW) approach provides the most reliable results; thus, we consider the REW approach to test the causality relationship. In the REW procedure, the endpoint $\tau_2 = \{\tau_0, \ldots, T\}$, and the starting point of the regression τ_1 vary from 1 to $\tau_2 - \tau_0 + 1$ where $\tau_1 = [f_1 T]$ and $\tau_2 = [f_2 T]$.

4. Empirical Results and Discussion

Before testing the long-run relationship, the integration levels of the variables must first be tested, as the cointegration tests require the variables to be integrated at one, I(1). Therefore, the Fourier augmented Dickey-Fuller (FADF) unit root test has been applied. This test was introduced by Enders and Lee (2012) and allow for multiple structural breaks through a Fourier function. An advantage of theh FADF unit root test is there is no need to determine the location or number of the breaks a priori. We only determine the optimal frequency value of the Fourier function which minimizes the sum of squared residuals and then test the significance of the Fourier function using a usual F test. If the Fourier function is statistically significant, it is needed to assess the results of the FADF test statistics, else this study should use the unit root test that does not employ a Fourier function. Results of the FADF unit root test are reported in Table 2.

Table 2. FADF unit root test results (with a constant)

Series	**Optimal Frequency**	**F Test Statistics**	**FADF Test Statistics**
CO_2	2	5.279	-2.91 (5)
EC	1	3.983	-3.496 (5)
GDP	1	3.867	-1.277 (13)
GDP^2	1	4.040	-1.056 (13)

Note: The numbers in parentheses show the optimal lag lengths. The critical value at the 10% level for the F test is 6.25 (Enders and Lee, 2012).

The findings of the F test statistic show that Fourier functions are not statistically significant for all series. So, next this study employs the ADF unit root test and present the results in Table 3.

Table 3. ADF unit root test results

Series	ADF Test Statistics (with a constant)
CO_2	-2.182 [0.214] (9)
EC	-2.021 [0.278] (7)
GDP	1.117 [0.998] (11)
GDP^2	1.338 [0.999] (11)

Note: The numbers in parentheses show the optimal lag lengths, and the numbers in brackets show the p-values.

The findings in Table 3 show that all the series have a unit root. In other words, any shocks to these series have permanent effects. Therefore, we apply the Johansen cointegration test, and present the results in Table 4.

Table 4. Johansen cointegration test results

Number of Cointegrating Equations	Trace Statistics	Critical Value	Max-Eigen Statistics	Critical Value
None	74.713^{*}	55.246	41.791^{*}	30.815
At most 1	32.922	35.011	20.823	24.252

Note: * denotes statistical significance at the 1% level

The empirical results in Table 4 prove the cointegration relationship among the following variables: emission level, income level, the square of income level, and energy consumption. To check the robustness of the results, we also employ a recently introduced cointegration test. Fourier Engle-Granger (FEG) cointegration test which is proposed by Yilanci (2023), allows multiple structural break in the cointegration relationship with a Fourier function. Yilanci (2023) modifies the Engle-Granger cointegration test by adding a Fourier function to the test equation in the first stage. After finding the optimal frequency considering the minimum sum of squared residuals, the residuals of the test equation is obtained and the stationarity of the residuals are tested using the ADF unit root test. The necessary critical values are tabulated in Yilanci (2023). We report the findings of the FEG cointegration test in Table 5:

Table 5. FEG cointegration test results

Optimum Frequency	FEG Test Statistics
1	-6.17 (0)*

Note: * denotes the significance at the 1% level. The numbers in parentheses show the optimal lag lengths.

The test results in Table 5 indicate that there is a long-run relationship between the series which proves that the result obtained is robust. However, the Johansen cointegration test only allows to test the time-invariant long-term relationship. To consider the presence of a time-varying cointegration relationship, Bierens and Martins' (2010) cointegration test was also used and the results are provided in Table 6.

Table 6. Bierens and Martins' (2010) time-varying cointegration test results

Number of m	Test Statistics	Probability
$m = 1$	11.94**	0.01781
$m = 2$	32.53*	0.00007
$m = 3$	74.48*	0.00000

Note: * and ** show the significance at the 1% and 5% levels, respectively. m denotes the degree of the Chebyshev time polynomial.

Table 6 shows that the null hypothesis of time-invariant cointegration was rejected. This implies that there is a time-varying long-run nexus between the variables. Therefore, time-varying coefficients should be estimated throughout the sample.

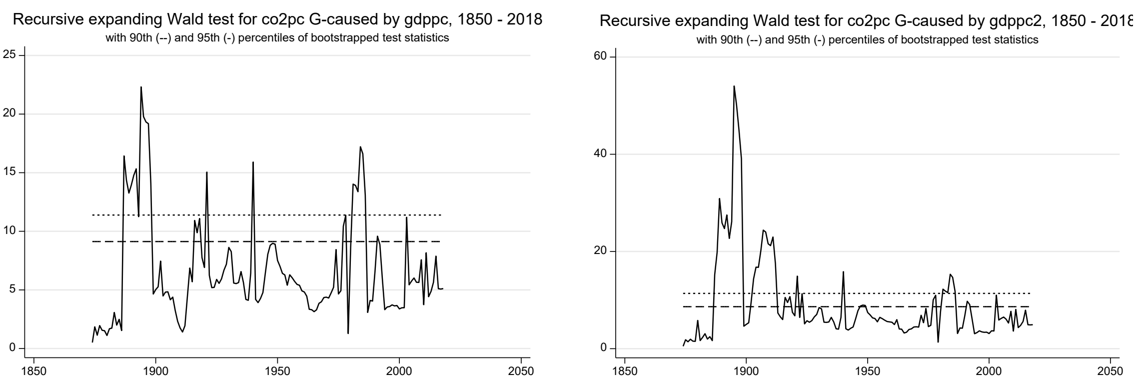
Table 7. Long-run coefficients for the full sample (1850-2018)

Variables	Coefficients	Standard Errors	t-statistics	Probability
C	-15.074*	4.344	-3.470	0.001
GDP	1.677*	0.936	1.792	0.075
GDP^2	-0.108*	0.047	-2.297	0.023
EC	1.248*	0.130	9.636	0.000

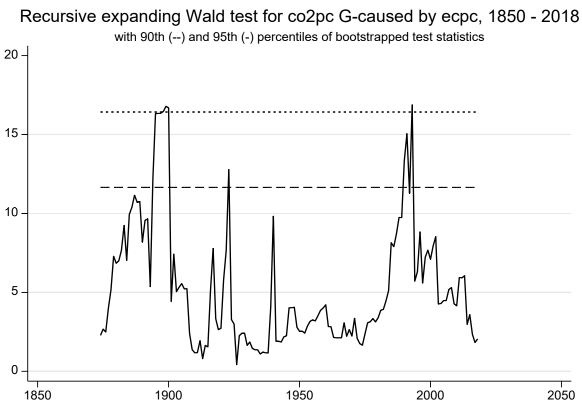
Note: *, **, and *** denote statistical significance at the 1%, 5%, and 10% levels, respectively. We compute HAC standard errors which are robust to autocorrelation as well as heteroscedasticity (R^2=0.88, F=403.835).

The empirical results derived from Table 7 reveal that an increase in per capita energy consumption causes an increase in the emission level in the UK for the whole sample. In addition, it is found that an increase in per capita income pollutes the environment up to a threshold point; after that, its effect turns positive; in other words, it increases environmental quality after the turning point. These findings validate the EKC hypothesis for the UK during the observed period. However, as indicated above, as time progresses, the impact of the regressors on the dependent variable may change; thus, time-varying coefficients must be estimated throughout the sample. To this purpose, the time-varying coefficients have been estimated by using rolling regressions, which are based on the estimation of the parameters using a fixed window of observations and then rolling the window across the data. By using Eq. (7), a window length of 25 is determined. Figure 4 illustrates the time-varying coefficients.

Figure 4



(a) Granger causality from GDP to CO_2 (b) Granger causality from GDP^2 to CO_2



(c) Granger causality from EC to CO_2

The figures show that the impact of per capita income on CO_2 emissions increased, especially around the first quarter of the 20th century. However, its polluting effects began to significantly mitigate after the 1920s. Around these dates, the government introduced the Public Health Act of 1936 and the Clean Air Act of 1936 to mitigate air pollution by using a bunch of policy tools. After the 1950s, its pollutive impact remained stable compared with the prior period. The 1950s were a milestone for the environmental awareness of the UK's people and the government. In 1952, London faced a very thick and polluting fog that killed several thousands of people and damaged ten thousand people's health (Met Office, 2023). Subsequently, people began to demand stricter environmental standards from the authorities, and the government launched the Clean Air Act in 1956. In the following years, especially after the 1970s, the worldwide recognition of the environmental problems led governments to cooperate to decrease environmental degradation through international initiatives (see the Stockholm Conference in 1972, the Vienna Convention in 1985, the Kyoto Protocol in 1997, and so on). It is seen that, in the early stage of economic development, the pollutive effect of income level was high; after a threshold point (around the 1920s), the environmental quality began to rise with an increase in economic growth. Even though there are different shapes (U-shaped, inverted U-shaped, N-shaped, so on) in the sub-samples, the whole sample confirms the presence of the EKC hypothesis in the United Kingdom. Different shapes in the sub-samples can be explained by the fact that the EKC hypothesis is not a smooth process; there may be many ups and downs throughout the whole sample regarding the relationship between per capita income and environmental quality. These ups and downs can be accounted by the external and internal shocks, for instance, oil price shocks, economic recessions and depressions, changes in the energy and environmental policies, so on.

Similarly, it was found that an increase in energy use had a detrimental impact on the environment by emitting greenhouse gases because of fossil fuel combustion. At the end of the 19th century, coal dominated the energy mix in almost all the countries. Wood had been surpassed by coal as the primary energy source by 1885 (Schwarz, 2018). Coal is known to be the most polluting energy source; thus, at the initial stage, the detrimental effect of energy consumption can be attributed to this fact. However, the impact on CO_2 emissions remained low between 1908 and 1922. During this period, European countries faced World War I, and the economy of the UK was significantly affected, like its counterparts. After Subsequently, the UK entered a post-war recovery process, and the economy began to grow significantly. Therefore, energy consumption rose, which is an important factor in production. Thus, the impact of per capita energy consumption on the environment started to increase. However, it began to decline after the 1950s; its trend is downward sloping until this date.

The polluting impact of energy during the 19th and early 20th centuries (except for the 1908-1922 period) can be explained by the utilization of fossil fuels alone. During this period, almost all the energy needs were met by oil, natural gas, or coal. These energy resources emit significant amounts of greenhouse gases into the atmosphere. Among fossil fuels, coal is the most polluting energy resource regarding, emitting pounds of CO_2 emissions per million btu; oil and natural gas follow it (EIA, 2023). In the second half of the 20th century, the foundation of the OPEC in 1960, the first oil crisis in 1973, and the second oil crisis in 1979 led to a significant increase in oil prices. High oil prices have forced countries whose economies mostly depend on oil imports to seek alternative energy sources, such as renewable and nuclear energy (Schwarz, 2018). Thus, the energy mix of most of the developed countries (like the United Kingdom) has changed, and they have started to use cleaner energy sources than fossil fuels.

Next, we test the causality relationship between the variables using the bootstrap causality test of Hacker and Hatemi-J (2012).

Table 8. Causality test results

Null Hypothesis	Optimal Lag	Wald Test Stat	Critical Values		
			1%	*5%*	*10%*
$EC \nrightarrow CO_2$	2	2.143	12.308	6.642	4.742
$GDP \nrightarrow CO_2$	2	10.928^{*}	10.277	6.328	4.800
$GDP^2 \nrightarrow CO_2$	2	11.010^{*}	10.182	6.334	4.792

Note: * shows the significance at the 1% level. The critical values are obtained using 10,000 simulations.

The results in Table 8 show that there is a unidirectional causality running from GDP and GDP^2 to CO_2, that is, both variables may help to forecast the future values of CO_2. However, the causal relationships between the above variables can be changed over time. For this reason, the time-varying Granger causality should be examined to get more accurate results.

In addition, this empirical study produces time-varying Granger causality test results for the aforementioned variables. The empirical findings in Figure 5 demonstrate episodic Granger causality from regressors to CO_2. There are causality runs from GDP to CO_2 in the late 1800s (see Figure 5.a). In addition, Figure 5.b. shows that there are causality relationships between GDP^2 to CO_2 in the late 1800s and early 1900s. In the last quarter of the 19th century, from 1873 to 1897, the United Kingdom faced a great depression: the overall price level decreased by a third and wages dropped significantly. Therefore, economic agents postponed their consumption and investment behavior because of deflation. These developments have caused huge economic contractions in the country (Johannessen, 2017). This is called *The Long Depression* in economic history. Even though the UK exhibited economic recovery and showed remarkable growth performance up to the *Depression of 1920-1921* after the economic crisis, a long-lasting economic depression between 1873 and 1897 had a significant impact on emission levels. This may be one of the main reasons why there is a causality from economic growth to carbon dioxide emissions in the late 1800s.

Besides, Figure 5. c. supports evidence of fewer causality relationships compared to the others. Only in 1890 and 1980, there exists causality from EC to CO_2. The existence of Granger causality on these dates can be attributed to the industrialization process of the UK and the second oil crisis in 1979. These events changed the energy consumption level and energy mix; therefore, the predictive power of per capita energy consumption for CO_2 emissions was significantly affected during the examined period.

The inverted U-shaped relationship between per capita income and CO_2 emissions found in this study corroborates the findings of Ubaidillah (2011), Fosten et al. (2012), Sephton and Mann (2016), Shahbaz et al. (2017), Ben Amar (2021), Caglar (2023), Magazzino et al. (2023b), and Vanli (2023) in a time-series setting. Despite the contradictory results provided by previous studies, the analysis conducted in this paper adds a shred of evidence supporting the presence of a nonlinear relationship between pollution level and income in the UK. In addition, the novel methodological approach, able to account for the time-varying nature of this relationship, has been useful to track the impacts of economic, financial, and policy shocks, together with disasters and wars.

5. Conclusion and Policy Implications

This study aimed to test the EKC hypothesis for the United Kingdom during the period 1850-2018. To this purpose, an innovative approach based on the use of time-varying estimation techniques (e.g., time-varying cointegration test and time-varying causality test), added to the traditional time-series methods (e.g., ADF unit root test and Johansen cointegration test) has been adopted. The objective was to check the EKC hypothesis for the UK by considering the possible impacts of socioeconomic, financial, and policy shocks.

The empirical findings suggest that per capita income, per capita CO_2 emissions, and per capita energy consumption move together in the long-run. In particular, the model, which considers the time-varying coefficients, indicates that an increase in income level has a negative impact on the environment first; then, it increases environmental quality in the later stages of economic development. This finding provided a shred of evidence for the presence of the EKC hypothesis in the United Kingdom for the period examined. The present study also identified that energy use followed a nonlinear pattern, as its damaging impact on the environment started to decline after the 1950s.

Moreover, the results of the time-varying causality test demonstrate that Granger causality runs from per capita income to CO_2 emissions in the late 1800s. In addition, it was found that there was one-way causality from per capita energy consumption to carbon dioxide emissions only in the 1890s and the 1980s. We can conclude that per capita income and per capita energy consumption have predictive power on per capita carbon dioxide emissions in the United Kingdom; however, this predictive power is limited only in particular periods.

The evidence provided should be considered when designing and implementing economic, environmental, and energy policies. According to these findings, policymakers could adhere to current policies because environmental quality has started to increase for several decades in the UK. However, if they desire to accelerate environmental recovery, they should continue their efforts to decrease fossil fuel energy use. They can invest in nuclear energy which does not emit any greenhouse gases into the atmosphere; however, it produces nuclear waste. Therefore, permanent storage facilities should be constructed (see Yucca Mountain project) instead of temporary on-site storage. Also, nuclear reprocessing should be considered by policymakers to decrease the amount of nuclear waste. Even though it has a high nuclear proliferation risk and high cost, its advantages and disadvantages should be discussed by authorities.

Also, policymakers need to focus on renewable energy projects to generate electricity without damaging the environment. However, it is almost impossible to generate all electricity from renewable energy sources because they are intermittent and non-dispatchable. Therefore, authorities should be careful to design energy policies to get rid of potential blackouts. Besides, as Balsalobre-Lorente et al. (2021) proposed, economic agents should care about energy innovation-oriented projects to decrease environmental degradation. In addition, they should support energy-efficiency improvements to implement energy-conservation policies. Policymakers should, therefore, provide an energy transition to mitigate the negative effects of this transformation.

As a result, policymakers should try to increase overall environmental policy stringency within the country. Even though the UK's environmental standards are higher than most of the OECD countries, they are behind some of the leading countries such as France, Switzerland, Finland, Norway, Sweden, and so on. According to the Environmental Policy Stringency Index data of Kruse et al. (2022), the UK had the 9th highest index value among OECD countries. The authorities can impose harsher environmental standards on both domestic and international firms to protect the environment (Balsalobre-Lorente et al., 2023).

Further studies should be conducted to validate the EKC hypothesis in a larger sample. This, for example, can be achieved by adding further developed areas. In addition, the use of time-varying panel data techniques can also contribute to generating more reliable econometric results.

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Declaration of competing interest

None

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