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**RESEARCH ARTICLE**

# Is the EKC Valid for Cement $CO_2$ in the G7? A Rolling Window Approach

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**Abstract**

*This study investigates the Environmental Kuznets Curve (EKC) hypothesis for cement-related $CO_2$ emissions in the G7 economies over the period 1960–2023. Cement production is among the most carbon-intensive industrial activities, making its environmental impact especially relevant for advanced economies committed to decarbonization. Methodologically, the analysis integrates the full-sample bootstrap panel causality test with a rolling-window bootstrap framework, allowing for both static and time-varying causal inference. The full-sample results suggest broad causality from growth to emissions, with the exception of Canada and the United States. However, the rolling-window estimations uncover hidden causality across all G7 members, which emerges episodically and clusters around economic downturns, energy crises, and regulatory transitions. These findings indicate that the growth–emissions nexus is highly conditional and state-dependent, underscoring the importance of dynamic econometric approaches. Policy recommendations emphasize the adoption of cleaner production technologies, integration of climate objectives into national strategies, and stronger international cooperation to ensure sustainable growth.*

**Keywords:** Environmental kuznets curve (EKC); cement carbon dioxide emissions; G7 economies; bootstrap panel causality; sustainable growth
**Jel Codes:** C23, Q53, Q56

## *G7 Ülkelerinde Çimento Kaynaklı $CO_2$ İçin Çevresel Kuznets Eğrisi Geçerli mi? Kayan Pencere Yaklaşımı*

***Özet***

*Bu çalışma, 1960–2023 dönemi için G7 ekonomilerinde çimento üretimi kaynaklı $CO_2$ emisyonları açısından Çevresel Kuznets Eğrisi (EKC) hipotezini incelemektedir. Çimento üretimi, en yüksek karbon yoğunluğuna sahip sanayi faaliyetlerinden biri olduğundan, bu sektörün çevresel etkileri özellikle karbonsuzlaşma hedefi güden gelişmiş ekonomiler açısından büyük önem taşımaktadır.Yöntem olarak analiz, tam örneklem bootstrap panel nedensellik testi ile kayan pencere (rolling-window) bootstrap yaklaşımını birleştirerek hem durağan hem de zamana bağlı nedensellik ilişkilerini incelemektedir. Tam örneklem sonuçları, Kanada ve Amerika Birleşik Devletleri dışında genel olarak ekonomik büyümeden emisyonlara doğru bir nedensellik olduğunu göstermektedir. Buna karşın, rolling-window tahminleri tüm G7 ülkelerinde gizli nedensellik ilişkilerinin dönemsel olarak ortaya çıktığını ve bunların genellikle ekonomik durgunluklar, enerji krizleri ve düzenleyici geçiş dönemlerinde yoğunlaştığını ortaya koymaktadır. Bu bulgular, büyüme–emisyon ilişkisinin koşullara bağlı ve duruma göre değişen (state-dependent) bir yapıda olduğunu göstermekte; dolayısıyla dinamik ekonometrik yaklaşımların önemini vurgulamaktadır. Politika önerileri, daha temiz üretim teknolojilerinin benimsenmesi, iklim hedeflerinin ulusal stratejilere entegre edilmesi ve sürdürülebilir büyümenin sağlanması için uluslararası iş birliğinin güçlendirilmesi yönündedir.*

**Anahtar kelimeler:** Çevresel kuznets eğrisi (EKC); çimento karbondioksit emisyonları; G7 ekonomileri; bootstrap panel nedensellik; sürdürülebilir büyüme
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## 1. INTRODUCTION

Cement production is widely acknowledged as one of the most carbon-intensive industrial activities. It relies heavily on raw materials and fuels—ranging from petroleum coke, coal, natural gas, and fuel oil to biomass and even certain waste streams—alongside substantial inputs of electricity, heat, and water (Valderrama et al., 2012; Galvez-Martos and Schoenberger, 2014). A central stage in the process is the calcination of limestone ($CaCO_3$), during which the conversion to lime (CaO) releases significant amounts of carbon dioxide ($CO_2$). This release is further magnified by the combustion of fossil fuels required to reach kiln temperatures exceeding 1,400 °C, making the industry both energy-intensive and emission-heavy (Gibbs et al., 1997). Beyond occasional wastewater, solid waste, and noise, the primary environmental burden stems from energy use and atmospheric emissions (Schorcht et al., 2013; Georgiopoulou and Lyberatos, 2018).

Cement plants emit a broad spectrum of pollutants including sulfur oxides (SOx), nitrogen oxides (NOx), carbon monoxide (CO), carbon dioxide ($CO_2$), and fine particulate matter (PM2.5). On average, the production of 1 kg of cement generates roughly 0.8 kg of $CO_2$. In China alone, cement activities are responsible for nearly 5% of total global $CO_2$ discharges (Lei et al., 2011; Chen et al., 2015; Xi et al., 2016). As noted by Habert (2013), the sector's contribution to $CO_2$ is more critical than that of most other energy-intensive industries. Among non-metallic mineral processes, cement is the most energy demanding, with the European Cement Association reporting that 1 ton of output requires between 60 and 130 kg of fuel oil (depending on process and product type) and approximately 105 kWh of electricity (Lei et al., 2011; Chen et al., 2015; Xi et al., 2016).

Globally, cement production is estimated to account for 5–7% of anthropogenic $CO_2$ emissions and nearly 3% of total greenhouse gas (GHG) releases (Galvez-Martos and Schoenberger, 2014) while consuming about 12–15% of industrial energy (Aranda-Usón et al., 2012). Producing 1 ton of cement typically consumes 4.7 million BTUs—comparable to burning 181 kg of coal—and releases nearly 1 ton of $CO_2$ (Gibbs et al., 1997). These figures explain why the sector has become central in debates on climate change mitigation.

In addition to global climate effects, local environmental and health risks are significant. Workers and nearby residents are exposed to dust and hazardous compounds released during production, including polychlorinated biphenyls (PCBs), dibenzofurans (PCDD/Fs), dioxins, NOx, SOx, CO, $CO_2$, hydrogen chloride, chlorine, and ammonia (Chinyama, 2011; Mosca et al., 2014; Leone et al., 2016; Zou et al., 2018; Raffetti et al., 2019). Heavy metals also play a role: studies in Germany found cement plants to be a notable source of thallium (Brockhaus et al., 1981; Dolgner et al., 1983). Furthermore, both production and transport phases release particulate matter and gases that add to environmental burdens.

Emission-reduction strategies in the cement sector generally focus on reducing the clinker ratio, introducing waste-derived fuels, and upgrading technologies (Hasanbeigi et al., 2012; Stafford et al., 2016). A widely adopted option is co-processing, or the use of alternative fuels and raw materials (AFR). These include refuse-derived fuel (RDF), waste oils, used tires, plastics, sewage sludge, solvents, and various agricultural residues (Lamas et al., 2013). RDF, derived from municipal solid waste, is attractive because of its high calorific value and relatively low nitrogen and sulfur content (Hasanbeigi et al., 2012; Rahman et al., 2015). Waste oils are also used due to their high energy density (33–41 MJ/kg), though they typically contain more heavy metals and halogens than crude-based fuels (Rahman et al., 2015). Dried sewage sludge serves both as a raw material and a fuel, reducing waste volumes and contributing to resource efficiency. However, sludge drying is energy-intensive, and its net environmental effect depends on the specific technology employed (Jungbluth et al., 2007; Valderrama et al., 2013; Haque et al., 2015).

The primary aim of this study is to examine whether the Environmental Kuznets Curve (EKC) hypothesis holds for $CO_2$ emissions from cement production in the G7 economies. While the EKC has been extensively tested for aggregate emissions, its sector-specific validity, particularly in highly carbon-intensive industries such as cement, remains underexplored. By employing a rolling window approach, this paper seeks to capture the dynamic and time-varying relationship between economic growth and cement-related $CO_2$ (CCO2) emissions, accounting for potential structural breaks and policy shifts. Through this analysis, the study provides empirical insights into whether economic growth in advanced economies leads to eventual decoupling from cement-related emissions, or whether the growth–emissions nexus persists across different periods.

To guide the reader, the next section reviews prior studies on how cement production relates to environmental pollution and public health. The paper then turns to the data and methodology, before presenting the empirical results. These are followed by a discussion of the findings, and the study closes with a summary of the main conclusions.

## 2. THE LITERATURE ON CEMENT PRODUCTION, ENVIRONMENTAL POLLUTION, AND HEALTH

The EKC has been widely used to analyze the relationship between economic growth and environmental quality. First introduced by Kuznets (1955), the hypothesis suggests that environmental degradation initially rises with income but eventually declines, creating an inverted U-shaped trajectory. This pattern is often explained as a byproduct of industrialization and later deindustrialization, as well as the relocation of polluting activities from advanced to developing economies (Fæhn and Bruvoll, 2009; Cherniwchan, 2012). Early empirical contributions—such as Grossman and Krueger (1991), Shafik and Bandyopadhyay (1992), Selden and Song (1994), Cole et al. (1997), and Stern et al. (1996)—largely confirmed the inverted U-shaped EKC for different pollutants, reinforcing the view that environmental pressures follow a nonlinear path as economies develop.

Building on these macro-level insights, scholars increasingly turned to sectoral case studies. The cement industry has been a particular focus because of its high energy intensity and disproportionate share of global emissions. Research has consistently documented the sector's significant environmental footprint across both developed and developing economies: Hanle et al. (2004) for the United States (US), Mandal and Madheswaran (2010) for India, Hasanbeigi et al. (2010), Xu et al. (2014), and Lin and Zhang (2016) for China, and Dirik et al. (2019) for Türkiye. Bildirici (2019) further identified unidirectional causality from cement production to environmental pollution in China and the US, while studies such as Wang et al. (2013) and Ali et al. (2015) examined GHG dynamics and the interplay between local pollutants and climate impacts.

Beyond $CO_2$, researchers have investigated particulate matter (PM2.5) as a critical health risk. Donkelaar et al. (2010) and He et al. (2016) highlighted China's severe PM2.5 concentrations, while Keene and Deller (2015) and Hao and Liu (2016) confirmed inverted U-shaped EKC relationships for PM2.5 in the US and China, respectively. Parallel medical and epidemiological studies connect cement sector emissions to severe health consequences. Occupational studies such as McDowall (1984), Amandus (1986), and Jakobsson et al. (1990) emphasized risks for workers, while Mehraj et al. (2013) and Meo et al. (2013) showed that cement dust impairs lung function. Other works linked cement emissions to cardiovascular and respiratory diseases (Bertoldi et al., 2012) and even cancer risks (Magnani et al., 2001; Amendola et al., 2003; Musti et al., 2009). Studies across Europe and Asia also found elevated risks of colon, lung, laryngeal, and stomach cancers, as well as pediatric bone tumors, among populations exposed to cement pollution (Maier et al., 1992, 1999; Jakobsson et al., 1993; Magnani and Leporati, 1998; Koh et al., 2011; Lopez-Cima et al., 2013; Eom et al., 2017; Garcia-Perez et al., 2017). Mortality studies further underscore these findings, linking cement exposure to higher rates of leukemia, cardiovascular deaths, and cerebrovascular conditions (Knox and Gilman,

1997; Legator et al., 1998; Smailyte et al., 2004; Peters et al., 2009; Aydin et al., 2010; Giordano et al., 2012). Collectively, these studies confirm that the cement sector is not only a major driver of global emissions but also a serious threat to human health.

Within this broader context, numerous studies have tested the EKC specifically for $CO_2$ emissions in G7 countries, producing mixed evidence. For Canada, results range from an N-shaped relationship (Day and Grafton, 2003) to monotonically increasing trends (Lantz and Feng, 2006) and even no EKC at all (He and Richard, 2010; Lipford and Yandle, 2010). For the US, Aldy (2005) reported an inverted U-shaped EKC, whereas Dogan and Turkekul (2016) identified a U-shape, and Lipford and Yandle (2010) found no EKC. France has shown more consistent support for the EKC, with inverted U-shaped curves confirmed by Ang (2007) and Iwata et al. (2010), though Lipford and Yandle (2010) suggested an N-shape. For Japan, evidence spans inverted U-shaped relationships (Yaguchi et al., 2007; Onafowora and Owoye, 2014) to no EKC (Lipford and Yandle, 2010; Hossain, 2012). Long-run studies for the United Kingdom (UK) revealed both N-shaped (Fosten et al., 2012) and inverted U-shaped (Sephton and Mann, 2016) results, alongside mixed findings from Lipford and Yandle (2010). Italy and Germany remain less studied, though Lipford and Yandle (2010) suggested N-shaped trajectories.

Contrary to the notion of a universal inverted U-shaped trajectory, post-2020 evidence increasingly suggests that growth-driven emissions dynamics in advanced economies are nonlinear, heterogeneous, and time-varying, with limited support for a stable turning point. For instance, Yilanci and Pata (2022) show that economic growth continues to exert a positive influence on $CO_2$ emissions in most G7 countries, providing little evidence that higher income levels alone lead to sustained emission reductions. Similarly, Liu et al. (2022) report that the decoupling of growth from emissions remains incomplete, indicating that structural and income effects have not been sufficient to reverse long-run emission trends. Khalfaoui et al. (2023) document that the growth–emissions nexus in G7 countries varies considerably across time, with periods of economic expansion often coinciding with rising emissions, and only sporadic episodes of weakening or reversal. These findings imply that any observed EKC behavior is episodic rather than persistent. Complementing this view, Jebabli et al. (2023) demonstrate that the interaction between economic growth and $CO_2$ emissions is asymmetric and regime-dependent, with emissions remaining closely tied to growth even at higher income levels in several G7 economies. This challenges the assumption that advanced economies naturally transition toward cleaner growth paths as income rises. Evidence from Jia et al. (2023) further highlights the absence of a uniform EKC pattern. Their results indicate that in major G7 economies such as the US, the UK, and Canada, economic growth continues to drive $CO_2$ emissions, while feedback effects dominate in others, underscoring strong cross-country heterogeneity. Likewise, Xu et al. (2023) find that although technological progress and innovation can mitigate emissions growth, economic expansion remains a significant contributor to $CO_2$ emissions, suggesting that EKC turning points are conditional rather than automatic. The most recent studies continue to question the robustness of the EKC framework. Dritsaki and Dritsaki (2024) report persistent bidirectional linkages between growth and emissions, while Zhang et al. (2024) and Özmerdivanlı and Sönmez (2025) show that emission reductions at higher income levels are neither systematic nor durable across G7 countries. Similarly, Azimi and Rahman (2024) reveal that periods of apparent decoupling are frequently followed by renewed growth-driven emission increases. Overall, this growing body of evidence suggests that EKC dynamics in G7 economies are state-dependent and policy-contingent, rather than an inherent outcome of economic development.

Taken together, the literature points to two important insights. First, cement production is a uniquely carbon-intensive and health-damaging industry, making it a critical sector for environmental policy and EKC testing. Second, the empirical evidence on EKC dynamics for $CO_2$ emissions in the G7 is highly inconsistent, with results sensitive to model choice, time span, and country context. This

suggests that static models may be inadequate to capture the true dynamics of the growth–emissions relationship.

Despite the large body of work on environmental impacts of cement production and on the EKC for aggregate $CO_2$ emissions, a clear gap remains. To the best of our knowledge, there is no study that has directly examined the EKC hypothesis for $CO_2$ emissions from cement production itself. Existing research tends to focus either on overall national emissions or on the health and pollution effects of cement activities, but not on testing the growth–emissions dynamics of this specific sector using econometric methods.

To address this shortcoming, the present study explores whether the EKC framework is valid for CCO2 emissions in the G7 economies. By applying a rolling window approach together with the bootstrap panel causality test, the analysis captures both long-term patterns and short-term variations, offering more robust insights into the time-varying relationship between economic growth and cement-based emissions. In doing so, the paper contributes to a sector-specific understanding of the EKC in advanced economies, where cement remains a critical driver of industrial emissions.

## 3. DATA AND METHODOLOGY

### 3.1 Data

This study examines the validity of the EKC framework for CCO2 emissions in the G7 economies—Canada, France, Germany, Italy, Japan, the UK, and the US—covering the period 1960–2023. Annual data on gross domestic product (GDP) are sourced from the World Bank's World Development Indicators, while CCO2 emissions are drawn from the Global Carbon Atlas. Descriptive statistics for the variables are reported in Table 1 while the time paths of both variables are depicted in Figure 1.

**Table 1.** Descriptive Statistics for the G7 Economies

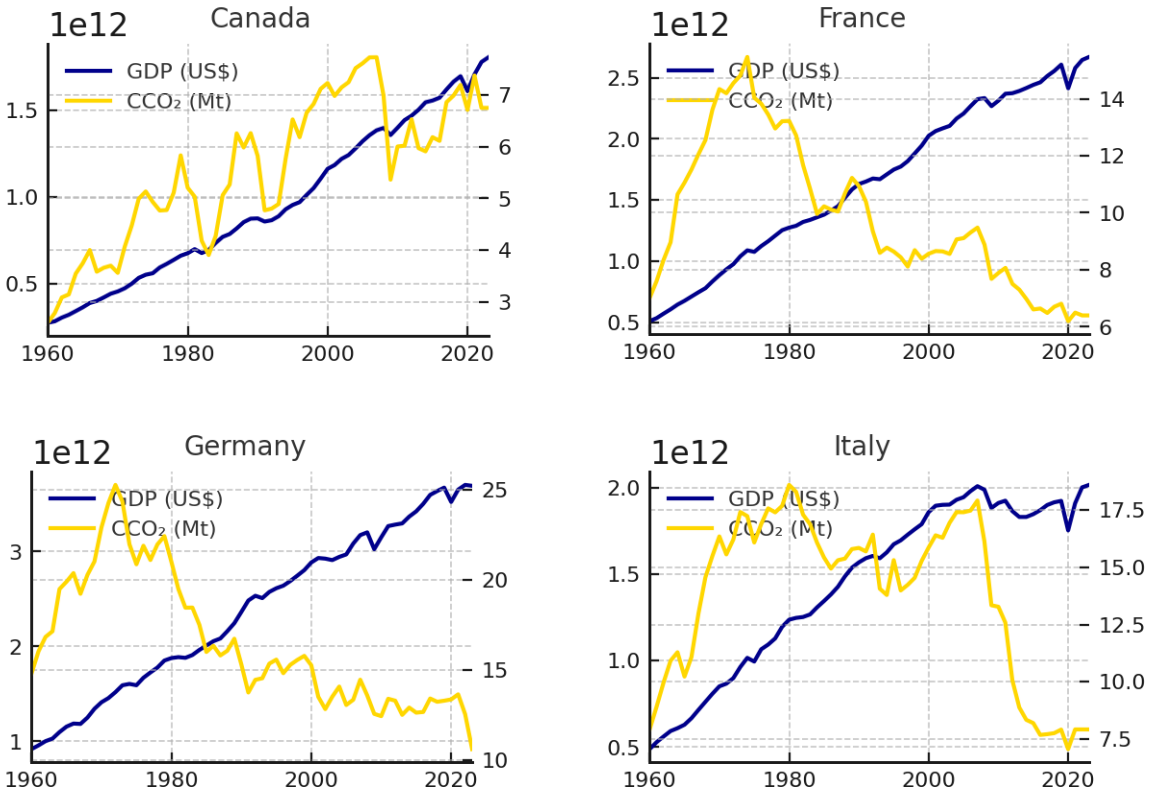
| **CCO2 (Mt)** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Country** | Mean | Median | Max. | Min. | Std. | Skewness | Kurtosis |
| **Canada** | 5.551 | 5.823 | 7.731 | 2.595 | 1.378 | -0.303 | 2.066 |
| **France** | 9.836 | 9.108 | 15.466 | 6.197 | 2.541 | 0.508 | 2.191 |
| **Germany** | 16.466 | 15.545 | 25.245 | 10.604 | 3.599 | 0.717 | 2.430 |
| **Italy** | 13.801 | 15.307 | 18.597 | 7.059 | 3.529 | -0.652 | 1.987 |
| **Japan** | 31.051 | 31.991 | 46.044 | 11.139 | 8.717 | -0.320 | 2.407 |
| **UK** | 6.435 | 6.435 | 9.884 | 3.616 | 1.628 | -0.087 | 2.084 |
| **US** | 36.243 | 35.616 | 46.851 | 28.441 | 4.583 | 0.432 | 2.465 |

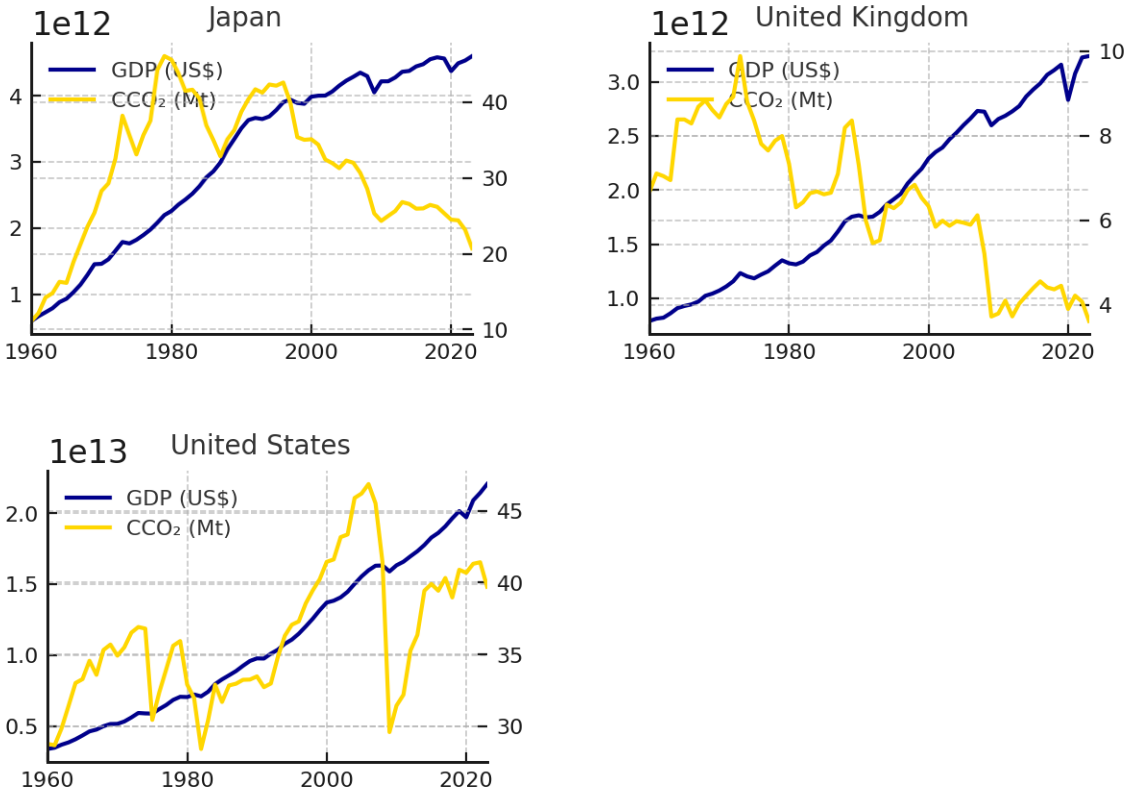
| ***GDP* (2015, US$)** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Country** | Mean | Median | Max. | Min. | Std. | Skewness | Kurtosis |
| **Canada** | 961,973.89 | 876,935.24 | 1,805,692.18 | 276,385.63 | 452,516.18 | 0.226 | 1.804 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **France** | 1,646,883.44 | 1,660,574.80 | 2,671,234.71 | 508,897.75 | 656,476.73 | -0.103 | 1.745 |
| **Germany** | 2,377,378.72 | 2,496,337.31 | 3,702,231.00 | 917,491.58 | 853,364.48 | -0.078 | 1.748 |
| **Italy** | 1,441,887.69 | 1,590,780.78 | 2,014,392.57 | 488,503.13 | 481,255.16 | -0.544 | 1.908 |
| **Japan** | 3,064,064.79 | 3,641,113.56 | 4,601,203.39 | 595,545.66 | 1,302,838.17 | -0.488 | 1.772 |
| **UK** | 1,906,290.60 | 1,761,353.96 | 3,236,345.54 | 793,127.69 | 766,438.43 | 0.212 | 1.651 |
| **US** | 11,127,177.77 | 9,952,094.39 | 22,062,578.28 | 3,406,320.76 | 5,506,714.52 | 0.327 | 1.814 |

As given in Table 1, GDP levels vary substantially across countries, reflecting differences in economic size, while cement-related emissions display notable cross-country heterogeneity and temporal variation. In several countries, emissions exhibit relatively high dispersion, indicating pronounced structural change in cement activity over the sample period.

**Figure 1.** Time Paths of GDP and CCO2 Emissions in the G7






The time-series patterns for the G7 economies reveal a clear divergence between the trajectories of growth and CCO2 emissions over the 1960–2023 period. GDP in all seven countries displays a strong and nearly uninterrupted upward trend, reflecting sustained economic expansion and rising national incomes. In contrast, CCO2 emissions follow a more complex, nonlinear path.

For most countries—particularly Germany, France, Italy, and the UK—CCO2 emissions rose until the late 1970s or early 1980s, after which they either plateaued or declined, even as GDP continued to grow. This decoupling suggests that structural shifts, such as reduced reliance on cement-intensive industries, adoption of cleaner technologies, and environmental regulation, played a role in lowering the emissions intensity of production. Japan exhibits a prolonged rise in emissions through the 1990s, followed by a gradual decline, aligning with its rapid post-war industrialization and subsequent technological maturity. In Canada and the US, emissions fluctuate but remain relatively stable over the long run, indicating slower or weaker decoupling compared to European peers.

Overall, the evidence is consistent with the EKC framework: emissions tend to increase during early phases of industrialization but stabilize or decline once economies reach higher income levels and implement environmental policies. Nevertheless, the degree and timing of this turning point vary substantially across countries, underscoring the importance of national context in shaping growth–emissions dynamics.

Such visual contrasts highlight the limits of static estimations and reinforce the necessity of a dynamic framework. By applying the bootstrap rolling-window causality test, it becomes possible to detect not only whether the EKC holds in the cement sector, but also when the relationship tightens, weakens, or reverses. This time-varying perspective allows us to identify episodes where GDP growth amplifies emissions, where it becomes neutral, and where it potentially contributes to mitigation—insights that a full-sample analysis alone would obscure.

### 3.2. Methodology

To investigate the causal relationship between CCO2 emissions and economic growth, this study applies the bootstrap panel causality framework proposed by Kónya (2006). This approach provides several methodological strengths. First, it bypasses the need for preliminary unit root or cointegration testing, which is particularly useful when the dataset may contain non-stationary variables. Second, it generates country-specific bootstrap critical values, enabling inferences that are tailored to each country rather than relying on pooled results. Third, the method explicitly accounts for cross-sectional dependence and heterogeneous slope coefficients, both of which are common features of panel data covering advanced economies such as the G7.

The basic econometric specification can be expressed as:

$$lnCCO2_{it} = \alpha + \beta lngrowth_{it} + \varepsilon_{it} \quad (1)$$

Here, $CCO2_{it}$ denotes cement-related emissions (measured in $MtCO_2$), and $growth_{it}$ represents GDP in constant 2015 US dollars. The subscript *i* indexes countries ($i = 1, \dots, N$), while *t* denotes time ($t = 1, \dots, T$). The error term is given by $\varepsilon_{it}$. To improve consistency and address possible heteroscedasticity, all variables are expressed in natural logarithms.

In this study, the EKC hypothesis is not examined through a conventional quadratic income specification (i.e., GDP and $GDP^2$), but is instead operationalised within a dynamic causality framework. The EKC is interpreted as a time-varying relationship between economic growth and CCO2 emissions, where the sign, magnitude, and persistence of the estimated growth–emissions coefficients reflect different phases of the EKC. Specifically, sustained positive causal effects of GDP on $CCO_2$ are interpreted as the rising segment of the EKC, weakening or vanishing effects as proximity to a turning point, and negative effects as evidence consistent with the declining segment. This approach allows the EKC hypothesis to be evaluated dynamically, without imposing a priori functional form restrictions.

Prior to applying the bootstrap procedure, it is essential to examine whether cross-sectional dependence is present, as ignoring it can bias the results. For panels where the time dimension ($T$) is relatively large compared to the number of cross-sections ($N$), the LM test of Breusch and Pagan (1980) is commonly used. The statistic is calculated as:

$$LM = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} T_{ij} \rho_{ij}^2 \sim X^2_{N(N-1)/2} \quad (2)$$

When both $T$ and $N$ are large, the Pesaran (2004) $CD_{LM}$ test is more appropriate, expressed as:

$$\mathrm{CD_{LM}} = \left(\frac{1}{N(N-1)}\right)^{\frac{1}{2}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N-1} \left(T\rho_{ij}^2 - 1\right) \sim N(0,1) \quad (3)$$

In cases where $T$ is small and $N$ is large, the CD test from Pesaran (2004) offers a more robust alternative:

$$CD = \sqrt{\left(\frac{2T}{N(N-1)}\right)} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} (\rho_{ij} - 1) \sim N(0,1) \tag{4}$$

If dimension distortions are suspected in the CD test, the Pesaran et al. (2008) adjusted LM ($LM_{adj}$) test is recommended:

$$LM_{adj} = \sqrt{\left(\frac{2}{N(N-1)}\right)} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \left[\rho_{ij}^2 \left(\frac{(T-k)\rho_{ij}^2 - \mu_{Tij}}{\upsilon_{Tij}}\right)\right] \sim N(0,1) \tag{5}$$

Here, $k$ is the number of regressors, while $\mu_{Tij}$ and $\upsilon_{Tij}$ are the mean and variance of $(T-k)\rho_{ij}^2$, respectively (Pesaran et al., 2008).

To determine whether the slope coefficients across panel units are homogeneous, the delta test by Pesaran and Yamagata (2008)—based on Swamy's (1970) framework—is employed. The test statistics are defined as:

$$\mathcal{S} = \sum_{i=1}^{N} (\beta_i - \beta_{WFE}) \frac{'X_i' M_T X_i}{\sigma_i^2} (\beta_i - \beta_{WFE}) \tag{6}$$

$$\Delta = \sqrt{N}\left(\frac{N^{-1}\mathcal{S} - k}{\sqrt{2k}}\right) \tag{7}$$

$$\Delta_{adj} = \sqrt{N}\left(\frac{N^{-1}\mathcal{S} - E(z_{iT})}{\sqrt{Var(z_{iT})}}\right) \tag{8}$$

If cross-sectional dependence and slope heterogeneity are confirmed, the bootstrap panel causality framework proposed by Kónya (2006) is used. This test is built upon the SUR (Seemingly Unrelated Regressions) methodology of Zellner (1962), which exploits contemporaneous correlations across individual equations for efficiency. Wald tests are then applied to assess the statistical significance of coefficients using unit-specific bootstrap critical values.

The general SUR-based panel regression for this study is specified as:

$$lnCCO2_{1,t} = \alpha_{1,1} + \sum_{l=1}^{lnCCO2_1} \beta_{1,1,l} lnCCO2_{1,t-1} + \sum_{l=1}^{lngrowth_1} \gamma_{1,1,l} lngrowth_{1,t-1} + \varepsilon_{1,1,t} \tag{9}$$

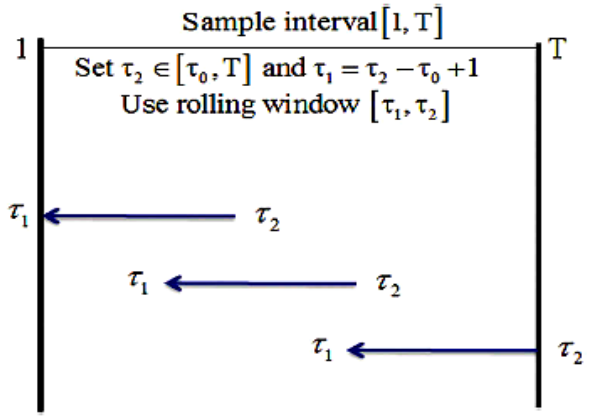
…

$$lnCCO2_{N,t} = \alpha_{1,N} + \sum_{l=1}^{lnCCO2_1} \beta_{1,N,l} lnCCO2_{N,t-1} + \sum_{l=1}^{lngrowth_1} \gamma_{1,N,l} lngrowth_{N,t-1} + \varepsilon_{1,N,t}$$

Optimal lag length $l$ is chosen based on the Akaike Information Criterion (AIC). The null hypothesis that *growth* Granger-causes *CCO2* is tested by examining whether γ coefficients are jointly significant.

Recognizing that causal relationships may not be stable over time, this study supplements the full-sample analysis with rolling-window bootstrap panel causality tests. This allows detection of time-varying causality patterns as suggested by Foon (2008) and Yilanci and Ozgur (2019). The rolling-window methodology re-estimates the model for each subperiod $t = \tau - 1 + l, \tau - 1, \tau = l, l + 1, ..., T$, where $l$ is the window size (see Figure 2).

**Figure 2:** Illustration of the Rolling Window Procedure




**Source:** Arora and Shi (2016).

To mitigate small sample bias, bootstrap resampling techniques are employed to generate appropriate p-values and critical values. The number of sub-windows is calculated following the suggestion by Brooks and Hinich (1998) and as formalized by Caspi (2017):

$$ss = \left[T\left(0.01 + \frac{1.8}{\sqrt{T}}\right)\right] \quad (10)$$

This methodology enables dynamic exploration of causal effects, capturing both stable and episodic connections between *growth* and *CCO2* across countries and over time.

## 4. EMPIRICAL FINDINGS

Preliminary diagnostics indicate that the panel data exhibit both cross-sectional dependence and heterogeneity in slope parameters across countries. These findings support the use of the bootstrap panel causality approach, which is specifically designed to handle such features. Using the entire sample, the method evaluates the causal direction running from growth to CCO2 at the individual country level. The results of this exercise are presented in detail in Table 2**.**

**Table 2:** Diagnostic Results for Cross-Sectional Dependence and Slope Heterogeneity

| | Direction of Causality (*growth* → *CCO2*) | | | | | |
|---|---|---|---|---|---|---|
| Tests | LM | $CD_{LM}$ | CD | $LM_{adj}$ | Δ | $\Delta_{adj}$ |
| | 489.591* | 72.305* | 21.387* | 156.800* | 48.571* | 49.732* |

**Note**: *, indicates 1% significance level.

The causality analysis between growth and CCO2 emissions in the G7 indicates statistically significant evidence that growth Granger-causes CCO2 over the full sample period. This result implies a direct causal influence of growth on CCO2 in France, Germany, Italy, Japan, and the UK, as identified through the bootstrap panel causality framework. The corresponding results are presented in Table 3.

**Table 3:** Bootstrap Panel Causality Test Results

| Countries | Wald Statistics | Bootstrap Probability Value | Critical Values | | |
|---|---|---|---|---|---|
| | | | %1 | %5 | %10 |
| $H_0$: *growth* ↛ *CCO2* | | | | | |
| Canada | 7.925 | 0.999 | 36.853 | 31.013 | 28.457 |
| France | 40.473 | 0.000* | 17.221 | 15.067 | 14.021 |
| Germany | 22.734 | 0.000* | 17.578 | 16.075 | 15.169 |
| Italy | 15.252 | 0.000* | 4.603 | 3.598 | 3.099 |
| Japan | 19.770 | 0.000* | 3.252 | 2.261 | 1.835 |
| UK | 24.307 | 0.007* | 23.561 | 20.764 | 19.371 |
| US | 3.731 | 0.992 | 16.665 | 13.921 | 12.562 |

**Note:** *, indicates 1% significance level. Critical values are obtained with 10000 bootstrap cycles.

Beyond stationarity and cointegration properties, shifts in economic structure, technological progress, and institutional change can reshape or even eliminate causal linkages between variables. Yilanci and Ozgur (2019) highlight that such transformations may cause causality to evolve over time. To capture this temporal variation, a rolling-window analysis was applied to subsamples constructed according to Equation (10). A 15-year window was employed, with the optimal lag length in each case determined by the AIC.

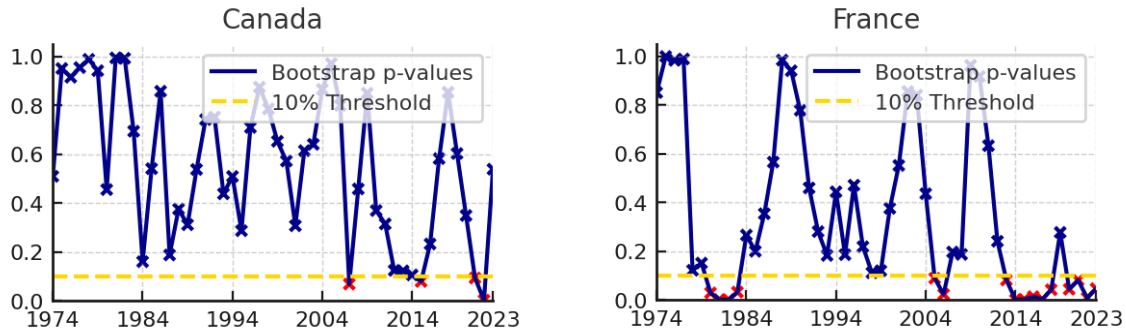
Figure 3 presents the rolling-window bootstrap p-values for the causality running from growth to CCO2, together with the 10% critical threshold. These time-varying estimates both confirm and

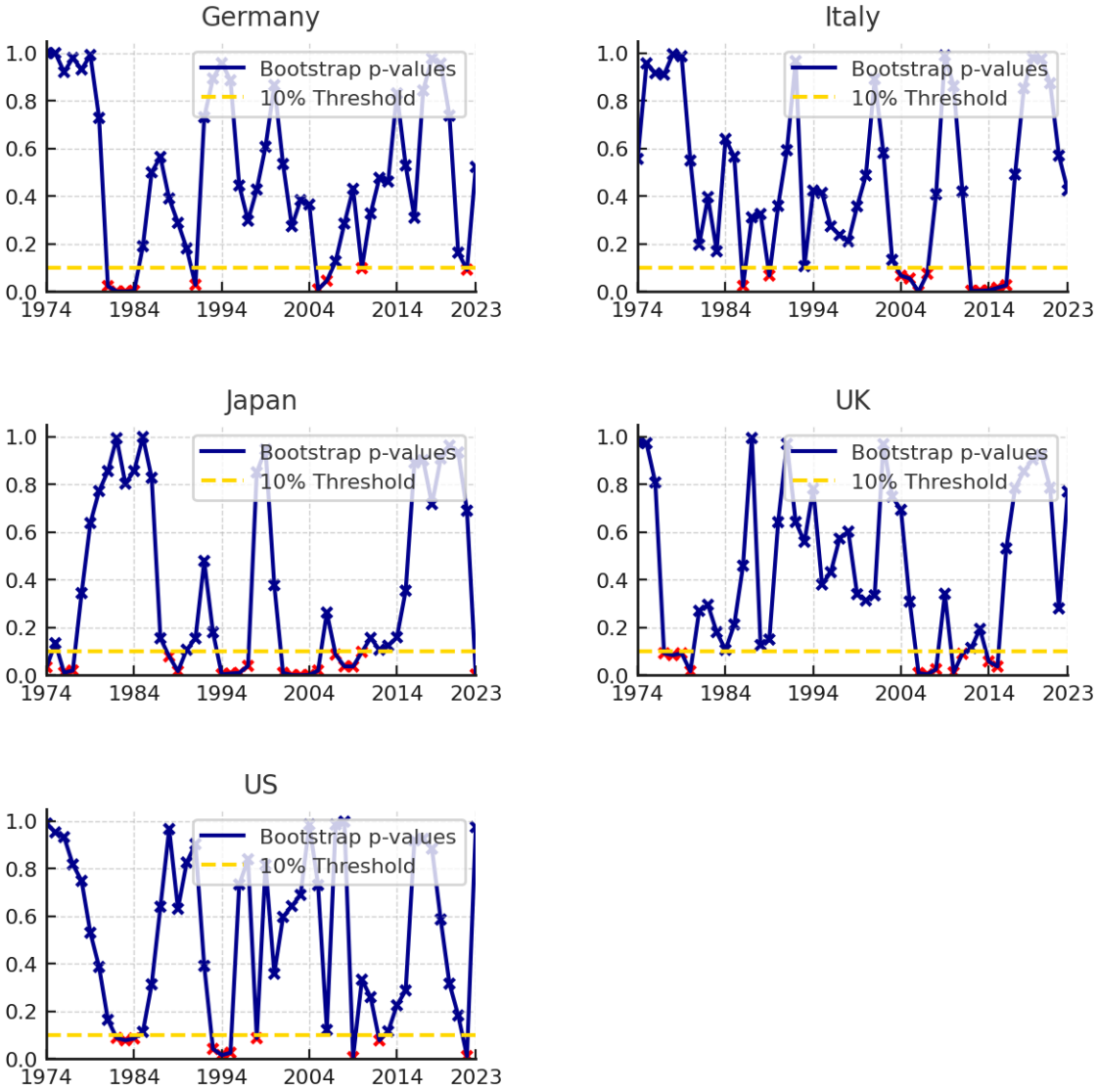
substantially extend the insights from the full-sample panel causality test. In particular, the null hypothesis that *"growth does not Granger-cause CCO2"* is rejected in several sub-periods across different countries, indicating episodic and time-dependent causal linkages that static, full-sample models fail to capture. The rolling-window framework thus offers clear advantages by uncovering country- and period-specific causal dynamics otherwise masked in aggregate analysis. Sub-sample intervals with statistically significant causality ($p < 0.1$) from growth to CCO2 emissions are observed for:

- Canada in 2007, 2015, and 2021–2022.
- France in 1980–1983, 2005–2006, 2013–2018, and 2020–2023.
- Germany in 1981–1984, 1991, 2005–2006, 2010, and 2022.
- Italy in 1986, 1989, 2004–2007, and 2012–2016.
- Japan in 1974, 1976–1977, 1988–1989, 1994–1997, 2001–2005, 2007–2010, and 2023.
- UK in 1977–1980, 2006–2008, 2010–2011, and 2014–2015.
- US in 1982–1984, 1993–1995, 1998, 2009, 2012, and 2022.

The results collectively show that no country exhibits stable long-run causality, but instead a patchwork of episodic causal links emerges. Importantly, these dates often cluster around economic downturns, energy crises, and regulatory transitions, suggesting that the growth–CCO2 relationship is highly sensitive to macroeconomic shocks and policy interventions. This evidence indicates that the EKC hypothesis for CCO2 emissions in the G7 is not a smooth deterministic process but rather conditional and state-dependent, requiring dynamic econometric approaches such as rolling-window estimation to capture its true character. Accordingly, the next section examines the validity of the EKC for each country by analyzing the impact of growth on CCO2.

**Figure 3:** Rolling Window Estimation Results of Causality From *growth* to *CCO2*

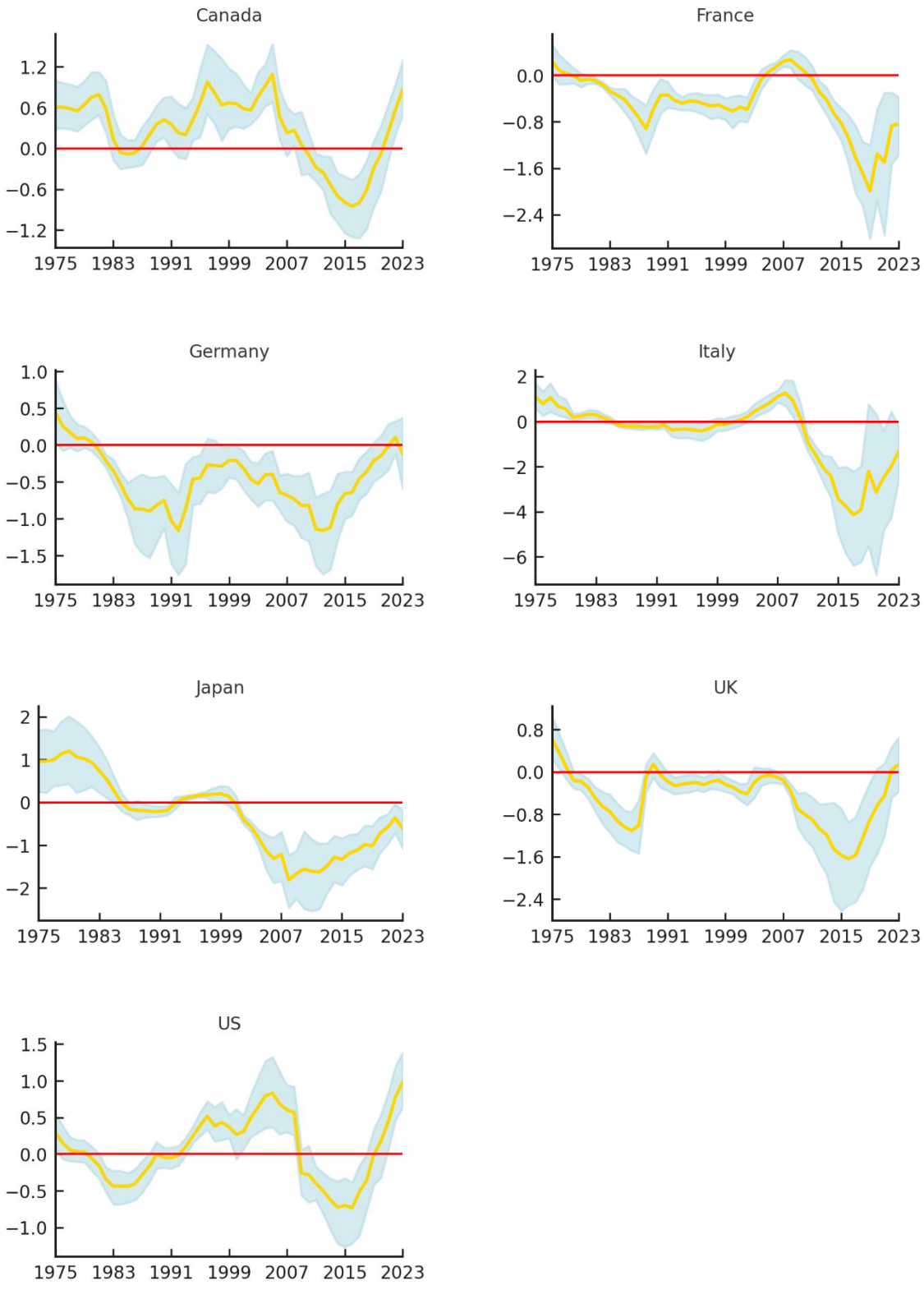





## 5. DISCUSSION

This study employed both the full-sample bootstrap panel causality test and the rolling-window bootstrap panel causality framework to analyze the dynamic relationship between economic growth and CCO2 emissions in the G7 economies. While the full-sample approach provides a static, average view of causality, the rolling-window design adds substantial value by uncovering the time-varying and episodic nature of the growth–emissions nexus, thereby capturing structural breaks, policy shifts, and macroeconomic shocks that conventional models overlook.

**Figure 4:** Rolling Window Estimation Results for the Impact of *growth* to *CCO2*




As illustrated in Figure 4, the empirical evidence provides clear support for the EKC hypothesis in Canada and the US. In Canada, the impact of growth on CCO2 emissions increases between 1987 and 2005 and subsequently reverses sign after reaching a peak in 2005, indicating an inverted U-shaped relationship consistent with the EKC hypothesis. A similar pattern is observed for the US, where the

impact of growth on CCO2 intensifies from 1993, peaks in 2005, and then declines thereafter, further corroborating the EKC framework.

By contrast, the results do not provide clear evidence in support of the EKC hypothesis for Germany. For the remaining countries, although certain sub-periods exhibit an upswing in the growth–CCO2 relationship reflected in positive coefficients, these patterns do not form a complete inverted U-shaped trajectory. As such, the evidence for EKC validity in these countries remains weak or inconclusive.

Crucially, the rolling-window results reveal that the growth–emissions relationship is neither linear nor stable but contingent on historical context. Episodes of global energy crises, recessions, and the implementation of environmental policy regimes coincide with shifts in causality, highlighting that EKC dynamics in the cement sector are highly state-dependent. These findings echo recent contributions that interpret the EKC not as a deterministic path but as a conditional process shaped by institutional quality, technological innovation, and sector-specific policies.

The periods in which statistically significant growth–emissions causality emerges coincide with well-documented macroeconomic and policy shocks. For instance, stronger positive effects during the late 1970s and early 1980s align with the oil crises, when energy-intensive production and cost-driven fuel substitution amplified emissions responses to economic activity. Similarly, renewed significance around the early 2000s and the global financial crisis reflects construction booms and subsequent adjustment phases in which cement demand and emissions reacted sharply to growth fluctuations. In contrast, the weakening or reversal of causality observed in the post-2010 period corresponds to the expansion of climate regulations, energy-efficiency standards, and emissions-trading mechanisms, suggesting that institutional and technological changes moderated the growth–emissions link.

From a policy perspective, the results indicate that emission reductions in the cement sector do not arise automatically from income growth but instead coincide with periods of targeted intervention. The observed turning points align with the diffusion of energy-efficient kiln technologies (e.g., large-scale adoption of preheater–precalciner kilns in North America and Europe) (Worrell et al. 2001; IEA, 2009; Hasanbeigi et al. 2010; 2011), the increased use of alternative fuels and clinker substitutes (such as biomass co-firing and supplementary cementitious materials, including fly ash and blast-furnace slag) (Schneider et al., 2011; Benhelal et al., 2013; IEA and WBCSD, 2018) and the strengthening of carbon pricing and emissions-trading schemes (notably the expansion and tightening phases of the EU Emissions Trading System after the mid-2000s) (Ellis et al., 2019; EC, 2020). These findings suggest that decarbonising the cement sector requires sustained policy support for low-carbon production technologies, stricter regulatory standards, and credible carbon pricing mechanisms, rather than reliance on economic growth alone. Accordingly, the EKC in this sector should be interpreted as policy-contingent rather than income-driven.

Taken together, the results indicate that sustained growth in G7 economies has not only fueled industrialization but also progressively fostered institutional and technological conditions conducive to decarbonization in cement production. This supports the argument that economic performance and environmental quality are not inherently conflicting objectives; rather, they can advance together once economies surpass critical thresholds of development and governance.

Although this study provides novel evidence on the EKC hypothesis for CCO2 emissions in the G7 economies, several limitations should be acknowledged. First, the analysis relies on aggregate national data, which may mask sub-sectoral variations within the cement industry, such as differences in plant technology, fuel mix, and efficiency levels. Second, while the rolling-window bootstrap approach accounts for structural breaks and temporal dependence, it does not explicitly model the role of external shocks such as global trade dynamics, carbon pricing, or environmental

regulations that could directly influence the growth–emissions link. Third, the study employs GDP as the sole indicator of economic development, even though other measures—such as industrial output, investment in cleaner technologies, or energy intensity—may provide complementary insights.

Future research can address these limitations in several ways. Incorporating plant-level or regional data would allow for a more granular assessment of emissions dynamics within and across G7 economies. Expanding the econometric framework to include policy variables (e.g., emissions trading schemes, carbon taxes, or renewable energy adoption) would improve understanding of the mechanisms driving the EKC. Moreover, applying alternative methodologies—such as nonlinear ARDL, Fourier-based cointegration, or machine learning models—could enhance robustness and capture complex, nonlinear patterns in the growth–emissions relationship. Finally, comparative studies between advanced and emerging economies would help identify whether the EKC dynamics observed in the G7 can be generalized to countries at different stages of industrialization and institutional development.

## 6. CONCLUSION

This study investigated the validity of the EKC hypothesis for CCO2 emissions in the G7 economies by employing a combination of full-sample bootstrap panel causality and rolling-window bootstrap causality approaches. This dual framework enables the analysis to account for cross-sectional dependence, slope heterogeneity, and temporal instability in the growth–emissions relationship. While the full-sample results provide a static benchmark, the rolling-window analysis offers deeper insights by revealing episodic, country-specific, and historically contingent causal patterns, underscoring the importance of dynamic econometric tools when evaluating environmental hypotheses.

The empirical findings indicate that EKC-type dynamics are not uniform across the G7. Clear evidence consistent with an inverted U-shaped relationship between growth and CCO2 emissions is observed in Canada and the US, where emissions rise with income up to a turning point and subsequently decline. By contrast, for other G7 economies, the results do not support a complete EKC trajectory. Although some countries exhibit partial or temporary upswings in the growth–emissions relationship, these patterns do not culminate in a sustained turning point, suggesting that economic growth alone is insufficient to guarantee emission reductions in the cement sector.

Importantly, the rolling-window results show that shifts in the growth–emissions relationship coincide with major macroeconomic shocks and policy regimes, such as energy crises, financial downturns, and periods of intensified environmental regulation. This evidence indicates that EKC dynamics in the cement sector are state-dependent rather than deterministic, and that observed turning points are closely associated with institutional, technological, and regulatory changes rather than with income thresholds per se.

The policy implications of these findings are clear. Decarbonisation in the cement sector does not arise automatically from economic growth but instead reflects targeted and sustained policy interventions. Emission reductions are more likely during periods characterized by the diffusion of energy-efficient production technologies, increased use of alternative fuels and clinker substitutes, and the strengthening of carbon pricing and emissions-trading mechanisms. Accordingly, policies aimed at reducing cement-related emissions should prioritize technological upgrading, regulatory stringency, and credible carbon pricing frameworks, rather than relying on growth-driven adjustment alone.

Overall, this study contributes to the EKC literature by demonstrating that, in a highly carbon-intensive and process-driven sector such as cement, the EKC should be interpreted as a policy-contingent and time-varying phenomenon. Future research could extend this analysis by

incorporating explicit policy indicators, firm-level technological adoption data, or sector-specific carbon pricing measures to further disentangle the mechanisms underlying growth–emissions dynamics in advanced economies.

## DECLARATIONS

**FUNDING / SUPPORT INFORMATION**

No financial support was received.

**CONTRIBUTIONS OF AUTHORS**

All stages of the study, including conceptualization, data collection, analysis, writing, editing, and supervision, were carried out solely by the author.

**CONFLICT OF INTEREST**

The author declares that there is no conflict of interest with any person, institution, or organization during the preparation, conduct, or publication of this study.

**DATA AVAILABILITY**

The data are publicly available.

**ETHICAL STATEMENT**

The study requires no approval from an ethics committee.

**ARTIFICIAL INTELLIGENCE (AI) USAGE STATEMENT**

No AI-based tools were used in this study.

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