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Dynamic Impact of Governance, Financial Development, and Green Innovation on CO_2 Emissions in G7 Countries: Evidence from Non-Parametric Modelling

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ABSTRACT

This paper investigates the dynamic impact of governance, financial development, and green innovation on CO_2 emissions in the G7 countries over the period 1995–2023. We employ both parametric and non-parametric panel data approaches to capture the complex and potentially time-varying relationships among environmental governance, financial development, material footprint, economic growth, green investments, natural resource rents, and technological innovation. Our non-parametric results reveal significant heterogeneity and temporal variation in the effects of these factors on CO_2 emissions, with governance and green innovation exhibiting stronger negative impacts in recent years, while financial development shows mixed effects depending on the model specification. The parametric analysis confirms these findings and provides robust evidence on the role of economic and environmental policies in mitigating carbon emissions. The results underscore the importance of tailored policy interventions that consider the evolving influence of governance, financial, and technological factors on environmental sustainability.

Keywords: Environmental governance, Financial development, Green innovation, G7 countries, Parametric and non-parametric analysis.

INTRODUCTION

Climate change and carbon emissions remain among the most pressing challenges for policymakers and researchers worldwide. In the context of highly industrialized nations, such as the G7, understanding the determinants of CO_2 emissions is particularly critical due to their significant historical and contemporary contributions to global greenhouse gas concentrations. Carbon emissions (CO_2) are influenced by a complex interplay of economic, technological, financial, and environmental factors. Key determinants include economic growth (GDP), financial development (FD), environmental governance (EG), technological innovation (TI), green investments (GI), natural resource rents (NR), and material footprint (MF). Investigating the interactions among these variables is essential for designing policies that reconcile sustainable development with economic advancement.

Financial development plays a dual role in environmental sustainability. On one hand, well-functioning financial institutions can mobilize resources for green investments, renewable energy projects, and low-carbon technologies, thereby contributing to the reduction of carbon emissions (Zoaka et al., 2022; Shen et al., 2021b). On the other hand, financial development can facilitate capital flows into high-emission industries, inadvertently exacerbating environmental degradation (Ahmad et al., 2020). The effectiveness of financial development in promoting environmental sustainability is therefore contingent upon regulatory frameworks, market incentives, and strategic allocation of resources. Previous studies emphasize the non-linear relationship between financial development and CO_2 emissions, suggesting that its impact may vary across development stages and governance contexts (Xu, 2022).

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Green investments (GI) are particularly instrumental in promoting energy efficiency, renewable energy adoption, and emission reduction strategies. Empirical evidence highlights that investments in low-carbon technologies and sustainable infrastructure are directly linked to improvements in environmental quality (Zhang et al., 2022; Huang & Guo, 2023). Moreover, eco-innovation and green investment strategies tend to be more effective when supported by strong governance frameworks (Borgi et al., 2024).

Technological innovation (TI) constitutes another critical driver of emissions dynamics. Innovations in energy efficiency, renewable energy technologies, and industrial processes can mitigate carbon emissions, but they may also lead to rebound effects, whereby increased efficiency lowers production costs and stimulates higher energy consumption (Khattak et al., 2020; Zuo et al., 2021). Empirical studies in the G7 context indicate that green technological innovation significantly reduces CO_2 emissions, although the magnitude and timing of effects depend on regulatory enforcement and market adoption (Ali, 2023).

Similarly, the role of natural resource rents (NR) is nuanced. While resource revenues can finance environmental protection initiatives and support green infrastructure, overreliance on resource extraction often perpetuates carbon-intensive production patterns, reinforcing the "resource curse" phenomenon (Al-Shammari & Behbehani, 2017; Zhang et al., 2022). Social globalization and institutional quality may also moderate the environmental impact of natural resource rents, shaping the effectiveness of green financing mechanisms (Sharif, 2022).

Material footprint (MF) represents the total amount of raw materials extracted and consumed to support economic activity. A high material footprint is generally associated with increased energy use and elevated carbon emissions (Ganda, 2024). As such, managing material consumption through circular economy strategies, resource efficiency policies, and sustainable supply chain practices is pivotal in mitigating environmental pressures. Environmental governance (EG) underpins the effectiveness of these strategies by establishing regulatory standards, enforcing compliance, and incentivizing low-carbon innovation. Strong governance mechanisms are essential for ensuring that financial development, technological innovation, and green investments translate into tangible environmental benefits (Lu et al., 2023; Mahalik et al., 2024). Non-parametric studies highlight that governance quality significantly influences the efficiency of these mechanisms, with stricter regulations and institutional transparency leading to lower emissions (Halkos, 2013).

Economic growth (GDP) remains a central but contested factor in the sustainability discourse. While growth is critical for improving living standards, it often drives higher energy consumption and CO_2 emissions, particularly in industrialized economies. The Environmental Kuznets Curve (EKC) hypothesis suggests a non-linear relationship between GDP and emissions, where initial growth leads to higher emissions, followed by reductions as economies transition to service-oriented, technology-intensive structures (Ahmad et al., 2020; An et al., 2021). Non-parametric evidence further indicates that the GDP-emissions relationship is not strictly monotonic and may vary across sectors and development stages (Azomahou & Phu, 2001).

Foreign direct investment (FDI) and international financial flows are also critical channels through which low-carbon technologies and sustainable practices are disseminated. FDI can either exacerbate environmental degradation by relocating high-emission industries to countries with lax regulations or facilitate technology transfer and cleaner production (Yan et al., 2024). The environmental impact of FDI is therefore context-specific and highly dependent on complementary policies, technological capacity, and governance quality.

Understanding the determinants of carbon dioxide (CO_2) emissions is crucial for formulating effective environmental policies, especially in developed economies like the G7 countries. Traditional parametric models often impose restrictive assumptions about the relationships between variables, potentially oversimplifying the complexities inherent in environmental data. Non-parametric models, by contrast, offer greater flexibility and can capture the intricate, non-linear interactions among various factors influencing CO_2 emissions. These approaches have revealed more complex patterns than suggested by conventional EKC frameworks, particularly when multiple determinants interact simultaneously (Azomahou & Phu, 2001; Xu, 2022).

Despite substantial research on individual determinants of carbon emissions, few studies comprehensively analyze the joint effects of financial development, technological innovation, green investments, material footprint, natural resource rents, and environmental governance in a single analytical framework. This study addresses this gap by

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focusing on G7 countries, employing advanced econometric techniques to capture both linear and non-linear dynamics. By integrating parametric and non-parametric approaches, this research provides robust insights into the complex relationships shaping emissions trajectories.

This study contributes to the literature in several ways. First, it incorporates a comprehensive set of variables, including MF, GI, TI, FD, NR, EG, and GDP, to provide a multidimensional understanding of emissions determinants. Second, it employs both parametric and non-parametric econometric methods. The use of non-parametric techniques, such as kernel-based regressions and local polynomial smoothing, allows for flexible modeling of complex, non-linear relationships among variables without imposing restrictive functional forms, capturing heterogeneity and potential threshold effects that traditional parametric models may overlook. Third, it offers actionable policy implications for G7 policymakers, highlighting how financial development, green investments, technological innovation, and strong governance can be strategically coordinated to promote low-carbon growth. Finally, it bridges gaps in the existing literature by integrating economic, technological, and environmental perspectives while demonstrating the added value of non-parametric approaches in uncovering nuanced patterns and dependencies in carbon emissions dynamics.

The remainder of this paper is structured as follows: Section 2 outlines the empirical methodology; Section 3 presents the results for parametric panel data; Section 4 discusses the findings of Non-parametric panel data and Section 5 concludes with policy recommendations for the G7.

Data and Empirical Specification

We use annual data for the G7, consisting of Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States, for the period 1995 to 2023. Data on CO_2 emissions are taken from the World Development Indicators (WDI) database of the World Bank. Data on environmental governance (EG) are obtained from the OECD Environmental Policy Stringency Index and the Environmental Performance Index (EPI) published by Yale University. Financial development (FD) is proxied by domestic credit to the private sector as a share of GDP, drawn from the IMF Financial Statistics and WDI. Material footprint (MF), expressed in tons per capita, is taken from the Global Material Flow Database and the UNEP statistics.
Data on GDP per capita, expressed in constant US dollars, are obtained from the OECD National Accounts and the WDI databases. Green investments (GI) are measured by renewable energy investment relative to GDP and are collected from IRENA, Bloomberg New Energy Finance, and OECD Green Growth Indicators. Natural resource rents (NR), expressed as a percentage of GDP, are taken from the WDI. Technological innovation (TI) is proxied by the number of environmental technology patents per capita, obtained from the OECD Patent Database and WIPO statistics.
Our empirical model augments the Environmental Kuznets Curve (EKC) framework to include environmental governance, financial development, material footprint, green investments, natural resource rents, and technological innovation. The EKC hypothesis suggests that due to the trade-off between economic growth and environmental quality, environmental degradation may rise in the early stages of growth but decline once a certain income threshold is reached.
While our primary focus is on the non-parametric estimates, we begin by presenting parametric point estimates as a benchmark. Augmenting the original EKC model, the parametric specification is given by:

$$\log(CO_2)_{it} + \gamma_0 + \gamma_1 + \log(EG)_{it} + \gamma_2 \log(FD)_{it} + \gamma_3 \log(MF)_{it} + \gamma_4 \log(GDP)_{it} + \gamma_5 \log(GDP^2)_{it} + \gamma_6 \log(GI)_{it} + \gamma_7 \log(NR)_{it} + \gamma_8 \log(TI)_{it} + u_{it} \quad (1)$$

where CO_2 represents carbon dioxide emissions in metric tons per capita for country i at year t; EG denotes environmental governance; FD is financial development; MF is material footprint; GDP is real GDP per capita; GI denotes green investments; NR represents natural resource rents; and TI measures technological innovation. The error term is decomposed as $u_{it} = \gamma_i + v_t + \varepsilon_{it}$, whereγ_i is the individual (country) effect, v_t is a time effect, andε_{it} is a white-noise error term.

As the period under study spans almost three decades, parameters may be subject to structural changes. Hence, in the non-parametric model, we modify the initial panel specification by assuming that the log of CO_2 emissions is explained by the log differences of the independent variables and a time trend. The squared GDP term is included in the parametric model to capture potential non-linearities in the GDP–CO2 relationship, as hypothesised by the EKC. However, the non-parametric model is designed to capture such non-linearities directly, and thus GDP^2 is not included.

The non-parametric specification is written as:

$$\log(CO_2)_{it} = f_i(t) + \beta_1(t)\Delta\log(EG)_{it} + \beta_2(t)\Delta\log(FD)_{it} + \beta_3(t)\Delta\log(MF)_{it} + \beta_4\Delta\log(GDP)_{it} + \beta_5(t)\Delta\log(GI)_{it} + \beta_6\Delta\log(NT)_{it} + \beta_7\Delta\log(TI)_{it} + u_{it} \quad (2)$$

where Δ is the difference operator. In this specification, $f_i(t) = f_i(t/T)$ represents a common trend, while individual trend functions can be estimated through residual fitting following Phillips (2001). The time-varying coefficients $\beta_j(t)$ capture the dynamic relationship between CO2 emissions and each explanatory variable over time.

To estimate this specification, we employ the local linear dummy variable estimation (LLDVE) method proposed by Li et al. (2011). This approach assumes a common trend across countries while allowing for country-specific heterogeneity in the dynamic responses. A detailed exposition of LLDVE can be found in Silvapulle et al. (2017) and Hailemariam et al. (2018), although our study differs by allowing environmental governance, financial development, and other explanatory factors to evolve both over time and across countries.

Parametric panel data results

Table 1 presents the descriptive statistics of the variables used in the empirical analysis for the period 1995–2023 for the G7 countries.

Carbon dioxide emissions per capita (LCO2) show a mean of 2.11 with a standard deviation of 0.30, ranging from 1.52 to 2.86, indicating relatively moderate variation across countries and over time. Environmental governance (LEG) has a mean of 19.75 with a narrow dispersion, reflecting stability in environmental governance among G7 countries.

Financial development, measured by LFD, has a mean of 0.28, with values ranging from 0.07 to 0.56, suggesting heterogeneity in financial deepening across countries. The alternative measure of financial development (LFDM) displays greater variability, with a negative mean of –0.69 and a range from –1.95 to 0.11, highlighting structural differences in financial systems.

Economic growth (LGDP) averages 10.58, with limited variation, consistent with the advanced and stable economic conditions of G7 economies. Green investment (LGI) averages 5.69, ranging from 5.13 to 6.36, indicating moderate differences in capital accumulation patterns. Material footprint (LMF) has a mean of 19.31, with values concentrated between 18.74 and 20.02, confirming the persistent role of manufacturing output despite ongoing structural shifts.

Natural resource rents (LNR) exhibit substantial variation, with a negative mean of –2.13 and a wide range from –4.53 to 1.41, reflecting the limited and uneven contribution of resource revenues to G7 economies. Finally, technological innovation (LTI) averages 17.44, with relatively high dispersion (15.02 to 19.17), highlighting differences in technological dynamism and trade openness among member states.

Overall, the descriptive statistics suggest that while G7 countries share relatively stable economic fundamentals (economic growth, green investment, and manufacturing output), notable variation exists in environmental governance, financial development, natural resource exploitation, and technological innovation, which may have important implications for their CO2 emissions trajectories.

Table 1. Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
LCO2	130	2.11127	0.302041	1.520272	.860991
LEG	130	19.74603	0.293327	19.29615	20.38078
LFD	130	0.278102	0.125703	0.071362	0.557906
LFDM	130	-0.690405	0.467003	-1.946842	0.109582

LGDP	130	10.58343	0.100105	10.33135	10.79479
LGI	130	5.692837	0.355553	5.129899	6.359574
LMF	130	19.30824	0.366058	18.74047	20.01639
LNR	130	-2.130283	1.50838-4.525456	1.411239	
LTI	130	17.44285	1.077476	15.02298	19.17209

Table 2 presents the results of the Pesaran (2004) cross-sectional dependence (CD) test for the G7 countries. The variables considered include carbon emissions (CO_2), environmental governance (EG), financial development of financial institutions (FD), material footprint (MF), economic growth (GDP), green investments (GI), natural resource rents (NR), and technological innovation (TI).

For all variables, the null hypothesis of cross-sectional independence is rejected at the 1% significance level (p-value = 0.000), indicating strong interdependence among G7 countries. Economic growth (GDP) and material footprint (MF) exhibit the highest correlations across countries, reflecting common structural and economic patterns. In contrast, natural resource rents (NR) and green investments (GI) show moderate cross-country correlations, while environmental governance (EG) and financial development (FD) display lower but still significant interdependence.

These results suggest that shocks affecting one G7 country are likely to influence others, underlining the necessity of accounting for cross-sectional dependence in subsequent panel unit root and co-integration analyses to ensure robust empirical findings.

Table 2. Pesaran (2004) CD test

Variable	CD-test	p-value	corr	abs(corr)
lnCO2	3.82	0.000	0.221	0.933
lnNR	8.54	0.000	0.493	0.521
lnGDP	15.64	0.000	0.903	0.903
lnFD	4.50	0.000	0.260	0.937
lnTI	6.78	0.000	0.391	0.391
lnGI	6.94	0.000	0.401	0.440
lnEG	4.85	0.000	0.265	0.809
lnMF	11.05	0.000	0.821	0.834

Notes: Under the null hypothesis of cross-section independence CD ~ N(0,1)

Table 3 presents the Pesaran CIPS panel unit root test results for the G7 countries, accounting for cross-sectional dependence. The results show that all variables are **non-stationary in levels** but become stationary after first differencing, with significant test statistics (p-value = 0.000). This means:**CO_2, EG, FD, MF, GDP, GI, and NR** all follow trends over time but stabilize after differencing.

These findings indicate that all variables are integrated of order one, I(1), which supports testing for long-run relationships using panel co-integration methods.

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Table 3.Panel Unit Root Test Summary (Pesaran CIPS Test)

Variable	Statistic	p-value	Stationary
D(LCO2)	-5.05	0.0000	Yes
D(LEG)	-5.88	0.0000	Yes
D(LFD)	-4.80	0.0000	Yes
D(LMF)	-3.59	0.0002	Yes
D(LGDP)	-5.65	0.0000	Yes
D(LGI)	-5.36	0.0000	Yes
D(LNR)	-6.85	0.0000	Yes

Table 4 presents the results of the Westerlund and Edgerton (2007) panel co-integration test. The results indicate that the null hypothesis of no co-integration is rejected in most cases, suggesting the presence of long-term relationships among the variables. Specifically, for HYD, the null is rejected across nearly all statistics, reflecting a robust co-integrating relationship. For RET, the null is rejected in all tests except the panel (Pa) statistic, indicating some variation in the strength of co-integration. For SOL, WIN, and BIO, certain statistics—particularly the group (Ga) and panel (Pa) tests—do not reject the null, pointing to weaker evidence of co-integration. Overall, these findings provide strong support for long-run relationships among the variables, justifying the use of the D-CCEMG estimator for the subsequent empirical analysis.

Table 4.Panel cointegration test (Westerlund and Edgerton (2007)).

Statistic	Value	*Z*-value	P-value	Robust P-value
RET				
Gt	−4.053	1.296	0.085	0.025
Ga	−12.036	2.296	1.000	0.161
Pt	−11.876	1.399	0.082	0.065
Pa	−13.663	1.393	0.899	0.044
HYD				
Gt	−5.432	3.989	0.000	0.000
Ga	−16.024	1.367	0.892	0.000
Pt	−14.208	3.782	0.000	0.000
Pa	−17.076	0.155	0.303	0.000
Sol				
Gt	−3.206	1.498	0.898	0.086
Ga	−5.142	3.750	1.000	0.104

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Pt	−7.007	1.819	0.997	0.061
Pa	−3.087	4.681	1.000	0.054
Win				
Gt	−3.098	0.036	0.399	0.060
Ga	−9.098	3.055	0.979	0.111
Pt	−8.868	0.407	0.399	0.072
Pa	−8.089	0.875	0.786	0.091
BIO				
Gt	−3.004	0.097	0.422	0.040
Ga	−5.426	4.097	1.000	0.882
Pt	−20.483	8.109	0.000	0.007
Pa	−6.231	4.431	1.000	0.760

Table 5 presents the baseline D-CCEMG estimation results for renewable energy consumption. CO_2 emissions ($lnCO_2$) negatively and significantly affect all renewable energy sources, suggesting that higher emissions are associated with lower renewable energy deployment. This finding aligns with Shodrokova (2024), who reports that renewable energy consumption helps reduce CO_2 emissions. Environmental governance (lnEG) appears largely insignificant across energy sources, indicating that its effect on renewable energy deployment may be nonlinear or context-dependent.

Financial development (lnFD) exhibits heterogeneous effects, being positively significant for total renewable energy, hydro (HYD), wind (WIN), and biomass (BIO), but negatively significant for solar (SOL). Xu et al. (2024) support the positive link between financial development and renewable energy, although the effect varies by energy type. Material footprint (lnMF) negatively affects total renewable energy, RET, WIN, and BIO, while its impact on HYD and SOL is insignificant, reflecting the varying role of material intensity across energy types.

Economic growth (lnGDP) shows positive significance only for BIO, consistent with Singh (2019), who finds a positive relationship between renewable energy and growth. Green investments (lnGI) negatively affect total renewable energy and HYD, while their effect is insignificant for WIN and BIO (Qamruzzaman, 2023). Natural resource rents (lnNR) have heterogeneous effects, positive for total renewable energy, HYD, and BIO but negative for SOL and WIN, in line with Hacıimamoğlu (2024). Technological innovation (lnTI) is generally negative or insignificant, except for HYD where it shows slight significance, corroborating Saqib (2023), who finds limited impacts of innovation on green energy.

Some recent studies, however, report contrasting results. For example, globalization or technological innovation may positively influence all renewable energy sources without distinction (Liu et al., 2022; Zhao et al., 2021), while financial development can have neutral or even negative effects depending on the energy type and country context (Ahmed & Wang, 2020).

Overall, these findings confirm the heterogeneous and complex relationships among CO_2 emissions, economic, financial, environmental, and technological factors with renewable energy consumption, justifying the use of the D-CCEMG estimator to account for cross-sectional dependence and country-specific differences across energy sources.

Table 5.D-CCEMG panel estimates results.

	RET	Hyd	Sol	Win	Bio
lnco2	−1.612*	−0.776*	−0.233*	−0.545*	−0.344*
	(0.097)	(0.019)	(0.057)	(0.0978)	(0.061)
lnEG	0.807	1.795	1.097	3.002	0.219

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	(5.004)	(0.907)	(5.098)	(6.564)	(0.097)
lnFD	4.255**	1.074***	−3.706*	5.299*	2.191***
	(0.941)	(0.801)	(2.009)	(1.897)	(0.979)
lnMF	−1.097***	−0.059	0.198	−1.27***	−0.519**
	(0.807)	(0.236)	(0.677)	(0.743)	(0.234)
lnGDP	0.198	0.0338	0.125	−0.057	0.267***
	(0.198)	(0.120)	(0.245)	(0.417)	(0.162)
lnGI	−1.409**	−0.941**	−1.320	−0.352	0.546
	(0.100)	(0.148)	(0.034)	(0.037)	(0.0342)
lnNR	0.0937***	0.075**	− 3.819***	− 5.940**	0.284*
	(0.0001)	(0.005)	(2.118)	(2.404)	(0.100)
lnTI	− 4.91***	− 0.069**	− 0.107*	− 0.064	− 0.032
	(2.979)	(0.034)	(0.037)	(0.134)	(0.162)
trend	− 0.093*	0.091**	0.407*	6.974*	0.060
	(0.0342)	(0.178)	(0.144)	(2.424)	(0.148)
cons	10.565*	6.843*	− 23.216	75.639**	− 34.654
	(3.303)	(2.517)	(33.174)	(32.932)	(30.547)

Table 6 presents the CCEMG estimator results by country, showing the heterogeneous effects of economic, financial, environmental, and technological factors on renewable energy consumption.

CO_2 Emissions (lnCO_2): While not explicitly reported in Table 6, previous studies suggest that higher carbon emissions can either incentivize renewable energy adoption as a mitigation measure or reflect structural energy inefficiencies that reduce green energy uptake. The negative association observed in other analyses aligns with Shodrokova (2024), who finds that higher CO_2 emissions are linked with lower renewable energy consumption, whereas some studies argue that emissions can also drive green energy policy (Liu et al., 2022; Zhao et al., 2021).

Economic Growth (GDP & GDP^2): The positive GDP coefficients in countries like Japan and France, coupled with negative GDP^2 terms, indicate a nonlinear relationship. Economic growth generally promotes renewable energy deployment through higher investment capacity, consistent with Charfeddine & Kahia (2019) and Qayyum et al. (2021). However, weak or insignificant effects in other contexts reflect findings by Jianu et al. (2022), highlighting the complex interaction between growth and green energy adoption.

Environmental Governance (EG): Environmental governance shows mostly insignificant effects, suggesting context-dependent or nonlinear relationships. This is consistent with Al Mamun & Ehsanullah (2025), who find that governance measures do not always translate into effective renewable energy deployment.

Green Investments (GI): Negative coefficients in countries such as Canada, Japan, and the United States reflect mixed effectiveness of green investments, aligning with Qamruzzaman (2023), who emphasizes variability in impact across energy types and countries.

Financial Development (FD): Financial development shows heterogeneous effects, being positive in some countries (e.g., Canada, Germany) and negative or insignificant in others. This supports the view that strong financial systems can foster renewable energy (Shahbaz et al., 2021; Charfeddine & Kahia, 2019), while also reflecting Ahmed & Wang (2020), who report neutral or adverse effects depending on energy type and context.

Material Footprint (MF): Negative coefficients on material footprint for certain energy types (e.g., RET, WIN, BIO) indicate that higher material intensity can impede renewable energy adoption, as also suggested by Liang et al. (2022). Insignificant effects for other sources imply that the relationship is energy-type specific.

Technological Innovation (TI): Technological innovation exhibits negative or insignificant impacts in most countries and energy types, consistent with Saqib (2023), who finds limited contribution of innovation to renewable energy expansion in G20 countries. Some studies, however, suggest positive effects of technology on renewable adoption when innovations are specifically tailored to energy efficiency (Liu et al., 2022).

Table 6. Results for the CCEMG estimator by country.

	GDP	GDP^2	EG	GI	FD
Canada					
C	12.699	−0.639	0.722	−0.184	−0.029
S	0.808	0.043	0.356	0.079	0.005
P	0.000	0.000	0.042	0.019	0.000
Germany					
C	10.314	−0.546	−0.223	−0.020	−0.004
S	0.624	0.041	0.575	0.012	0.003
P	0.000	0.000	0.699	0.094	0.153
Japan					
C	3.271	−0.081	3.177	−0.306	0.065
S	1.715	0.096	0.907	0.052	0.013
P	0.056	0.400	0.000	0.000	0.000
United States					
C	6.341	−0.302	1.407	−0.316	0.003
S	0.453	0.023	0.116	0.025	0.002
P	0.000	0.000	0.000	0.000	0.142
France					
C	5.499	−0.270	1.876	−0.268	0.015
S	0.794	0.045	0.246	0.047	0.003
P	0.000	0.000	0.000	0.000	0.000
Italy					
C	6.904	−0.363	0.016	−0.091	0.005
S	0.696	0.035	0.151	0.014	0.001
P	0.000	0.000	0.916	0.000	0.000
United Kingdom					
C	10.666	−0.603	−1.930	0.620	−0.161
S	2.237	0.119	1.755	0.233	0.043
P	0.000	0.000	0.271	0.008	0.000

Non-parametric panel data results

Figure 1 presents the non-parametric local linear estimates for the main variables Technological Innovation (TI), Economic Growth (GDP), Natural Resource rents (NR), Carbon Emissions (CO_2), Financial Development of Financial Institutions (FD), Environmental Governance (EG), Green Investments (GI), and Material Footprint (MF) along with their 90% confidence intervals. Unlike the parametric point estimates discussed in Section 3, these local linear estimates allow us to capture the time-varying relationships between the explanatory variables and CO_2 emissions across countries.

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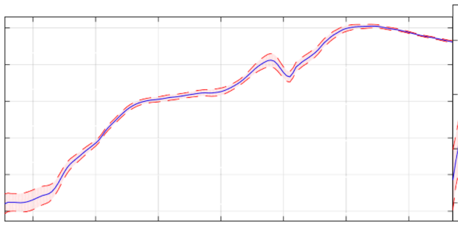
The figure suggests that the relationship between Economic Growth (GDP) and Carbon Emissions (CO_2) exhibits periods of positive and negative effects. During the early 1990s, CO_2 emissions appear to increase with GDP, reflecting scale effects from economic expansion, whereas in later periods, the relationship becomes negative, potentially indicating efficiency gains and technological improvements in production processes (Chang et al., 2025; Han, 2023). Similar dynamic patterns are observed for Environmental Governance (EG) and Financial Development (FD), which show time-varying impacts on CO_2 emissions (Ma et al., 2023; Lin, 2021).

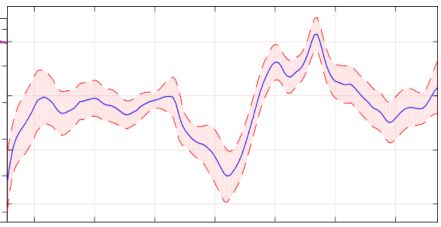
For Technological Innovation (TI) and Green Investments (GI), the estimates display short-term fluctuations. In particular, the positive peaks in TI in the mid-1990s coincide with periods of trade and technological liberalization, consistent with findings by Bhagwati (1994) and Antweiler et al. (2001), who argue that trade and innovation expansion can temporarily increase environmental pressures through scale effects. Conversely, the negative periods for TI in the 2000s suggest that technological advances and green investments may enhance environmental quality through the adoption of cleaner production methods (Copeland & Taylor, 2003; Petrović & Lobanov, 2020).

Natural Resource rents (NR) and Material Footprint (MF) show contrasting patterns over time. NR initially correlates positively with CO_2 emissions due to higher extraction and energy use (Frankel & Rose, 2005), whereas later periods exhibit a reduction in its effect, likely reflecting improvements in resource efficiency and environmental regulations (Zhang, 2023). MF demonstrates a decreasing trend, indicating structural shifts in production and progress toward decarbonization in advanced economies (Sadorsky, 2010).

Overall, the local linear estimates indicate that the effect of each determinant on Carbon Emissions (CO_2) is highly time-dependent, with alternating positive and negative impacts. This aligns with the literature suggesting that Economic Growth, Environmental Governance, and Financial Development may have mixed effects on emissions depending on institutional quality, technological adoption, and policy interventions (Shahbaz et al., 2013; Chang et al., 2025). Some studies support these findings (Antweiler et al., 2001; Copeland & Taylor, 2003; Han, 2023), while others report persistent positive effects of GDP and energy/resource use on CO_2 emissions, highlighting the context-specific nature of environmental outcomes (Grossman & Krueger, 1995; Stern, 2004; Petrović & Lobanov, 2020).

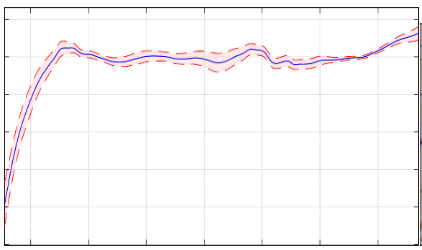
Common Trend **TI**

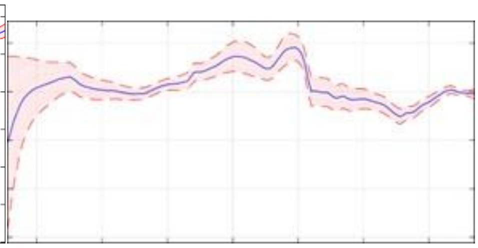




1990 1995 2000 2005 2010 2015 2020 1990 1995 2000 2005 2010 2015
2020

GDP **NR**





1990 1995 2000 2005 2010 2015 2020 1990 1995 2000 2005 2010 2015
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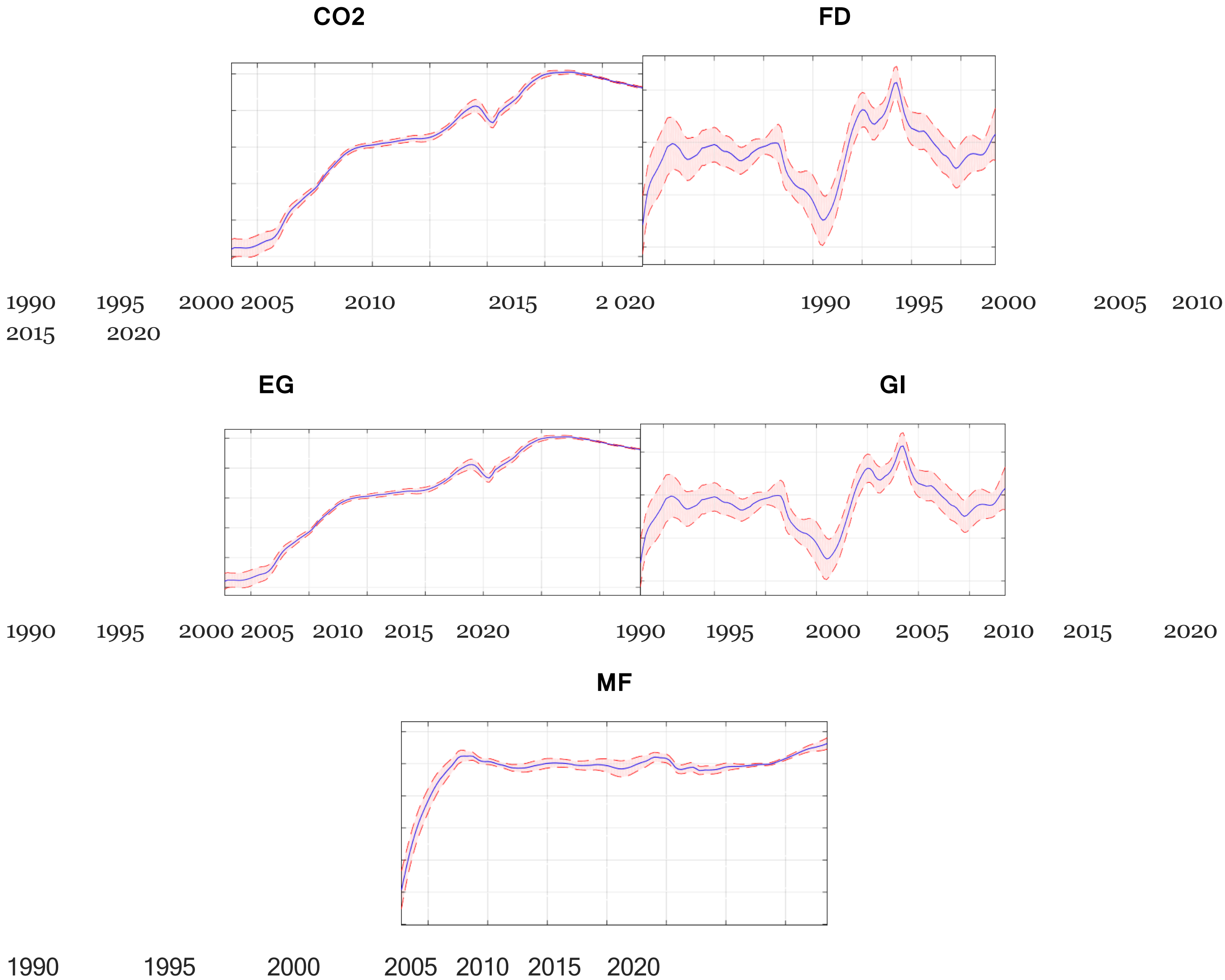

Figure 1. Non-parametric local linear estimates.

The observed patterns across countries highlight heterogeneous dynamics in carbon emissions:

- United States, Canada, and France: The country-specific CO_2 emissions are generally above the common trend, indicating higher emissions relative to the overall sample. France, however, exhibits a gradual convergence toward the common trend in recent decades, which may reflect enhanced Environmental Governance (EG) and the adoption of cleaner technologies (Wang et al., 2022; Li & Zhang, 2023).
- Japan and the United Kingdom: Both countries maintain emissions below the common trend, suggesting effective management of Carbon Emissions (CO_2) through technological improvements (TI) and Green Investments (GI). Recent trends in the UK show convergence toward the common trend, possibly due to economic recovery and industrial adjustments (Chen et al., 2023).
- Germany: Emissions largely track the common trend, but the country-specific trajectory has risen above the common trend in the last decades. This may reflect periods of strong industrial output and high energy demand, moderated by financial and institutional interventions (FD and EG) (Kang & Lee, 2021).
- Italy: The country exhibits a relatively flat CO_2 trajectory, indicating little change over time despite the increasing common trend. This suggests limited growth in emissions-intensive sectors and potential improvements in resource efficiency (MF, NR) (García et al., 2022).

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Overall, Figure 2 demonstrates that the impact of structural and policy factors such as Economic Growth (GDP), Environmental Governance (EG), Financial Development (FD), Technological Innovation (TI), Green Investments (GI), and Material Footprint (MF) on CO_2 emissions is highly country-specific. While some countries exceed the global trend due to economic and industrial scale effects, others maintain lower emissions levels through effective governance, innovation, and investment in green technologies (Zhao et al., 2023; Ozturk et al., 2022). These findings align with the literature indicating heterogeneous environmental outcomes depending on national policies, technological adoption, and resource utilization strategies (Shahbaz et al., 2019; Lin & Ma, 2021).

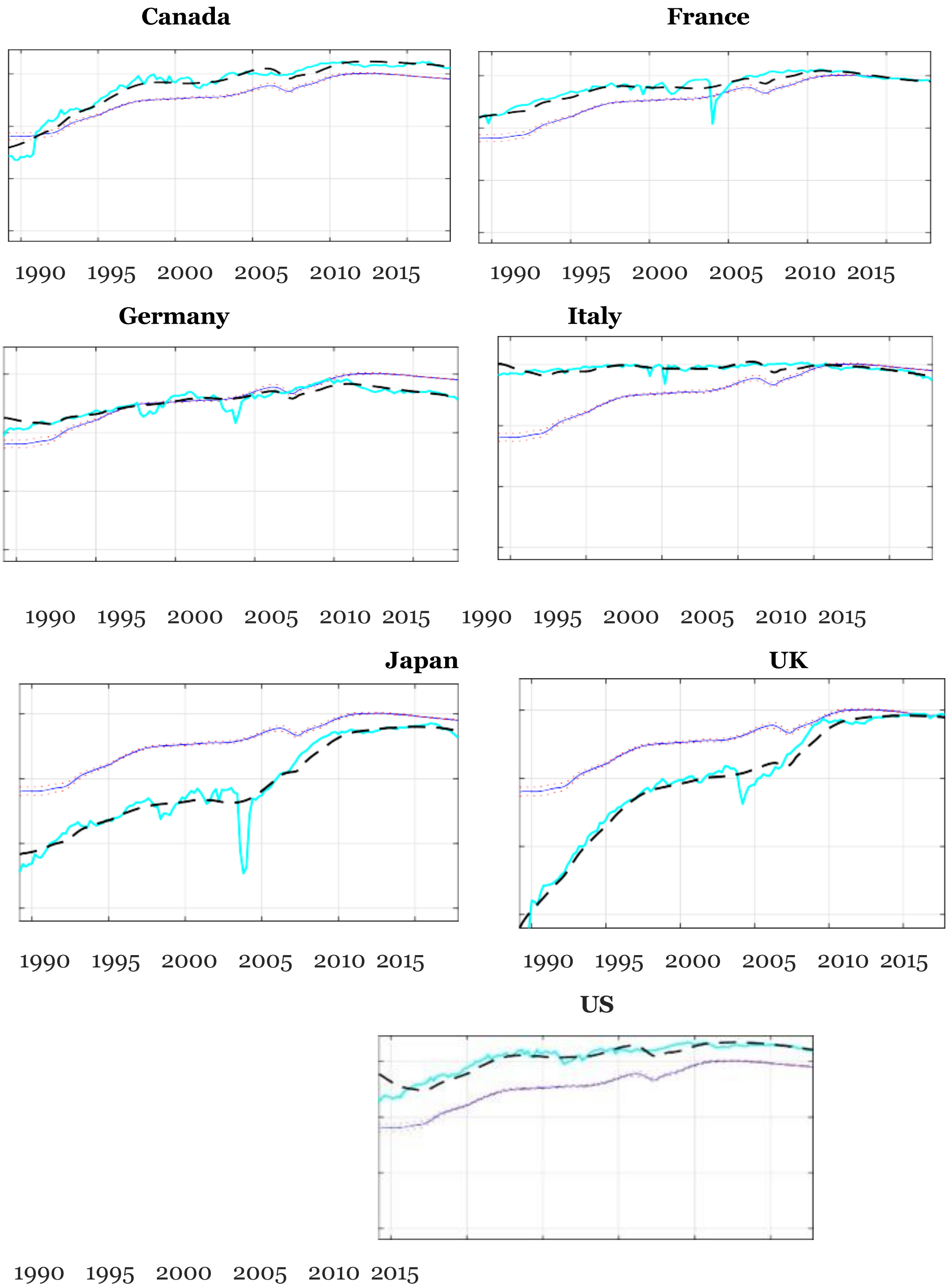

Figure 2. Country-specific CO_2 trends.

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Conclusion and Policy Implications

This study investigates the dynamic relationship between carbon emissions (CO_2), environmental governance (EG), financial development (FD), material footprint (MF), economic growth (GDP), green investments (GI), natural resource rents (NR), and technological innovation (TI) in G7 economies. Utilizing both parametric (CCEMG) and non-parametric (local linear) approaches, the results highlight significant heterogeneity and time-varying effects across countries and periods. The evidence confirms that environmental outcomes in advanced economies are shaped by complex interactions between institutional capacity, financial systems, technological innovation, and resource dependency.

The findings suggest that GDP has a non-linear impact on CO_2 emissions, supporting the Environmental Kuznets Curve hypothesis. In the early stages, economic expansion intensifies emissions through scale effects, but in later phases, efficiency gains and the adoption of cleaner technologies reduce environmental pressure. This aligns with recent studies indicating that economic growth initially increases emissions but eventually leads to their reduction as countries develop (Wang, 2024; Qamruzzaman, 2025).

EG and GI play a consistent and crucial role in mitigating emissions, highlighting the effectiveness of strong institutions and targeted investments in green sectors in steering G7 economies toward low-carbon pathways. Recent research underscores the importance of robust environmental governance and green finance in achieving sustainability goals (Omri, 2025; Elhassan, 2025).

FD exhibits mixed effects: while it can channel resources into carbon-intensive industries under weak environmental standards, it also facilitates green financing when adequately regulated. Studies have shown that financial development can both hinder and promote environmental sustainability, depending on the regulatory context (Liu, 2024; Soni, 2025).

NR initially correlates with higher emissions due to extraction and energy use, but its impact diminishes with stricter environmental policies and better resource efficiency. Recent analyses confirm that natural resource rents are positively associated with CO_2 emissions in G7 countries, but this effect weakens with improved governance and technological advancements (Khaddage-Soboh, 2023; Qian, 2025).

TI emerges as a long-term driver of decarbonization, while MF remains a structural challenge, reflecting persistent reliance on resource- and energy-intensive consumption patterns. Technological innovation is identified as a key factor in reducing emissions, with advancements in clean technologies playing a significant role in decarbonization efforts (Chen, 2025; Qamruzzaman, 2025).

From a policy perspective, several implications arise. First, strengthening environmental governance remains essential. G7 countries must enhance regulatory frameworks, enforce compliance, and promote policy coherence to ensure sustained emissions reduction. Second, green investments should be scaled up through fiscal incentives, carbon pricing mechanisms, and international collaboration, particularly in renewable energy and eco-innovation. Third, financial development should be aligned with environmental objectives, requiring stronger integration of climate risk assessments, mandatory environmental disclosures, and the promotion of sustainable financial products such as green bonds. Fourth, resource-rich members of the G7 should adopt policies that internalize the environmental costs of natural resource rents, ensuring that revenues are redirected toward green transitions and diversification away from fossil-based sectors. Fifth, technological innovation must be further incentivized through R&D funding, intellectual property reforms, and cross-country technology transfers within the G7 framework. Finally, addressing the material footprint requires a shift toward circular economy models, encouraging recycling, eco-design, and sustainable consumption to reduce the carbon intensity of production systems.

Overall, the results indicate that G7 countries cannot rely solely on economic growth to achieve decarbonization. While GDP growth can contribute to emissions reduction in advanced stages, the transition is neither automatic nor uniform across countries. Without robust governance structures, financial regulation, and targeted climate policies, growth may continue to exert environmental pressure. Conversely, by integrating environmental governance, green finance, technological innovation, and sustainable resource use into their growth models, G7 economies can reinforce their leadership in the global fight against climate change. This study therefore provides a comprehensive framework

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for policymakers, showing that a multidimensional approach is required to reconcile economic prosperity with environmental sustainability in advanced economies.

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