



Economic growth and environment in the United Kingdom: robust evidence using more than 250 years data

Amine Ben Amar¹

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Abstract

Using a long span of data (from 1751 to 2016), this paper empirically investigates the relationship between carbon dioxide (CO₂) emissions and economic growth (real GDP per capita) in the United Kingdom. The empirical results provide strong support for the existence of an Environmental Kuznets Curve (EKC) in the UK, i.e., an inverted U-shaped relationship between CO₂ emissions and economic growth, with turning point estimated around the mid-twentieth century. This turning point corresponds with the introduction of changes in environmental standards and policies, which reflects the regulatory efforts to limit pollution by reducing the discharge of grit into the atmosphere, as well as the decline in the use of coal as source of energy, which reflects the country willingness to ensure the energy transition necessary for sustainable development.

Keywords Environmental kuznets curve · Carbon dioxide emissions · Dynamic correlation · Wavelet coherency

JEL classification C2 · Q4

1 Introduction

In physics, the basic reasoning that is generally held around the issue of climate change is based on three points: (i) human activities emit CO₂, (ii) CO₂ is a greenhouse gas, (iii) the greenhouse effect warms the planet. However, in economics, the concept of sustainable development implies that the environment and economic development are not necessarily trade-offs but may rather coexist. More precisely, in the field of environmental economics, the Environmental Kuznets Curve (EKC)

✉ Amine Ben Amar
amine.ben-amar@uir.ac.ma; amine.benamar@gmail.com

¹ RBS College of Management, International University of Rabat, Technopolis Rabat-Shore
Rocade Rabat-Salé, 11103 Rabat, Morocco

hypothesis is used to represent the relationship between economic activity and environmental destruction.

Before the environmental Kuznets curve (EKC) hypothesis, it was widely accepted that wealthy countries were destroying the environment at a faster rate than poor ones. However, with the EKC, the relationship between environment degradation and income has been reexamined. The EKC hypothesis, which was first indicated in a study by Grossman and Krueger (1991) and popularized by the World Development Report (1992) of the World Bank, suggests an inverted U-shaped relationship between different pollutants and per capita income.¹ Indeed, the EKC hypothesis claims that environmental quality will worsen first as income increases until a certain point where the economy reaches a particular level of average income, and then improve as income increases over the long run (Grossman and Krueger 1995). The economic determinants of environmental quality can be decomposed into (i) *scale*, (ii) *composition* and (iii) *technique* (Grossman and Krueger 1995; Tsurumi and Managi 2010): (i) A larger-scale economic activity leads to increased environmental degradation; (ii) As the overall level of income increases, the economic structure initially shifts from an agrarian structure to an energy intensive industrial structure, increasing the share of polluting activities in the GDP, and then evolves towards a services-based and technologically-driven industries structure, increasing gradually and succinctly the share of cleaner activities in the GDP; (iii) The *technique effect* occurs when the society substitute non-polluting technologies for polluting ones, leading to the improvement in environmental quality.²

Is there some tendency for pollution to decrease after the economy reaches a specific threshold of income, as claimed by the EKC? The environmental effects of economic growth have been receiving increasing attention of economists and politicians³ in recent years. Even though a wide strand of the literature has examined the existence of the EKC, the link between pollution and economic growth remains ambiguous at the empirical level.⁴ For instance, Van Den Bergh and Van Veen-Groot (2001) construct aggregate indicators of the environment (actual environmental pressure, environmental quality and environmental policy) and economic activity

¹ The World Bank's World Development Report argues that "*the view that greater economic activity inevitably hurts the environment is based on static assumptions about technology, tastes and environmental investments [...]. As incomes rise, the demand for improvements in environmental quality will increase, as will the resources available for investment*". See, among others, Panayotou (1993), Grossman and Krueger (1995), Stern (2003; 2004), Tsurumi and Managi (2010), Bhattacharyya (2019) for further details.

² For instance, Tsurumi and Managi (2010) find that the *technique effect* plays a significant role in reducing SO₂ emissions in low, middle and high-income countries, and CO₂ emissions in high-income countries.

³ Climate change resulting from the increase in CO₂ and other greenhouse gases has potentially dangerous implications (Stern 2007), leading to the COP21 agreement in Paris in 2015 which seeks to limit the global rise in the temperature to less than 2C. More recently, the European Commission announced the European Green Deal, a new growth strategy aimed at transforming the EU into a fair and prosperous society where economic growth is decoupled from resource use (European Commission 2019).

⁴ Many special issues of academic journals have been devoted to contributions on the environment-income relationship. See, for instance, Halkos and Managi (2016, 2017) for a review of some recent developments on the EKC hypothesis.

for 12 OECD countries and find significant correlation between indicators of economic activities and both actual environmental pressure and environmental quality. Using annual data spanning from 1857 to 2007, Sephton and Mann (2013) record a non-linear cointegration relationship between income and CO₂ levels in Spain. Using data on GDP per capita and sulfur emissions, Markandya et al. (2006) report evidences of a U-shaped EKC for 12 European countries. Similarly, Fosten et al. (2012) and Sephton and Mann (2016) investigate United Kingdom data on both carbon dioxide (CO₂) and sulfur dioxide (SO₂). Their empirical results provide support for the Environmental Kuznets Curve.⁵ Moreover, following the Climate Change Act of 2008, the per capita CO₂ emissions in the UK have fallen dramatically in 2017 to levels below those of the 1860s (Hendry 2020).⁶ In a similar vein, Ahmad et al. (2017) focus on the existence of the EKC in Croatia using quarterly dataset spanning 1992Q1 to 2011Q1. Using the Autoregressive Distributed Lag (ARDL) and Vector Error Correction (VECM) models, they show the existence of an inverted U-shape relation between economic activity and carbon dioxide emissions in the long run. Their results also reveal a bidirectional Granger causality between CO₂ emissions and economic growth in the short run, and unidirectional Granger causality from growth to CO₂ emissions in the long run. Anastacio (2017) examine the validity of the EKC hypothesis for North America countries. Using a yearly dataset covering 1980 to 2008, the authors find a unidirectional Granger causality from energy consumption, electricity consumption and economic growth to carbon dioxide emissions in the long run. Apergis and Ozturk (2015) use a yearly dataset covering 1990 to 2011 to test the EKC hypothesis in 14 Asian countries. The authors empirical findings support the presence of the EKC hypothesis. Apergis (2016) uses data for 15 OECD countries for the period 1960 to 2013 and concludes that there is strong evidence in favor of an EKC for 12 countries out of 15. Using a sample of 120 economies over the period 2000–2009, Barra and Zotti (2018) demonstrate the existence of an inverted U-shaped relationship between income and CO₂ emissions. Their results also suggest that as population and industrial production grow, pressure on the environment will grow, calling for stricter environmental protection policies. Using a time-varying coefficient cointegration method, Mikayilov et al. (2018) investigate the EKC hypothesis on 12 Western European countries for the period 1861 to 2015. Their results reveal evidence in favor of relative decoupling in 8 out of the 12 countries. Using data on Gross State Product and CO₂ emissions, Churchill et al. (2019) examine the EKC hypothesis for a panel of 8 Australian states over the period 1990 to 2016. Their results provide support for the classic inverted U-shaped EKC hypothesis, with a peak reached in 2010. Bulut (2019) uses a cointegration test with a regime shift method on monthly data spanning the period 2000M1–2018M7

⁵ Sephton and Mann (2016) estimated turning points in 1966 and 1967 for CO₂ and SO₂, respectively. These dates are close to those reported by Fosten et al. (2012): 1954 for carbon dioxide and 1958–1959 for sulfur dioxide.

⁶ Hendry (2020) explains the CO₂ emissions in the UK over the period 1860–2017 in terms of coal and oil usage, capital stock and GDP. While his model entails an inverted U-shaped relationship between CO₂ emissions and GDP, the author claims that this relationship is likely to be an artefact of both being correlated with technology.

to study the impact of income on CO₂ emissions in the United States and concludes that there is strong evidence in favor of an inverted-U EKC pattern.

However, the EKC hypothesis has been subject to several criticisms, both theoretical and empirical. From a theoretical point of view, the main criticism of Arrow et al. (1995) is that the EKC hypothesis ignores the feedback from environmental damage to economic activities. But, if this damage is severe enough, ignoring this feedback may provide a biased and irrelevant picture as it is likely that the economic activity will be affected. Moreover, based on the Heckscher-Ohlin trade theory, Stern et al. (1996) argue that the EKC hypothesis, if it holds, may be a result of the effects of trade on the geographical distribution of polluting industries. In other words, part of the decline in environmental degradation levels in developed countries may reflect, on the one hand, their specialization in human capital and manufactured capital-intensive activities and, on the other hand, their increasingly strict environmental regulations. Thus, any apparent decrease in per capita pollution associated with an increase in per capita income along the Environmental Kuznets Curve would be exaggerated because the environmental regulation in developed countries might lead polluting industries to shift towards low and middle-income countries that are specialized in labor and natural resources (Lucas et al. 1992; Stern 2003). This reasoning implies that there is no standard and universal relationship between growth and pollution that is valid for all countries. Some empirical studies validate this theoretical hypothesis and conclude that there is a little evidence that countries follow a common inverted U-shaped pathway for environmental destruction as their income rises.⁷ For instance, Managi et al. (2009) use the instrumental variables technique and annual data for OECD and non-OECD countries covering the period 1973–2000 to assess the global impact of trade openness on the environment. Their results suggest that while trade is beneficial for the environment in OECD countries, it has adverse effects in non-OECD countries. In the same way, Tsurumi and Managi (2012) examine the effect of trade intensity on deforestation for a panel of 142 countries over the period 1990–2003. Their results show that higher trade openness reduces deforestation for OECD countries but not for non-OECD countries, and suggest that both environmental-regulation and capital-labor effects have a positive impact on deforestation in OECD countries but a negative impact in non-OECD countries. Stern and Common (2001) use a yearly dataset covering 1960 to 1990 to examine the validity of the EKC hypothesis for 74 countries. Their results suggest that the EKC hypothesis is an incomplete model. Coondoo and Dinda (2002) examine the validity of the EKC hypothesis by testing for Granger causality between income and carbon dioxide emissions in various countries and regions. Their results suggest that there is no strong evidence of an EKC type effect. Wang et al. (2011) focus on China over the period 1995–2007 and find an increasing relationship between economic growth and CO₂ emissions and that reducing CO₂ emissions may hamper China's economic growth. Kaika and Zervas (2013) argue that developed and developing countries are on different sides of the EKC, and that there is

⁷ According to Bhattacharyya (2019), the empirical results are highly sensitive to the econometric tools used and the datasets analyzed by researchers, reflecting the lack of robustness of the empirical results.

no reason to assume that developing countries will follow the path of the developed countries. Narayan and Narayan (2010) examine the EKC hypothesis for 43 developing countries based on the short and long run income elasticities. Their results show that CO₂ emissions have fallen over the long run in only 35 per cent of the sample. Moreover, the authors also examined the EKC hypothesis at regional level and found an income elasticity in the long run smaller than the short run (which implies that carbon dioxide emission has fallen with a rise in income) only for the Middle Eastern and South Asian panels. Similarly, Al-Mulali et al. (2016) use non-stationary panel data techniques to investigate the existence of the EKC hypothesis in seven selected regions. Their result does not provide support for the EKC hypothesis in all regions under study: the EKC hypothesis was only found in the regions where renewable energy has a significant correlation with pollution in both the short and the long runs. Using data from 73 countries over the period 1980–2014, Halkos and Bampatsou (2019) find that the most environmentally efficient countries are those that have signed the Kyoto Protocol. Moreover, their findings suggest that the environmental effect of economic growth is determined by economies' level of development and their geographical region.

Other empirical studies find particular pollution-economic relationship and some of which support the EKC theory only partially. Friedl and Getzner (2003) investigate the existence of the EKC in Austria over the period 1960–1999. Their results reveal an N-shaped EKC, which suggest that environmental deterioration will resume beyond a certain income level. Likewise, Webber and Allen (2010) find that there is no single universal relationship between pollution and income. Similarly, Baek (2015) focus on the Arctic countries and reports an inverted U-shaped relationship between income and CO₂ emissions in Norway, an N-shape pattern in Sweden, and a linear relationship in Finland and Denmark. More recently, Allard et al. (2018) evaluate the N-shaped EKC using data for 74 countries categorized into three income groups over the period 1994–2012. They find evidence supporting the N-shaped EKC for all low/middle-income and high-income countries, but heterogenous and inconclusive results for the upper/middle-income countries. Zanin and Marra (2012) use a yearly dataset covering 1960 to 2008 to examine the validity of the EKC for 9 countries. Their results suggest an inverted U-shaped EKC for France and Switzerland, N-shaped relationship for Austria, M-shaped relationship for Denmark, Γ -shaped curve for Finland and Canada, and an increasing relationship for Australia, Italy and Spain.

Given the ambiguity of the income-pollution relationship from the empirical EKC literature, the challenge for research now is to re-examine some of the issues discussed earlier in the EKC literature using new and rigorous econometric methods. This paper aims to examine the relationship between CO₂ emissions and economic growth in the United Kingdom using a long span of data (from 1751 to 2016). To the best of the author's knowledge, this study is the first to use the bivariate dynamic correlation (Croux et al. 2001) and the squared cross-wavelet coherency (Torrence and Webster 1999), to assess the strength of links between a measure of environmental degradation (CO₂ emissions) and a possible source of this degradation (economic growth) in the UK over a period of 265 years.

The remainder of this paper is as follows: Sect. 2 presents the empirical strategy and the data. Section 3 documents our results. Section 4 conclude.

2 Empirical strategy and data

Our empirical strategy consists of two complementary measures of comovement: the dynamic correlation (Croux et al. 2001), which is defined in the frequency domain, and the squared cross-wavelet coherency (Torrence and Webster 1999), which is defined in the time–frequency domain.

As spectral methods allow us to decompose the links between variables into long and short-run fluctuations, we use the dynamic correlation developed by Croux et al. (2001) to bring attention to some features of comovement between CO₂ emissions and real GDP per capita at different horizons. Indeed, Croux et al. (2001) proposes a measure of dynamic comovement between economic variables defined in the frequency domain and names it dynamic correlation. This measure, which is appropriate for co-stationary processes, measures the co-movement between time series at different frequencies and the extent to which the cyclical component of two series are synchronized within a given frequency. It is useful to investigate short and long-run dynamic properties of time series. It is defined by

$$\rho_{xy}(\lambda) = \frac{c_{xy}(\lambda)}{\sqrt{S_x(\lambda)S_y(\lambda)}}$$

with $\rho_{xy}(\lambda)$ the correlation coefficient between the real waves of frequency λ , x and y , two zero-mean real stochastic processes, $S_x(\lambda)$ and $S_y(\lambda)$ the spectral density functions of x and y respectively ($-\pi \leq \lambda < \pi$), and $c_{xy}(\lambda)$ the cospectrum that measures the correlation between components of the same frequency of the x and y processes.⁸ $\rho_{xy}(\lambda)$ is defined only for nonnegative frequencies, on the interval $[0, \pi)$, and vary between -1 and 1 .

However, the dynamic correlation proposed by Croux et al (2001) has two main limitations. First, it is defined in the frequency domain only and neglects the time domain. Moreover, it can not be used to gain confidence in causal relationships between the time series. For these reasons, we also use the bivariate cross-wavelet coherency measure as developed by Torrence and Webster (1999) to measure the magnitude of the local correlation between pollution and income in the time–frequency domain. This approach will allow us to accurately represent how the normalized covariance between pollution and real income per capita has evolved over time and on different frequencies, and therefore to identify the frequency and time intervals where the times-series move together significantly.⁹ Thus, contrary to standard

⁸ As in Croux et al (2001), we use a Bartlett window with lag window size 6 to smooth the periodograms. To check that the size of the spectral window does not affect the results, a large window of size 7 and a small window of size 5 were also used. Those results are available upon request.

⁹ Grinsted et al. (2004) provide a brief review and an application of wavelet coherency to geophysical time series, and the interested reader is referred to that paper.

econometric tools, the measure proposed by Torrence and Webster (1999) does not require decomposition of the initial sample into subsamples to confirm or disprove the change in the relationship between the variables under study¹⁰ and make it possible to capture possible non-linearities between the variables in the time–frequency domain.

To investigate the relationship between two time-series, x and y , across frequencies and over time, Torrence and Webster (1999) define the squared cross-wavelet coherency, $R^2(u, s)$, as the squared absolute value of the smoothed cross-wavelet power spectrum, normalized by the product of the smoothed individual wavelet power spectra of each time series. Formally, it is obtained as

$$R^2(u, s) = \frac{\left| S(s^{-1} W_{xy}(u, s)) \right|^2}{S(s^{-1} |W_x(u, s)|^2) S(s^{-1} |W_y(u, s)|^2)}, R^2(u, s) \in [0, 1]$$

where $R^2(u, s)$, the squared wavelet coherency, ranges between 0 and 1 and can be conceptualized as the local linear correlation coefficient between x and y , S is a smoothing operator,¹¹ u and s are the control parameters of the wavelet (u is a location parameter that determines the exact position of the wavelet, and s is a scale parameter that defines to what extent the wavelet is stretched or dilated), $W_{xy}(u, s)$ is the cross-wavelet transform of two time-series x and y .¹² $|W_x(u, s)|^2$ and $|W_y(u, s)|^2$ are the wavelet powers of x and y , respectively. The cross-wavelet power, $|W_{xy}(u, s)|$, represents the local covariance between x and y at each scale s : it reveals areas in the time–frequency space where the time-series show a high common power. As the theoretical distribution of $R^2(u, s)$ is unknown, we use Monte Carlo methods to test the statistical significance, following the approach of Torrence and Compo (1998) and Grinsted et al. (2004).

Our data are yearly times-series, running from 1751 to 2016 (265 years), of the UK real GDP per capita (UKGDP) and the UK carbon dioxide emissions as a percent of GDP (UKCO₂E). The real GDP per capita and population¹³ data were collected from the Bank of England (A Millennium of Macroeconomic Data, version 3.1).¹⁴ CO₂ emissions data prior to the year 1959 is sourced from the Carbon

¹⁰ Indeed, instead of decomposing the sample into several sub-samples, the variation of the normalized covariance over time and across frequencies makes it possible to date transitions accurately. Thus, the cross-wavelet coherency measure avoids the risk of information loss resulting from the decomposition of the sample, as well as the risk of having results that depend on the arbitrary choice of sub-samples.

¹¹ Smoothing is achieved by convolution in both time and scale. The time convolution is performed with a Gaussian window, while the scale convolution is done with a rectangular window. See Grinsted et al. (2004) for technical details.

¹² See Torrence and Compo (1998) for technical details about the cross-wavelet transform of two time-series x and y . In this research we use the Morlet wavelet, introduced by Goupillaud et al. (1984), and we set the central frequency of the wavelet equal to 6 to satisfy the admissibility condition (Farge 1992).

¹³ For population, we use the Broadberry et al. (2015) estimate for Great Britain.

¹⁴ See <https://www.bankofengland.co.uk/statistics/research-datasets>.

Dioxide Information Analysis Center,¹⁵ and data from 1959 is sourced from the Global Carbon Atlas.¹⁶ All data in metric tons of Carbon are converted to metric tons of CO₂ using a conversion factor of 3.664 (Clark 1982).

3 Empirical results

Figure 1 plots the relationship between the natural logarithm of UKGDP (x-axis) and the natural logarithm of UKCO₂E (y-axis) over the sample period. The resulting curve has two sides: it is at first increasing at an increasing rate (acceleration side), then decreasing at a decreasing rate (deceleration side), which supports the EKC hypothesis for the UK, i.e. the existence of an inverted U-shaped curve between per income CO₂ emissions and per capita income. In other words, the pressure on the environment grows up to a certain level as income goes up; after that, energy efficiency improves, i.e. economic activity starts to grow faster than the increase in CO₂ emissions, reflecting improved technology in energy use as well as a changing mix of fuels (Hendry 2020). However, a simple visual inspection reveals an asymmetry between the two sides of the EKC: while it accelerates along the upward-sloping phase, reflecting the fact that economic growth has led to a relatively large increase in pollution along this phase (i.e. deterioration of energy efficiency), it slows down smoothly throughout the downward-sloping side.

To explore the relationship in detail, we should look at the evolution of the dependence between UKGDP and UKCO₂E in time as well as frequency domain. More precisely, we use the dynamic correlation measure of Croux et al. (2001) and the cross-wavelet coherency measure of Torrence and Webster (1999) to study the dependence between economic growth and CO₂ emissions.

Figure 2a plots the dynamic decomposition of comovement, as measured by the dynamic correlation (Croux et al. 2001), between the first log-difference of UKGDP and UKCO₂E at different frequencies. As expected, the result suggests an asymmetry between the long-run and the short-run dynamics. It shows a negative comovement in the long run, i.e. at low frequencies (ranging between frequency 0 and frequency $\frac{2\pi}{3}$), and a positive comovement only in the short-run, i.e. at high frequency cycles (ranging between frequency $\frac{2\pi}{3}$ and frequency π), which is quite intuitive. In other words, in the short-run (i.e. at high frequency cycles), as the economy shifts towards development, the environment worsens (endogenous process). Then, in the long-run (i.e. at low frequency cycles), as the society become aware of the social cost of this negative externality, it introduces, through government regulations, changes in environmental standards and policies (exogenous process) and reinvests part of its income to improve the environment and restore the ecosystem (endogenous process). This first answer given by the dynamic correlation provide support for the environmental Kuznets curve in the UK, which correspond to the consensual view in the literature.

¹⁵ See <http://cdiac.ornl.gov/>.

¹⁶ See <https://doi.org/10.5194/essd-10-2141-2018>.

To clearly explore how the dependence between CO₂ emissions and real income per capita has evolved over time and on different frequencies, we adopt the bivariate cross-wavelet coherency measure of Torrence and Webster (1999). The estimated wavelet squared coherency, $R^2(u, s)$, and the phase difference, $\phi(u, s)$ ¹⁷, between the natural logarithm of UKGDP and the natural logarithm of UKCO₂E, from scale 1 (2–4 years) up to scale 5 (32–64 years), are displayed in Fig. 2b Time (from 1751 to 2016, i.e. 265 observations) appears on the x-axis, while scale, expressed in years, on the y-axis; the higher the scale, the lower the frequency.

The phase-difference (ϕ_{xy}), represented by arrows in Fig. 2, indicates whether the two time-series, x and y, move in-phase or out-of-phase and on the lead/lag relationship. The interpretation is summarized in the diagram of Fig. 3.

Arrows are rightward pointing when the two time-series under study are in-phase, i.e. $\phi_{xy} = 0$, and they are leftward pointing when the two time-series are out-of-phase, i.e. $\phi_{xy} = \pi$. Upward pointing arrows indicate that the first time-series (UKGDP) leads the second one (UKCO₂E) if they are in-phase, i.e. $\phi_{xy} \in \left(0, \frac{\pi}{2}\right)$, and that the second time series leads the first one if they are out-of-phase, i.e. $\phi_{xy} \in \left(\frac{\pi}{2}, \pi\right)$. Downward pointing arrows indicate that the second time series leads the first one if they are in-phase, i.e. $\phi_{xy} \in \left(-\frac{\pi}{2}, 0\right)$, and that the first one leads the second if they are out-of-phase, i.e. $\phi_{xy} \in \left(-\pi, -\frac{\pi}{2}\right)$.

Visual assessment of the plot representing the wavelet squared coherency allows detection of time and frequency varying dependencies between UKGDP and UKCO₂E, i.e. that the comovement between pollution and income per capita is not stable over time and across scales. The wavelet squared coherency shows that high coherencies occur at both high frequencies (short term) and low frequencies (long term). This result confirms the close link between UKGDP and UKCO₂E. Although high coherencies appear throughout the period studied over short cycles, reflecting a significant contagion effect between wealth creation and CO₂ emissions, we note that time–frequency areas with high coherency gradually shift towards longer cycles (i.e. low frequencies) till about the early twentieth century,¹⁸ oscillated violently till about the mid-20th following the great depression at the end of the First World War, the general strike and the Second World War, before returning towards shorter cycles from the mid-twentieth century onwards. In other words, in the short-run (i.e. at high frequency cycles), as the world economy shifts towards development, the environment worsens. Then, in the long-run (i.e. at low frequency cycles), as the society become aware of the social cost of this negative externality, it introduces, through government regulations, changes in environmental standards and policies and reinvests part of its

¹⁷ The phase difference can be derived from the cross-wavelet transform as follows $\phi(u, s) = \text{tang}^{-1}\left(\frac{\Im\{S(s^{-1}W_{xy}(u,s))\}}{\Re\{S(s^{-1}W_{xy}(u,s))\}}\right)$. It represents the relative phase between x(t) and y(t), where \Im and \Re are imaginary and real part operators, respectively

¹⁸ This high coherency at low frequencies reflects that the intensity of the interdependence between UKGDP and UKCO₂E is more persistent in the long term.

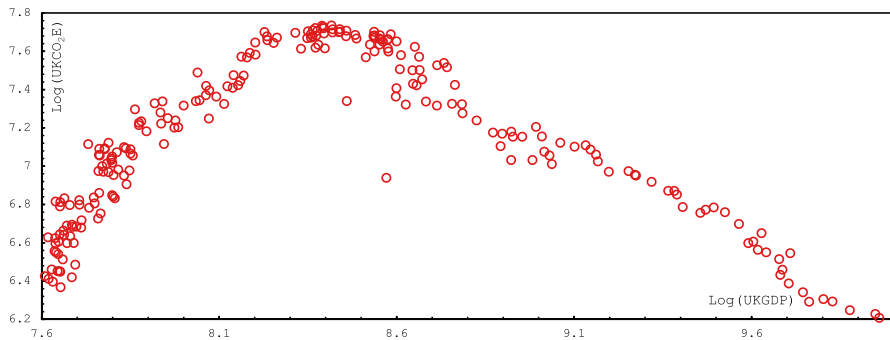


Fig. 1 Environmental Kuznets Curve in the UK

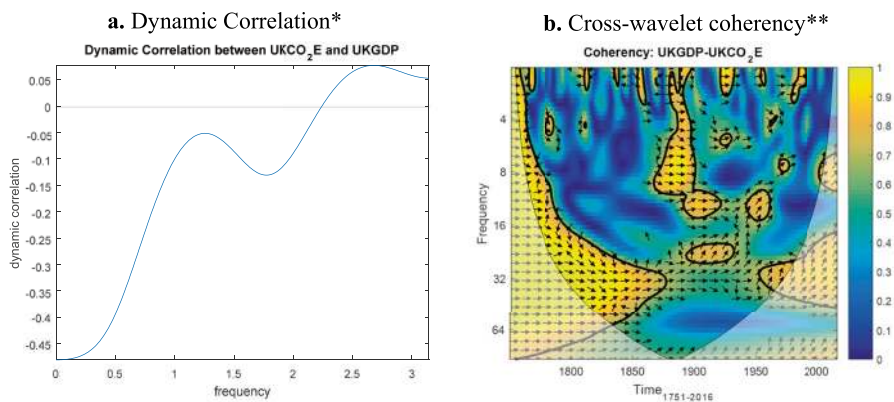


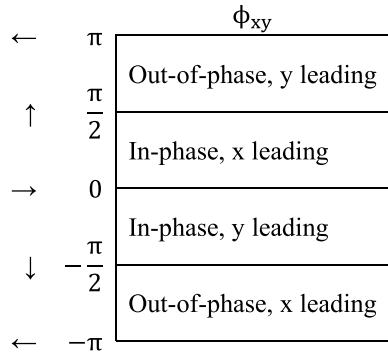
Fig. 2 Economic growth- CO_2 emissions nexus. * Since high frequencies correspond to short time periods, and vice versa, the dynamic correlation graphs are inverted: low frequencies (close to 0 on the x-axis) correspond to long-run persistent movements, while high frequencies (close to π on the x-axis) correspond to short-run fluctuations. ** The cone of influence where edge effects should be considered is shown as a lighter shade. The color scale represents the magnitude of R^2 . The thick black continuous line contours isolate areas where the wavelet squared coherency is statistically significant at the 5% level. Yellow time–frequency areas that appear inside the thick black lines are spaces where correlation between the two series considered is strong (R^2 close to 1). Areas with weak dependence are those containing the blue color. The darker the blue is, the less dependent the series are (R^2 close to 0)

income to improve the environment and restore the ecosystem. This result provides further evidence of the existence of an inverted U-shaped environmental Kuznets curve in the UK, with a turning point estimated around the mid-twentieth century. This estimated turning point, which is close to those reported by Fosten et al. (2012), Sephton and Mann (2016) and Hendry (2020), corresponds roughly with the introduction of the Smoke Abatement Act in 1926¹⁹ and the Clean Air Act in the UK in the summer of 1956²⁰ to combat the discharge of

¹⁹ The Smoke Abatement Act of 1926 amends and extends the Public Health Acts of 1875 and 1891.

²⁰ The Clean Air Act is the result of the Great London Smog of December 1952 which resulted in around 4000 extra premature deaths in the city. It was revised in 1968. Markandya et al. (2004) provides

Fig. 3 Interpretation of the wavelet phase-difference between x and y



grit into the atmosphere. This turning point also coincides with the decreasing use of coal and traditional biomass as sources of energy, the development of new and more efficient combustion technologies (e.g. the Carbon Capture and Storage technology), and the emergence and development of alternative energy sources (See Fig. 4 in the appendix).²¹ Indeed, the Industrial Revolution in the eighteenth and nineteenth centuries were based on the use of coal whose burning, for industrial and domestic purposes, has caused air pollution to often reach very high levels. Since the early 1960s, the country has shown a willingness to ensure the energy transition necessary for sustainable development: from the late 1950s to the early 1960s, the United Kingdom’s energy balance declined from about 90% coal to 75% due to the introduction of nuclear power²² and, later, the discovery and development of North Sea oil. Wavelet phase-differences reveal that the UKGDP and the UKCO₂E fluctuate synchronously in a clear in-phase relationship, i.e. significant local correlations are positive (rightward pointing arrows), and that the UKGDP leads the UKCO₂E most of the time (upward pointing arrows). This finding suggests that from the mid-twentieth century onwards, i.e. along the decreasing side of the Environmental Kuznets Curve, pollution mitigation was not attributed to slowdown in economic growth, but regulatory efforts to limit pollution in the UK as well as the country willingness to ensure the energy transition necessary for sustainable development. More recently, government policies during the COVID-19 medical shock, aiming at flattening the epidemiological curve, have deepened the economic recession and, consequently, significantly affected the global energy demand. Most countries imposed several

Footnote 20 (continued)

a review of key dates for antipollution relevant legislation in the UK, and the interested reader is referred to that paper.

²¹ Until the early 1900’s, traditional biomass was the source of nearly all of the world’s energy needs. From the mid-1900s onwards, coal, crude oil, and natural gas (i.e. fossil fuels) have been the major sources of energy. The share of the renewable energies has also increased since the late 1900’s.

²² The United Kingdom was pioneer on nuclear power generation by inaugurating the world’s first commercial nuclear power station in Cumbria in 1956 (Sephton and Mann 2016).

strict containment measures, including lockdowns, restrictions on travel, schools shutting down and the prohibition of large gatherings for an extended period. As a result, the global GDP is expected to shrink by 5.2 percent in 2020 (World Bank 2020). While “*the recession is a necessary public health measure*” (Baldwin and Weber di Mauro 2020), the recent “ecological pause” is an unavoidable mechanical consequence of the economic recession. Thus, the negative economic impact of the COVID-19 medical shock implies a positive environmental impact, which could therefore accelerate the downward phase of the EKC. By compiling government policies and activity data to assess the reduction in CO₂ emissions under forced containments, Le Quéré et al. (2020) find that daily global carbon dioxide emissions decreased by 17 percent by early April 2020 with respect to average levels in 2019, and expect that the impact on 2020 annual CO₂ emissions will be between -7% (high estimate) and -4% (low estimate).

4 Conclusion and policy implications

The Environmental Kuznets Curve hypothesis claims that environmental quality will worsen first as income increases and then improve as income increases over the long term. Using the dynamic correlation measure, developed by Croux et al. (2001), and the bivariate cross-wavelet coherency, developed by Torrence and Webster (1999), this paper contributes to the literature by bringing attention to some features of comovement between economic growth (real GDP per capita) and carbon dioxide (CO₂) emissions, that have been overlooked in previous studies. The results obtained are supportive of the existence of an inverted U-shaped Environmental Kuznets Curve in the UK, with a turning point estimated around the mid-twentieth century.

This turning point corresponds with regulatory efforts to limit pollution and the country willingness to ensure the energy transition necessary for sustainable development. Indeed, the introduction of the Clean Air Act in the summer of 1956 to limit the discharge of grit into the atmosphere, together with the transition of the UK’s energy balance, i.e. the reduction of the use of coal as the main energy source, are among the main forces that have driven the turning point in the relationship between income per capita and carbon dioxide emissions in UK.

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Appendix

See Fig. 4.

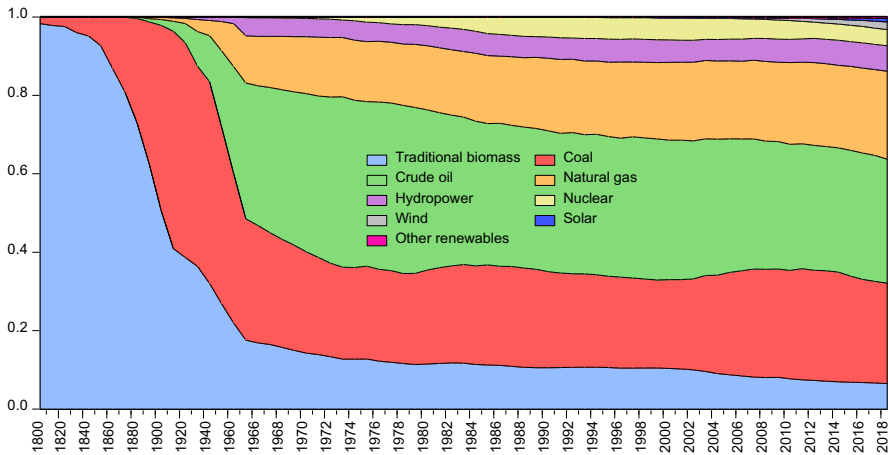


Fig. 4 Shares of global primary energy consumption by major sources (1800–2018). * Other renewables include renewable technologies other than solar, wind, hydropower and traditional biofuels. Sources: Smil (2017) for data prior to 1965 & BP Statistical Review (2019) for data from 1965 onwards

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