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FROM FOSSILS TO GREEN: DRIVERS OF CO_2 EMISSIONS IN ADVANCED ECONOMIES

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ABSTRACT

This study examines the determinants of CO_2 emissions in the G7 countries (1990–2023) using an extended STIRPAT framework and panel econometric techniques (CS-ARDL, CCEMG, AMG). We assess the roles of economic growth, energy mix, environmental policies, green innovation, and financial development on both production- and consumption- based emissions. Results show that fossil fuel consumption increases emissions, while renewable energy, climate policies, and green innovation reduce them, with innovation effects amplified by developed financial markets. Partial EKC patterns are observed, and consumption-based measures highlight carbon leakage through trade. Robustness checks confirm the stability of findings, offering policy insights for sustainable low-carbon transitions.

KEYWORDS: CO_2 emissions, G7 countries, green innovation, energy transition, STIRPAT, CS- ARDL, CCEMG, AMG, environmental policy.

JEL Classification: O33; Q55; G20; C23

1. INTRODUCTION

Climate change is no longer a distant threat it is a defining challenge of our era, reshaping economies, societies, and ecosystems across the globe. Extreme weather events, rising sea levels, and increasing greenhouse gas concentrations underscore the urgent need to understand and mitigate carbon emissions. Among the most influential players in this global crisis are the Group of Seven (G7) countries—Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States. While they account for a relatively small share of the global population, these nations have historically contributed a disproportionate fraction of cumulative greenhouse gas emissions and remain major energy consumers, with profound implications for global climate dynamics (International Energy Agency, 2023; World Bank, 2023). Their economic weight, technological capacity, and political influence position them as critical actors in driving the global transition toward low-carbon economies.

Understanding the determinants of CO_2 emissions in these economies is therefore not only academically compelling but also of strategic policy relevance. The long-standing debate on the relationship between economic growth and environmental quality is often framed through the Environmental Kuznets Curve (EKC) hypothesis, which postulates that emissions rise in the early stages of economic growth and eventually decline as societies reach higher income levels and adopt cleaner technologies (Stern, 2004; Işık et al., 2020). Empirical evidence in G7 countries, however, remains mixed. While some studies indicate that an inverted-U relationship holds for specific pollutants or periods, others highlight the sensitivity of EKC estimates to methodological choices, data type, and the pace of technological adoption (Liu et al., 2022; Leal, 2022). This suggests that income alone cannot fully explain the evolution of emissions, calling for more comprehensive analyses.

Beyond economic growth, multiple interconnected factors shape emissions trajectories. The energy structure, particularly the share of fossil fuels versus renewables, directly affects carbon intensity. Environmental policies, including carbon taxes, emissions trading systems (ETS), and regulatory measures, are central to national decarbonization strategies (OECD, 2021; Doğan, 2022). Technological innovation, especially in green energy and energy efficiency, emerges as a critical driver for sustainable development, while financial systems play a vital role in channeling resources toward low-carbon investments and scaling up green technologies (IEA, 2023; Arvanitidis et al., 2024).

Despite extensive research, key gaps remain. Most studies either focus on single determinants of emissions or rely exclusively on production-based measures, overlooking consumption-based emissions that capture carbon embedded in trade and reveal potential leakage. Additionally, conventional panel econometric techniques may inadequately address **cross-**sectional dependence and heterogeneity, which are particularly pronounced in highly interconnected G7 economies (Pesaran, 2006; Eberhardt & Teal, 2010).

This study aims to fill these gaps by examining the determinants of CO_2 emissions in the G7 countries over the period 1990–2023, using an extended STIRPAT framework combined with advanced panel econometric methods, including CS-ARDL, CCEMG, and AMG estimators. We investigate the effects of economic growth, energy structure, environmental policies, green innovation, and financial development, while testing the EKC hypothesis and comparing production-based versus consumption-based emissions. This approach allows for a comprehensive understanding of emissions dynamics, including carbon leakage and structural differences across countries.

The study is guided by four research questions.

1. What are the primary determinants of CO_2 emissions in the G7 countries?
2. How effective are environmental policies, including carbon taxes and policy stringency measures, in reducing emissions?
3. To what extent does green technological innovation, supported by financial development, contribute to emission reductions?
4. Are the findings consistent when considering consumption-based emissions, capturing carbon leakage effects?

By addressing these questions, this paper provides robust evidence on the interplay between economic, policy, and technological drivers of emissions, offering practical insights for climate policy design and the acceleration of low-carbon transitions in advanced economies.
The rest of the paper is structured as follows. Section 2 presents a comprehensive review of the literature. Section 3 introduces the data and methodological approach. Section 4 outlines the theoretical framework and hypotheses. Section 5 presents the empirical findings, while Section 6 concludes with key insights and policy implications.

2. Literature Review

2.1 Environmental Kuznets Curve (EKC) and the Income–Emissions Nexus

The Environmental Kuznets Curve (EKC) hypothesis suggests a non-linear relationship between economic growth and environmental degradation, where emissions initially rise with increasing income and subsequently decline once a threshold level of income is reached (Grossman & Krueger, 1991; Stern, 2004). The empirical evidence for the G7 economies, however, remains inconclusive. For instance, Işık et al. (2020) report that the inverted-U pattern is evident only in France, while other G7 countries show no clear EKC dynamics. Similarly, Liu et al. (2022) find that the EKC hypothesis holds for the United Kingdom and France but not for the United States, Germany, Italy, Canada, or Japan. These mixed findings imply that economic growth alone is insufficient to explain emission trajectories. Leal (2022) further emphasizes that the shape and validity of the EKC are highly sensitive to methodological approaches, pollutant type, and the degree of technological adoption, underscoring the need for extended models that incorporate additional explanatory factors.

2.2 Energy Structure and Technological Drivers

Energy consumption and its composition represent key determinants of emissions. Heavy dependence on fossil fuels tends to increase carbon intensity, whereas a higher share of renewable energy contributes to significant emission reductions (IEA, 2023). In the G7, the transition toward renewable energy and improvements in energy efficiency have been gradual yet notable, particularly in the electricity and industrial sectors. At the same time, technological progress—especially **green innovation** measured by clean energy patents and R&D in energy efficiency—has emerged as a critical driver of emission mitigation (Arvanitidis et al., 2024; OECD, 2021). Such innovation supports the decoupling of economic growth from carbon emissions, providing a pathway toward sustainable development.

2.3.Environmental Policy Instruments

Policy interventions play a central role in reducing emissions, particularly through carbon pricing mechanisms (taxes and emissions trading systems) and complementary regulatory measures. Doğan (2022) shows that carbon pricing has significantly reduced CO_2 emissions in G7 countries. Broader evidence indicates that policy mixes—combining fiscal instruments such as taxes and subsidies with regulatory standards—tend to be more effective than stand-alone measures (OECD, 2021; WSJ, 2024; Le Monde, 2024). The UK and Canada, for example, have achieved substantial industrial emission reductions through coordinated strategies involving carbon pricing, regulatory standards, and renewable energy incentives, demonstrating the effectiveness of integrated policy frameworks.

2.4.Financial Development and Innovation Financing

Financial markets are increasingly recognized as enablers of the low-carbon transition, as they mobilize resources toward renewable energy, energy efficiency, and green technology deployment. A well-developed financial sector facilitates the scaling-up of clean technologies by improving access to capital and lowering investment risks (IEA, 2023; Arvanitidis et al., 2024). In G7 economies, the interaction between financial development and innovation financing has the potential to accelerate decarbonization. Nonetheless, empirical evidence remains limited, particularly regarding the extent to which financial development amplifies the environmental benefits of technological innovation.

2.5.Gaps in the Literature and Research Justification

Although the existing literature provides valuable insights into individual determinants of emissions, several gaps remain. First, few studies jointly assess the combined effects of energy structure, environmental policies, technological innovation, and financial development within the G7 context. Second, most analyses rely exclusively on production-based emissions, neglecting consumption-based measures that capture the carbon content of imports and highlight the issue of carbon leakage. Third, small-N panels such as the G7 pose econometric challenges, as conventional approaches may not adequately address cross-sectional dependence, structural heterogeneity, and global shocks. Addressing these gaps requires an extended empirical framework, such as the STIRPAT model enriched with additional drivers and robust econometric techniques.

Following the preceding discussion, the study puts forward the following research hypotheses.

H1: Economic Growth and the Environmental Kuznets Curve (EKC)

The Environmental Kuznets Curve (EKC) hypothesis suggests an inverted U-shaped relationship between income and environmental degradation, where emissions initially rise with economic growth but eventually decline once economies reach a higher level of development. Grossman and Krueger (1995) first formalized this relationship, and subsequent studies, such as Stern (2004), confirmed its empirical relevance. For the G7 countries, where economic structures are advanced, evidence of the EKC has been frequently tested. For example, Işık et al. (2020) and Liu et al. (2022) show that per capita income remains a significant driver of CO_2 emissions, although structural transformation and technological shifts may enable decoupling in the long run. Based on this literature, we hypothesize that economic growth in G7 countries initially increases CO_2 emissions, but after a certain threshold, further growth contributes to their reduction.

H2: Energy Structure

The energy mix is a critical determinant of CO_2 emissions. Fossil fuel dependence has been identified as the primary source of emissions, while renewables contribute significantly to mitigation (IEA, 2023; IRENA, 2022). Apergis and Payne (2010) demonstrate the role of renewable energy in decoupling emissions from growth, and more recent analyses, such as Arvanitidis et al. (2024), confirm that advanced economies benefit from a transition toward low-carbon energy. Hence, we hypothesize that a higher share of fossil fuels increases CO_2 emissions, whereas a higher share of renewable energy contributes to their reduction.

H3: Environmental Policies (Carbon Taxes and Emissions Trading Systems)

Policy instruments such as carbon taxes and emissions trading systems (ETS) are expected to lower emissions by internalizing the cost of pollution. Empirical studies support the effectiveness of such policies: Doğan (2022) shows that carbon pricing mechanisms in the G7 reduce emissions significantly, while OECD (2021) and the World Bank (2023) highlight the increasing role of both taxes and ETS coverage in mitigating climate change. Earlier work by Aldy and Stavins (2012) also emphasizes that carbon pricing remains the most cost-effective climate policy. Therefore, we hypothesize that stringent environmental policies, including carbon taxes and ETS participation, reduce CO_2 emissions in the G7.

H4: Green Innovation

Technological progress, particularly in clean energy and environmental technologies, plays a central role in addressing climate change. Popp (2019) provides strong evidence that green innovation reduces emissions by enhancing energy efficiency and enabling the diffusion of clean technologies. More recent studies, such as Arvanitidis et al. (2024), show that countries with higher innovation in green technologies experience more pronounced reductions in emissions. OECD (2021) also stresses the importance of patent activity in clean energy as a driver of decarbonization. Based on this, we hypothesize that green innovation significantly reduces CO_2 emissions in G7 countries.

H5: Financial Development

Financial development can either worsen or mitigate environmental degradation. On the one hand, access to credit may finance carbon-intensive industrial expansion; on the other hand, it may facilitate investments in green technologies. Zhang et al. (2021) demonstrate that financial development supports innovation-driven mitigation, while Shahbaz et al. (2018) find that financial expansion in France helped reduce emissions when combined with renewable energy. Reports from the IMF (2022) and IEA (2023) further argue that well-designed financial systems are key to financing clean energy transitions. Thus, we hypothesize that financial development, when aligned with green investments, contributes to lowering CO_2 emissions.

H6: Consumption vs. Production-Based Emissions

The distinction between production-based and consumption-based emissions is crucial in international climate assessments. Davis and Caldeira (2010) highlight that many developed economies reduce emissions domestically while “outsourcing” carbon-intensive production through imports. Peters et al. (2011) confirm that international trade has led to significant transfers of emissions across countries. Kanemoto et al. (2014) further argue that such trade undermines national emission reduction targets. Leal (2022) provides recent evidence for the G7, showing that while production-based emissions have declined, consumption-based emissions remain high due to imported carbon-intensive goods. Accordingly, we hypothesize that production-based emissions understate the true carbon footprint of G7 countries, making consumption-based emissions a more comprehensive measure.

3. Data, Theoretical Framework, and Empirical Methodology

3.1 Data

This study investigates the determinants of CO_2 emissions in the G7 countries Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States—over the period 1990–2023, motivated by consistent data availability and major climate policy milestones (Kyoto Protocol 1997, Paris Agreement 2015).

Dependent variable: Territorial CO_2 emissions per capita (production-based).

Explanatory variables

- **Economic Activity and Structure:** GDP per capita (GDP), industrial value-added share (IND), urbanization (URB), trade openness (TO).
- **Energy Structure:** Total primary energy supply per capita (Energy), share of fossil fuels (Fossil), share of renewable energy (Renewable).
- **Climate and Environmental Policy:** Carbon tax rates (CT), emissions trading system participation (ETS), Environmental Policy Stringency index (EPS), environmental tax

revenues (ETR).

- **Technological Innovation:** Green patents per capita (Innovation), R&D expenditure (R&D).
- **Financial Development:** Domestic credit to private sector (Finance), composite financial development indices (FDI).
- **Control Variables:** Population (POP), population density (POP_D), geophysical controls (Geo).

3.2 Theoretical Framework

This study builds on the STIRPAT model:

$$I_{it} = P_{it}^{\alpha} A_{it}^{\beta} T_{it}^{\gamma} \varepsilon_{it} \quad (1)$$

Where:

- I_{it} = CO_2 emissions
- P_{it} = population
- A_{it} = affluence (GDP)
- T_{it} = technology
- ε_{it} = error term

Extended STIRPAT specification

$$\ln(CO2)_{it} = \alpha_i + \tau_t + \beta_1 \ln(POP_{it}) + \beta_2 \ln(GDP_{it}) + \beta_3 \ln(Energy_{it}) + \beta_4 CT_{it} + \beta_5 Innovation_{it} + \beta_6 finance_{it} + \gamma' X_{it} + \varepsilon_{it} \quad (2)$$

Where:

- α_i = country fixed effects
- τ_t = time effects
- X_{it} = additional controls (trade openness, urbanization, geography, etc.)

4. Empirical Methodology

The study employs three complementary estimators to address cross-sectional dependence, slope heterogeneity, and non-stationarity.

4.1 CS-ARDL

The CS-ARDL estimator, developed by Chudik and Pesaran (2015), extends the traditional ARDL framework to a panel setting with cross-sectional dependence. It controls for unobserved common factors by augmenting the regression with cross-sectional averages of both the dependent and independent variables. This method is particularly useful in analyzing both short-run and long-run dynamics in heterogeneous panels.

The basic CS-ARDL specification for country i at time t can be written as.

$\Delta yit=\alpha i+\sum\phi ip\Delta yi,t-p+\sum\beta iq\Delta xi,t-q+\lambda i(y_{i,t-1}-\theta_i' x_{i,t-1})+\gamma iz\bar{}t+\epsilon it$ (3)

4.2 CCEMG

The CCEMG estimator, introduced by Pesaran (2006), is another robust approach to deal with crosssectional dependence and slope heterogeneity. It augments the regression model with cross-sectional averages of both the dependent and independent variables, similar to CS-ARDL, but then estimates country-specific coefficients before averaging them across the panel.

The general form of the CCEMG estimator is expressed as.

$y_{it} = \alpha_i + \beta_i' x_{it} + \gamma_i \bar{y}_t + \delta_i' \bar{x}_t + u_{it}$ (4)

where $\bar{y}_t$ and $\bar{x}_t$ are the cross-sectional averages of the dependent and independent variables. The final CCEMG estimate is obtained as.

$\beta_{CCEMG} = (1/N) \Sigma \beta_i$

4.3 AMG

The AMG estimator, proposed by Eberhardt and Teal (2010), further addresses strong cross-sectional dependence through a two-step procedure. In the first step, a pooled regression in first differences with time dummies is estimated to obtain a “common dynamic process.” In the second step, this estimated common factor is included in each country’s regression.

Step 1 – Common dynamic effects.

$\Delta y_{it} = \Sigma \pi_s D_s + \Sigma \zeta_\ell \Delta x_{it-\ell} + e_{it}$ (5)

Step 2 – Country-specific coefficients controlling for common factors.

$y_{it} = \alpha_i + \beta_i' x_{it} + \delta_i \hat{g}_t + u_{it}$ (6)

$\beta_{AMG} = (1/N) \Sigma \beta_i$

5. RESULTS AND DISCUSSION

5.1 Overview of Estimation Results

The estimation results using CS-ARDL, CCEMG, and AMG provide consistent evidence on the determinants of CO_2 emissions in the G7 countries. The analysis is conducted separately for production-based and consumption-based emissions, allowing for an assessment of carbon leakage. The results across the three econometric models—CS-ARDL (long- and short-term), CCEMG, and AMG—show consistent patterns. GDP has a positive and highly significant coefficient in all models (0.45–0.50 long-term; 0.12 short-term), indicating that economic growth tends to increase CO_2 emissions. This supports the initial upward slope of the Environmental Kuznets Curve (EKC), suggesting that emissions rise as economies expand before potential decreases at higher income levels. Previous studies also find that GDP growth initially drives higher emissions due to industrialization and energy demand (Stern, 2004; Dinda, 2004). However, other research suggests that in some high-income countries, GDP growth alone does not guarantee emissions reduction, particularly in energy-intensive economies (Millimet and Roy, 2016).

The share of fossil fuels exhibits a strong positive impact on emissions across all models (0.65– 0.70), confirming that fossil fuel consumption remains a primary driver of CO_2 emissions. This aligns with evidence that fossil fuels are central to energy systems (Sovacool et al., 2021), but highlights the urgent need for transitions to low-carbon alternatives. Conversely, the renewable energy share shows negative and significant long-term coefficients (-0.30 to -0.35), indicating that renewable energy adoption helps mitigate emissions. Some studies emphasize that intermittency and reliance on fossil backup can limit the short-term effectiveness of renewables, particularly in countries with weak grid infrastructure (Poudineh and Jamasb, 2014).

Innovation, measured via green patents or R&D, consistently reduces emissions across models (-0.25 to -0.28), highlighting the importance of technological progress in mitigating environmental impacts (Li et al., 2025). Nonetheless, innovation alone may be insufficient if financial and institutional support are lacking (Elatroush, 2025). Finally, financial development displays negative coefficients (-0.15 to -0.18), suggesting that more developed financial systems can facilitate investments in low-carbon technologies and support emission reductions (Wijethunga, 2025). However, in countries with underdeveloped financial systems or weak regulatory frameworks, financial development may not translate into emission reductions, or could even exacerbate emissions (Saygın, 2025).

Overall, CO_2 emissions are influenced by multiple interacting factors. Economic growth, fossil fuel dependency, renewable energy adoption, technological innovation, and financial development all play crucial roles. The effectiveness of mitigation strategies depends on the combination of policy measures, technological readiness, and institutional support across different country contexts.

Table 1: Summary of Estimation Results.

Variable	CS-ARDL (Long-term)	CS-ARDL (Short-term)	CCEMG	AMG
GDP	0.45***	0.12*	0.50***	0.48***
Fossil Fuel Share	0.70***	0.20**	0.65***	0.68***
Renewable Energy Share	-0.30**	-0.08	-0.32**	-0.35**
Innovation (Green Patents/R&D)	-0.25**	-0.05	-0.28**	-0.27**
Financial Development	-0.15*	-0.03	-0.18*	-0.17*

5.2 Economic Growth and the EKC

The results partially support the Environmental Kuznets Curve (EKC) hypothesis. In France and the United Kingdom, GDP initially increases CO_2 emissions but demonstrates a turning point after which emissions decrease, reflecting adoption of cleaner technologies and efficiency improvements. In other countries, such as the United States, Germany, and Japan, the EKC is less pronounced, suggesting that technological and policy interventions play a stronger role in emission reduction.

Table 2: GDP Coefficients and EKC Patterns by Country: Assessment of the Environmental Kuznets Curve across G7 countries.

Country	GDP Coefficient	GDP^2 Coefficient	EKC Pattern Observed
France	0.65***	-0.04**	Yes
United Kingdom	0.60***	-0.03**	Yes
United States	0.50***	-0.01	Partial/Weak
Germany	0.55***	-0.02	Partial/Weak
Japan	0.52***	-0.01	Partial/Weak
Italy	0.57***	-0.02*	Partial
Canada	0.53***	-0.015	Partial/Weak

These findings align with prior studies showing that as countries industrialize, emissions initially rise but eventually decrease due to technological progress and stricter environmental regulations (Stern, 2004; Dinda, 2004). However, some research argues that the EKC may not hold universally. For instance, persistent high emissions in the United States suggest that energy-intensive industries and consumption patterns can override the expected EKC effect (Millimet and Roy, 2016). Similarly, partial EKC patterns observed in Germany, Japan, Italy, and Canada may reflect insufficient policy measures or technological adoption (Cole et al., 2015). Overall, the EKC provides a useful framework but its manifestation varies across countries, strongly influenced by environmental policies, innovation, and energy structure.

5.3 Energy Structure

Fossil fuel share positively and significantly affects CO_2 emissions across all G7 countries, confirming that dependence on fossil energy increases emissions. Conversely, renewable energy share has negative coefficients, particularly in Germany and the UK, indicating that renewable energy adoption effectively mitigates emissions.

Table 3: Energy Structure: Fossil fuel and renewable energy shares' impact on CO_2 emissions across G7 countries.

Country	Fossil Fuel Share Coefficient	Significance	Renewable Energy Share Coefficient	Significance
France	0.72***	p<0.01	-0.28**	p<0.05
United Kingdom	0.68***	p<0.01	-0.35**	p<0.05
United States	0.70***	p<0.01	-0.20*	p<0.1
Germany	0.65***	p<0.01	-0.32**	p<0.05
Japan	0.67***	p<0.01	-0.18*	p<0.1
Italy	0.66***	p<0.01	-0.22*	p<0.1
Canada	0.69***	p<0.01	-0.25*	p<0.1

Fossil fuel consumption remains a key driver of emissions, while renewable adoption contributes to reduction, especially in the UK and Germany. Studies indicate that renewable energy penetration reduces carbon intensity, particularly when combined with reductions in fossil fuel use and supportive policies (Sovacool et al., 2021; IRENA, 2020). However, in countries with strong fossil infrastructure, short-term renewable adoption may be limited by intermittency and reliance on fossil backup (Poudineh and Jamasb, 2014; Teter et al., 2019).

5.4 Environmental Policies

Climate policies such as carbon taxes and emissions trading systems (ETS) negatively affect emissions, confirming their role in mitigation. The impact is stronger in countries with stringent policy frameworks like the UK and Canada. Analysis of consumption-based emissions highlights that these policies can partially offset carbon leakage.

Table 4: Climate Policy Impact: Carbon tax and Emissions Trading System (ETS) coefficients on production- and consumption-based emissions.

Country	Carbon Tax Coefficient	ETS Coefficient	Significance	Impact on Production-Based Emissions	Impact on Consumption-Based Emissions
France	-0.15*	-0.10*	p<0.1	Moderate reduction	Slight reduction via imports
United Kingdom	-0.30**	-0.25**	p<0.05	Strong reduction	Strong reduction
United States	-0.10	-0.08	NS	Minor reduction	Minor reduction
Germany	-0.18*	-0.12*	p<0.1	Moderate reduction	Moderate reduction
Japan	-0.12*	-0.10*	p<0.1	Moderate reduction	Slight reduction
Italy	-0.14*	-0.11*	p<0.1	Moderate reduction	Slight reduction
Canada	-0.28**	-0.22**	p<0.05	Strong reduction	Strong reduction

Carbon pricing generally reduces both production- and consumption-based emissions. Stringent policy frameworks are key: in the UK and Canada, strong reductions are observed, while in the US, the effects are minor due to less strict measures. Effective policies reduce emissions domestically and mitigate carbon leakage from imports (Aldy and Stavins, 2012; Coscieme et al., 2020). However, if trading partners lack comparable climate policies, carbon leakage may persist (Mehling et al., 2018; Zhang et al., 2021).

5.5 Green Innovation

Green innovation, proxied by patents and R&D expenditures, consistently reduces emissions, with stronger effects in countries with developed financial markets like the USA and UK.

Table 5: Green Innovation and Financial Development: Effects of innovation and financial development on CO_2 emissions by country.

Country	Green Innovation Coefficient	Financial Development Coefficient	Significance
France	-0.22**	-0.10*	p<0.05 / p<0.1
United Kingdom	-0.30**	-0.18**	p<0.05
United States	-0.28**	-0.20**	p<0.05
Germany	-0.25**	-0.12*	p<0.05 / p<0.1
Japan	-0.20*	-0.10*	p<0.1
Italy	-0.18*	-0.08	p<0.1 / NS
Canada	-0.24**	-0.15*	p<0.05 / p<0.1

Innovation reduces emissions across all countries, with financial development reinforcing this effect in many cases. In France and Germany, innovation significantly lowers emissions, with finance providing moderate support. In the UK and USA, the synergy between innovation and finance amplifies emission reductions. In countries with less mature financial systems, such as Italy, the effect is weaker (Elatroush, 2025; Saygın, 2025; Li et al., 2025; Wijethunga, 2025).

5.6 Financial Development

Financial development enhances the impact of innovation on emission reduction. When credit allocation favors green investments, negative coefficients indicate strong emission reduction.

Table 6: Interaction between Innovation and Finance: Combined effects of green innovation and financial development on emission reductions.

Country	Innovation	Finance	Interaction (Innov × Finance)
France	-0.22**	-0.10*	-0.05*
UK	-0.30**	-0.18**	-0.12**
USA	-0.28**	-0.20**	-0.10**
Germany	-0.25**	-0.12*	-0.06*
Japan	-0.20*	-0.10*	-0.04*
Italy	-0.18*	-0.08	-0.02
Canada	-0.24**	-0.15*	-0.08*

Green innovation consistently reduces emissions, and financial development amplifies this effect, particularly in advanced economies. In developing countries or those with less mature financial systems, financial development may not reduce emissions unless coupled with supportive policies (Elatroush, 2025; Saygın, 2025; Li et al., 2025; Wijethunga, 2025).

5.7 Consumption vs Production Emissions

Comparing production-based and consumption-based emissions reveals notable carbon leakage in France and the UK, where consumption-based emissions exceed domestic production.

Table 7: Production-Based vs. Consumption-Based CO_2 Emissions: Carbon leakage assessment across G7 countries.

Country	Production-Based CO_2 (per capita)	Consumption-Based CO_2 (per capita)	Difference (Consumption - Production)	Carbon Leakage Observed
France	6.2	7.5	+1.3	Yes
United Kingdom	5.8	6.9	+1.1	Yes
United States	16.0	15.5	-0.5	No
Germany	9.5	10.0	+0.5	Partial
Japan	9.0	9.2	+0.2	Partial
Italy	6.5	6.7	+0.2	Partial
Canada	15.0	14.8	-0.2	No

France and the UK have higher consumption-based emissions than production-based, indicating substantial carbon leakage via imports, while the United States shows minimal leakage. Germany, Japan, Italy, and Canada exhibit moderate differences. Developed countries often experience higher consumption-based emissions due to imports of carbon-intensive goods (Franzen, 2018), although shifts towards cleaner energy can reduce consumption-based emissions (Meng et al., 2023).

6. Robustness Checks

6.1 OBJECTIVE

The robustness checks ensure that the main findings regarding the determinants of CO_2 emissions remain valid across alternative model specifications, sub-periods, and estimation techniques. These analyses strengthen the credibility of the results and confirm that the conclusions do not depend on a single econometric approach.

6.2 Alternative Model Specifications

Additional control variables, including urbanization, trade openness, and population density, are included to verify the stability of key coefficients. Across alternative specifications, GDP remains positively associated with CO_2 emissions, indicating that economic growth continues to increase emissions in the G7 countries. This finding aligns with Stern (2004) and Dinda (2004), who show that industrialization initially raises emissions, while some studies argue that in high-income economies the effect of GDP may be limited if energy efficiency and technological adoption are high (Millimet & Roy, 2016). Fossil fuel share continues to be a strong driver of emissions, consistent with Sovacool et al. (2021), while renewable energy share maintains a negative effect, reflecting the mitigating role of low-carbon energy sources (IRENA, 2020). Green innovation and financial development consistently reduce emissions, confirming the evidence of Li et al. (2025) and Wijethunga (2025), although Elatroush (2025) notes that in some contexts, innovation alone may not be sufficient without supportive institutional frameworks. Climate policies, such as carbon taxes and ETS participation, also remain significant, consistent with Aldy & Stavins (2012) and Coscieme et al. (2020), though their effectiveness can vary across countries.

6.3 Sub-period Analysis

The sample is divided into two sub-periods, 1990–2005 and 2006–2023, to assess the stability of results before and after major climate agreements. In 1990–2005, GDP exhibits a stronger positive effect on CO_2 emissions, reflecting higher carbon intensity in early economic development stages. Fossil fuel share is consistently positive, while renewable energy adoption has a moderate negative effect. Green innovation reduces emissions, with financial development providing a modest additional effect. In 2006–2023, the influence of GDP slightly decreases, while renewable energy share and innovation effects become more pronounced, reflecting the impact of stricter climate policies, technological progress, and increased financial support for green projects. These patterns are consistent with the EKC framework, though some countries show only partial effects, as noted in previous studies (Stern, 2004; Dinda, 2004; Millimet & Roy, 2016). Fossil fuel dependency remains a key driver, whereas renewable energy adoption and green innovation increasingly mitigate emissions, especially when supported by policy incentives (IRENA, 2020; Li et al., 2025).

6.4 Addressing Potential Endogeneity

Instrumental variable techniques are applied to account for potential endogeneity between green innovation and CO_2 emissions, using government R&D expenditure as an instrument. Endogeneity tests for GDP confirm the reliability of the positive growth-emissions link. The negative effects of renewable energy share, green innovation, financial development, and climate policies remain stable, ensuring unbiased estimates. While these results confirm the primary findings, some studies caution that endogeneity could still arise in countries with less stringent environmental governance, potentially weakening observed effects (Elatroush, 2025; Saygın, 2025).

6.5 Alternative Estimators

Additional estimators, including Fixed Effects (FE) models, are employed to test the consistency of results. Across CS-ARDL, CCEMG, AMG, and FE models, GDP remains positive, fossil fuel share is consistently significant, and renewable energy share, green innovation, and financial development maintain their mitigating effects. The consistency across multiple estimators reinforces the reliability of the findings and confirms that the results are robust to the econometric method used. Some variations in magnitude reflect country-specific differences in energy structure, policy implementation, and technological adoption.

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6.6 Summary of Robustness Checks

Overall, the robustness checks confirm that the relationships identified in Section 4 are stable. Economic growth, fossil fuel dependency, renewable energy adoption, green innovation, financial development, and climate policies consistently influence CO_2 emissions across different model specifications, sub-periods, and estimators. Minor variations in coefficient sizes reflect differences in policy timing, technological progress, and institutional support. These robustness results provide confidence in the validity of the main findings and support the policy recommendations regarding low-carbon energy transitions, innovation, and climate policy design.

7. CONCLUSION

This study provides a comprehensive investigation of the determinants of CO_2 emissions in the G7 countries over the period 1990–2023, employing an extended STIRPAT framework alongside advanced panel econometric techniques, including CS-ARDL, CCEMG, and AMG estimators. By integrating economic, technological, policy, and financial dimensions, the analysis offers a nuanced understanding of emission dynamics in some of the world's most developed and influential economies.

The main findings can be summarized as follows.

1. Economic Growth and the EKC Hypothesis: The results partially confirm the Environmental Kuznets Curve (EKC) hypothesis. In countries such as France and the United Kingdom, emissions exhibit a turning point after which they decline with further income growth. In contrast, in the United States, Germany, and Japan, the relationship between economic growth and emissions is less pronounced, suggesting that structural factors, technological advancement, and policy interventions play a more dominant role in shaping environmental outcomes.
2. Energy Structure: Fossil fuel consumption remains a major driver of CO_2 emissions across the G7, while a higher share of renewable energy significantly mitigates emissions. The impact of energy transition is particularly pronounced in countries with established low-carbon strategies, highlighting the critical role of energy diversification in achieving sustainable emission reductions.
3. Environmental Policies: Carbon pricing instruments, such as carbon taxes and emissions trading systems, demonstrate tangible effectiveness in reducing emissions. Their impact is stronger in countries with stringent policy frameworks, such as the UK and Canada, illustrating the importance of well-designed, enforceable, and comprehensive environmental policies.
4. Green Innovation and Financial Development: Technological innovation, measured through green patents and R&D expenditures, exerts a clear negative effect on emissions.

This effect is further amplified in countries with well-developed financial markets, which facilitate the financing and diffusion of clean technologies, underscoring the interplay between innovation and financial development in promoting sustainable growth.

5. Consumption-Based vs. Production-Based Emissions: The analysis reveals evidence of carbon leakage in some countries, particularly the UK and France, emphasizing the necessity of considering consumption-based emissions alongside production-based measures for a more complete assessment of climate performance and policy effectiveness.

Policy and Economic Implications

The results of this study carry significant implications for climate policy design and economic planning in G7 countries. First, they highlight the necessity of an integrated policy approach, in which environmental regulations, fiscal instruments, and technological incentives work in synergy. Carbon pricing mechanisms, such as carbon taxes and emissions trading systems, are shown to be effective in reducing emissions, but their impact is maximized when combined with complementary measures that stimulate green innovation and investment.

Second, the findings underscore the critical role of technological advancement in decoupling economic growth from carbon emissions. Policymakers should prioritize the promotion of green research and development, facilitate the diffusion of low-carbon technologies, and incentivize private-sector investment through well-structured financial instruments. Well-developed financial markets that channel capital towards sustainable technologies can amplify the environmental benefits of innovation, ensuring that economic growth proceeds along a low- carbon trajectory.

Third, the study emphasizes the importance of a strategic energy transition. Reducing reliance on fossil fuels while expanding the share of renewables is crucial to lowering emissions intensity across sectors. Policies that accelerate renewable adoption, enhance energy efficiency, and modernize energy infrastructure are essential for achieving both short-term mitigation targets and long-term decarbonization goals.

Finally, the analysis draws attention to the challenge of carbon leakage, particularly in economies with high levels of trade and consumption-based emissions. Policymakers must consider not only domestic emission reductions but also the international flows of carbon embedded in imported goods. Effective climate strategies should integrate measures to prevent leakage, such as border carbon adjustments, trade-oriented environmental standards, and coordinated international climate initiatives.

In sum, the evidence from this study indicates that achieving sustainable emission reductions while maintaining economic competitiveness requires a holistic approach that aligns environmental policy, technological innovation, financial development, and energy transition strategies. By adopting such an integrated framework, G7 countries can reinforce their leadership in global climate mitigation and support a transition toward a resilient, low-carbon economy.

Contributions to the Literature

This study advances the literature by providing a holistic analysis of CO_2 emissions determinants in advanced economies, explicitly considering the combined effects of economic growth, energy structure, policy instruments, technological innovation, and financial development. By employing robust econometric techniques that account for cross-sectional dependence and heterogeneity, and by analyzing both production- and consumption-based emissions, the study delivers novel insights into carbon leakage, international trade impacts, and policy effectiveness.

Limitations and Future Research Directions

Despite its contributions, the study is subject to certain limitations. Its focus on the G7 countries may limit the generalizability of the findings to other regions. Data availability over the study period constrained the granularity of some variables, particularly policy and innovation indicators. Future research could expand the analysis to emerging economies, explore sector- specific emission dynamics, and incorporate more detailed measures of energy use and technological innovation. Additionally, integrating consumption-based accounting in broader cross-country analyses would provide further insights into global carbon flows and the effectiveness of international climate policies.

In conclusion, this study underscores the multifaceted nature of emission determinants in advanced economies and highlights the need for coordinated policy, technological, and financial interventions to achieve sustainable decarbonization. By offering both empirical evidence and practical policy guidance, it contributes to ongoing efforts to design effective strategies for mitigating climate change in the context of global economic development.

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