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Determinants of CO_2 Emissions in G20 Economies: The Role of Financial Development, Technological Innovation, Renewable Energy, and Demographic Dynamics

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Abstract

This study examines the long- and short-run effects of financial development, technological innovation, renewable energy consumption, economic growth, and demographic pressure on CO_2 emissions in G20 economies over 1990–2021 using a Panel Mean Group ARDL framework. Panel cointegration tests confirm the existence of a stable long-run relationship among the variables. The results show that renewable energy consumption is the most effective and immediate driver of emission reduction, while financial development and technological innovation contribute to decarbonization primarily in the long run. In contrast, economic growth remains strongly emission-intensive, reflecting persistent scale effects. Population size exerts upward pressure on emissions, whereas the effects of urbanization depend on the stage of economic development. Robustness checks using alternative financial and innovation proxies, CCE/DCCE, CS-ARDL estimators, sub-period analysis, and the exclusion of the United States and China confirm the stability of the findings. The results underscore the need for differentiated climate strategies that integrate renewable energy expansion, innovation-oriented finance, and institutional reforms across heterogeneous G20 economies.

Keywords: Financial development, CO_2 emission, renewable energy, PMG ARDL

JEL classification: C1, E5, O11, Q4; Q5

1. Introduction

Climate change has emerged as one of the most pressing global challenges, with its economic, environmental, and social consequences increasingly documented across scientific, financial, and policy domains (Shaffril et al. 2025; Bhatti et al. 2024). Despite growing international commitments, including the Paris Agreement and the United Nations Sustainable Development Goals, global carbon dioxide (CO2) emissions continue to rise at an alarming rate (Jiang et al. 2025; Friedlingstein et al. 2024). This trend is driven disproportionately by advanced and emerging economies. The G20 countries alone account for nearly 80% of global CO_2 emissions (IEA 2023), making any credible pathway toward global decarbonization contingent upon understanding the structural drivers of environmental degradation within these economies.

A growing body of literature identifies several key determinants of CO_2 emissions. Economic growth remains a dominant driver, as expanding industrial activity and rising energy demand intensify environmental pressure (Segarra et al. 2026; Singh et al. 2026; Jiang et al. 2025; Raihan et al. 2024). In contrast, renewable energy consumption is widely recognized as an effective mechanism for emissions mitigation through substitution away from fossil fuels (Singh et al. 2026; Bilgili et al. 2025). Technological innovation has also gained prominence as a catalyst for low-carbon transitions, with evidence suggesting that clean technologies and R&D investment can reduce emissions (Anwar et al. 2025; Khan et al. 2024). However, this relationship is not always straightforward, as innovation-driven efficiency gains may induce rebound effects that offset environmental benefits (Yu et al. 2022).

Financial development represents another contested channel. While some studies argue that well-functioning financial systems facilitate green investment and accelerate technological diffusion (Hashmi et al. 2025; Dong et al. 2024; Habiba and Xinbang 2022), others suggest that credit expansion may instead reinforce carbon-intensive production structures (Zhang et al. 2025; Kayani et al. 2020).

Population dynamics constitute a fundamental driver of environmental pressure through scale effects on energy demand, land use, and resource consumption. Recent studies emphasize that population growth can amplify CO_2 emissions by increasing aggregate consumption and production, particularly in the absence of effective climate policies (Rahman and Salimullah 2026; Samways 2026).

Despite extensive empirical work, existing studies often examine these determinants in isolation, rely on static estimation techniques, or focus on limited regional samples. Consequently, the literature lacks a unified dynamic framework that simultaneously captures the joint effects of financial development, technological innovation, renewable energy adoption, economic growth, and population, particularly within highly industrialized economies responsible for the majority of global emissions.

To address this gap, the present study investigates the long- and short-run effects of technological innovation, renewable energy consumption, financial development, GDP per capita, and population size on CO_2 emissions in G20 countries over the period 1990–2021. The analysis employs the Panel Mean Group Autoregressive Distributed Lag (PMG-ARDL) approach, which allows for heterogeneity in short-run dynamics while estimating common long-run equilibrium relationships across countries. This framework is particularly suited to capturing adjustment processes in economies with diverse structural characteristics.

This study contributes to the literature in several important ways. First, it provides a comprehensive and integrated assessment of the main economic, financial, and technological drivers of CO_2 emissions within the G20, a group that has been largely underexplored in a unified dynamic setting. Second, by distinguishing between short-run and long-run effects, the PMG-ARDL approach yields policy-relevant insights that static panel models fail to capture. Third, the use of multiple proxies for financial development and technological innovation enhances the robustness of the findings. Finally, the results highlight a temporal asymmetry in sustainability transitions: while renewable energy adoption delivers immediate emissions reductions, the environmental benefits of financial development and technological innovation materialize gradually, underscoring the need for climate strategies that combine short-term energy reforms with long-term institutional transformation.

The remainder of the paper is organized as follows: Section 2 reviews the relevant literature; Section 3 describes the data and methodology; Section 4 presents and discusses the empirical results, and Section 5 concludes with policy implications and directions for future research.

2. Literature review

Research on CO_2 emissions has expanded substantially as scholars seek to identify the economic and structural determinants of environmental degradation and inform mitigation policies. The literature primarily emphasizes the roles of economic growth, financial development, renewable energy adoption, technological innovation, and urbanization, yet empirical evidence remains mixed and context-dependent across countries and periods.

Economic growth is among the most frequently cited drivers of CO_2 emissions, as industrial expansion, energy demand, and consumption intensity typically increase environmental pressure (Pradhan et al. 2024; Raihan et al. 2024; Nosheen et al. 2021). A large number of empirical studies report a positive association between GDP per capita and CO_2 emissions, particularly in rapidly industrializing contexts (Singh et al. 2026; Fasanya and Arek-Bawa 2025; Jiang et al. 2025; Pradhan et al. 2024; Raihan et al. 2024; Mikayilov et al. 2018). However, other findings suggest that this relationship may evolve as economies shift toward cleaner technologies and service-based structures (Narayan and Narayan 2010; Chaudhary and Bisai 2018). Overall, the dominant evidence indicates that economic expansion continues to exert substantial upward pressure on emissions, especially when the energy mix remains fossil-fuel dependent.

The environmental impact of financial development is also widely debated. One strand of literature argues that deeper and more efficient financial systems can reduce emissions by facilitating capital access for energy-efficient technologies, supporting green innovation, and improving firms' capacity to comply with environmental standards (Hashmi et al. 2025; Dong et al. 2024; Gokmenoglu and Sadeghieh 2019; Al-Mulali et al. 2015). Shahbaz et al. (2018) document that financial development, together with foreign direct investment and energy innovation, contributes to emissions reduction in France, while Abbasi and Riaz (2016) report similar evidence for Pakistan during the financial liberalization period. Habiba and Xinbang (2022) show that the environmental effect of financial development may differ across country groups, with market depth and institutional efficiency improving environmental quality in developed economies and producing heterogeneous effects in emerging economies. In contrast, other studies find that financial development increases emissions by stimulating credit-driven industrial activity and resource-intensive consumption (Habiba et al. 2021; Kayani et al. 2020; Hao et al. 2016; Sehrawat et al. 2015; Zhang 2011). A third strand reports insignificant effects (Omri et al. 2015; Jamel et al. 2017), implying that the finance–emissions nexus depends on institutional quality and the direction of capital allocation. Collectively, this evidence suggests that financial development is not inherently "green" or "brown," but conditional on financial structure and policy frameworks.

Renewable energy consumption is generally recognized as a central channel for emissions mitigation through substitution away from fossil fuels. Numerous studies document a negative relationship between renewable energy adoption and CO_2 emissions across regions. For instance, Liu et al. (2017) and Bhat (2018) report that renewable energy reduces pollution in BRICS countries, while Chandio et al. (2021) find that renewable energy improves environmental quality in China. Evidence from Pakistan using nonlinear ARDL (Riti et al. 2021) and from South Asia using panel approaches (Anser et al. 2021) supports similar conclusions. Nonetheless, some studies caution that the emissions impact of renewable energy may vary with energy composition, technological deployment, and scale effects (Apergis et al. 2010; Sinha and Shahbaz 2018), indicating the importance of considering both transitional dynamics and long-run equilibrium outcomes.

Technological innovation has also received growing attention as a mechanism for improving environmental performance by increasing energy efficiency and enabling cleaner production processes (Weitzman 1998; Yeh and Rubin 2012). Empirical studies commonly report that innovation proxies such as patent activity and R&D expenditure are associated with lower emissions (Anwar et al. 2025; Khan et al. 2024; Ben Abid et al. 2022; Sohag et al. 2015). However, other evidence highlights potential rebound effects or adverse outcomes when innovation is not oriented toward clean technologies or when efficiency gains increase production scale (Yu et al. 2022). Importantly, Yu et al. (2022) argue that innovation is more environmentally beneficial under stronger financial structures, suggesting that finance and innovation may operate as interdependent channels shaping environmental outcomes.

Recent evidence further indicates the complex interaction between technological innovation and environmental outcomes. Dunyo et al. (2024) examine the relationship between CO_2 emissions, technological innovation, and energy intensity for a panel of 58 countries. Accounting for cross-sectional dependence and endogeneity, the authors find that technological advancement generally contributes to emissions reduction; however, the environmental impact of innovation is moderated by economic and political uncertainty. In particular, while available technologies tend to reduce CO_2 emissions, R&D expenditures may increase emissions under heightened uncertainty. These findings suggest that the environmental effectiveness of innovation depends not only on technological capacity but also on macroeconomic and institutional conditions.

Population growth is widely recognized as an important driver of CO_2 emissions through its scale effects on energy demand and economic activity. Shi (2003) shows that demographic expansion has been a major contributor to the global increase in carbon emissions, as rising population levels increase aggregate consumption and energy use. Similarly, Sasana and Putri (2018) find that population growth significantly increases CO_2 emissions in Indonesia, highlighting that expanding populations intensify fossil energy consumption, particularly in developing economies. More recent studies also confirm that population dynamics amplify environmental pressure, especially in the absence of effective climate policies and clean energy transitions (Samways 2026; Rahman and Salimullah 2026). These findings suggest that population growth remains a key structural factor influencing carbon emissions, although its impact may depend on technological progress and energy structure.

Beyond population, urbanization represents a critical structural dimension shaping environmental outcomes. Urbanization exerts dual effects on environmental quality: it can exacerbate emissions through increased transport demand, infrastructure expansion, and residential energy consumption (Wang et al. 2016; Ouyang and Lin 2017), yet also promote efficiency gains via compact city structures and cleaner technology adoption (Singh et al. 2026; Huang et al. 2023; Zhang et al. 2017). These mixed findings indicate that the environmental impacts of finance, innovation, and urbanization are inherently dynamic and context-dependent.

Overall, while the literature provides valuable insights, it remains fragmented across individual drivers, regional samples, and methodological approaches. Many studies examine determinants in isolation, rely on static panel estimators, or do not distinguish between short-run adjustments and long-run equilibrium relationships, an important limitation given the potentially gradual effects of financial development and innovation. Moreover, evidence remains limited for highly emitting economies such as the G20 within a unified dynamic framework that can accommodate heterogeneity across countries.

To address these gaps, the present study examines the combined effects of financial development, technological innovation, renewable energy consumption, economic growth, and urbanization on CO_2 emissions in G20 countries over 1990–2021 using the PMG-ARDL approach. This method allows heterogeneous short-run dynamics while estimating common long-run relationships, offering a comprehensive assessment of sustainability determinants in major emitting economies and strengthening the policy relevance of the findings.

3. Methodology

In the empirical analysis, we utilize annual data for the period 1990–2021. The data are collected from multiple sources, including the World Development Indicators (WDI), and the International Monetary Fund (IMF). This study investigates the impact of technological innovation, renewable energy consumption, and financial development on environmental degradation across G20 countries.

The dependent variable is CO_2 emissions per capita (measured in metric tons per capita). The baseline set of explanatory variables includes patent applications as a proxy for technological innovation (TI), the financial development index (FD), economic growth measured by GDP per capita (GDP), renewable energy consumption (REC), and total population (POP), which captures the scale effect of demographic pressure on emissions. Urbanization (Urban), defined as the share of urban population in total population, is introduced only as a robustness variable to examine whether the results are sensitive to population structure rather than population size. All variables are transformed into natural logarithms to reduce potential problems of non-normality and heteroscedasticity (Vogelvang 2005). Table 1 presents the description of variables, data sources, and expected signs.

The baseline specification employs total population as the demographic variable, while urbanization is excluded from the baseline model and introduced only in robustness checks.

Baseline model (Population as main demographic variable)

The baseline specification can be expressed as follows.

Long-run model

$$\ln(CO2_{it}) = \alpha_i + \beta_1 \ln(FD_{it}) + \beta_2 \ln(TI_{it}) + \beta_3 \ln(GDP_{it}) + \beta_4 \ln(REC_{it}) + \beta_5 \ln(POP_{it}) + u_{it} \qquad (1)$$

Error-correction representation

$$\Delta\ln(CO2_{it}) = \phi_i[\ln(CO2_{it-1}) - \beta_1\ln(FD_{it-1}) - \beta_2 \ln(TI_{it-1}) - \beta_3 \ln(GDP_{it-1}) - \beta_4 \ln(REC_{it-1}) - \beta_5\ln\left(POP_{it-1}\right)\Big] + \sum_j \gamma_{ij}\Delta W_{it-j} + \varepsilon_{it} \qquad (2)$$

Where W includes .

$$\ln(CO2), \ln(FD), \ln(TI), \ln(GDP), \ln(REC), \ln(POP)$$

Where, i and t index represent the country and time dimension of the variables. Furthermore, $CO2$ represents $CO2$ emission, (dependent variable), FD: financial development index, TI: technological innovation, REC: renewable energy consumption, GDP: Growth Domestic Product per capita US $, POP: Total Population.

Table 1. Data description

Symbol	Variable	Definition and Measurement	Data sources	Expected sign
CO2	Carbon dioxide emissions	Carbon dioxide emissions per capita (metric tons of CO_2 equivalent per capita), excluding land use, land-use change, and forestry (LULUCF),	WDI	
FD	Financial Development	IMF Financial Development Index (0–1 scale)	IMF	+/-
TI	Technological Innovation	the number of patent applications	WDI	-
REC	Renewable Energy Consumption	Renewable energy consumption (% of total final energy consumption)	WDI	-
GDP	Economic growth	GDP per capita (constant 2015 US$)	WDI	+
POP	Population	Total Population (millions)	WDI	+
Urban	Urbanization	Urban population (% of total population)	WDI	+

To provide an intuitive illustration of the underlying dynamics and cross-country heterogeneity, we complement the descriptive statistics with joint time-series plots for key variables. Figures A1–A3 in the Appendix represent the evolution of financial development, technological innovation, CO_2 emissions, and renewable energy consumption across G20 countries over the sample period. These visualizations indicate substantial heterogeneity in levels, growth trajectories, and volatility across countries, as well as common long-run patterns such as the general rise in renewable energy consumption and divergent CO_2 emission paths. The figures also provide preliminary evidence of structural shifts and non-linear dynamics, thereby motivate the use of dynamic panel techniques that account for heterogeneity and cross-sectional dependence.

Table 2 reports the descriptive statistics of the variables used in the analysis, including the mean, median, standard deviation, minimum, and maximum values. The mean and median provide measures of central tendency, while the standard deviation reflects the dispersion of the data around the mean.The statistics reveal substantial variation across countries and over time, which is appropriate for panel data analysis and supports the reliability of the subsequent econometric estimations.

The descriptive statistics highlight notable cross-country heterogeneity in environmental, economic, and structural characteristics. The United States records the highest average CO_2 emissions (18.88 metric tons per capita), with a maximum value of 21.282, whereas India reports the lowest average emissions (1.2 metric tons per capita) and the minimum value of 0.664 in 1990. In terms of financial development (FD), the United States exhibits the highest average index value (0.853), while Australia records the maximum observed value (0.974) in 2007. Conversely, Türkiye shows the lowest minimum value (0.189), and Argentina has the lowest average level of financial development (0.311).

Regarding renewable energy consumption (REC), Brazil and India display the highest average shares of total final energy consumption (45.72% and 42.3%, respectively), with Indonesia recording the maximum value of 59.18%. In contrast, Saudi Arabia reports the lowest average share (0.016%). Technological innovation (TI) varies substantially across countries, with China exhibiting the highest average number of resident patent applications (396,829.3) and a peak value of 1,426,644 in 2021, while Saudi Arabia records the lowest average level (360.7). These patterns demonstrate the pronounced heterogeneity among G20 countries, reinforcing the suitability of the panel ARDL framework employed in the study.

Table 2. Descriptive statistics

Stats	Mean	Median	SD	Min	Max
CO_2	8.607	7.944	5.596	0.664	21.282
FD	0.575	0.542	0.214	0.189	0.974
GDP	21610.09	17045.17	16708.81	528.898	61829.84
TI	62272.32	5832	165414.7	16	1426644
REC	14.658	9.77	14.191	0.01	59.18
POP	215.801	69.153	359.155	16.005	1425.894
URBAN	71.667	77.222	16.199	25.547	92.229

Notes: CO_2 denotes carbon dioxide emissions per capita (metric tons); FD is the financial development index; GDP refers to GDP per capita (constant 2015 US dollars); TI denotes technological innovation measured by resident patent applications; REC represents renewable energy consumption as a percentage of total final energy consumption; POP denotes total population; URBAN refers to urban population as a percentage of total population.

Unit root test results

Panel unit-root tests are conducted to examine the stationarity properties of the variables, as non-stationary series may lead to spurious regression results. To this end, four panel unit-root tests are employed: Levin, Lin, and Chu (LLC), Breitung and Das (2005), and the second-generation tests of Pesaran (CADF and CIPS). The results are reported in Table 3 under both intercept-only and intercept-and-trend specifications.

Given the strong evidence of cross-sectional dependence, inference is primarily based on the second-generation CADF and CIPS tests, which are robust to common factors. The results indicate that CO_2 emissions, renewable energy consumption, population, urbanization, and GDP are non-stationary in levels but become stationary after first differencing, implying integration of order one, I(1). In the case of GDP, unit-root test outcomes are sensitive to the inclusion of a deterministic trend GDP appears stationary under the intercept-only specification but non-stationary when a linear trend is included. Given the trend-driven nature of economic output, GDP is therefore conservatively classified as I(1). In contrast, financial development and technological innovation are stationary in levels, indicating I(0) behavior. Although some first-generation tests occasionally suggest level stationarity for certain variables, these findings are not consistent across specifications and are therefore treated as supplementary. Importantly, none of the variables is integrated of order two. The resulting mixed I(0)/I(1) structure justifies the application of the PMG-ARDL framework in the subsequent analysis.

Table 3. Unit-root tests

a) Intercept

	Levin Lin and Chu t*		Breitung and Das test (2005)		CIPS test		CADF Test	
Variable	Level	First Diff	Level	First Diff	Level	First Diff	Level	First Diff
ln (CO2)	-2.625	-6.983***	5.0692	-11.175 ***	-1.580	-4.906***	-0.536	-7.641***
ln (FD)	-8.14***	-9.716**	3.1990	-9.816***	-2.28***	-5.187***	-3.484 ***	-10.251***
ln (TI)	-3.875***	-9.867**	5.7953	-7.602***	-2.919***	-5.119***	-4.335***	-10.340 ***
ln (REC)	0.143	-6.667***	4.8009	-9.921***	-0.396	-5.094***	5.922	-10.084***
ln (GDP)	-4.262***	-7.667***	8.5935	-7.887 ***	-2.159 **	-4.141 ***	-2.491***	-5.843***
ln (POP)	-4.391***	-6.036***	16.251	-3.762***	-1.401	-2.057*	0.227	-1.463*
URBAN	-6.093***	-11.395***	0.962	-7.075***	-1.370	-2.142**	-1.177	-2.770***

b) Intercept and trend

	Levin Lin and Chu t*		Breitung and Das test (2005)		CIPS test		CADF Test	
Variable	Level	First Diff	Level	First Diff	Level	First Diff	Level	First Diff
ln (CO2)	-0.677	-15.302***	3.260	-3.106***	-2.228	-5.013 ***	-0.160	-5.612***
ln (FD)	-2.754***	-14.779***	1.833	-9.872***	-2.93***	-5.063***	-2.913***	-8.560 ***
ln (TI)	3.492	-5.634***	2.999	-7.803 ***	-3.039 ***	-5.272 ***	-1.762 **	-9.832***
ln (REC)	-0.393	-13.261***	3.061	-5.669***	-2.323	-5.118***	0.435	-8.090***
ln (GDP)	-0.701	-14.389***	2.321	-2.148**	-2.260	-4.268 ***	-0.266	-4.600 ***
ln (POP)	-2.605***	-3.281***	14.113	-3.303 ***	-2.234	-3.303 ***	0.123	-4.905***
URBAN	-1.914***	-53.748***	1.644	-18.769 ***	-1.857	-5.419 ***	-1.501	-3.336***

*p<0.1; **p<0.05; ***p<0.01

Table 4 reports the results of Pesaran's (2015) cross-sectional dependence (CD) test for all variables included in the analysis. The null hypothesis of cross-sectional independence is strongly rejected at the 1% significance level for CO_2 emissions, financial development, technological innovation, economic growth, renewable energy consumption, population, and urbanization. The statistically significant CD statistics indicate the presence of substantial cross-country correlations, suggesting that these variables are jointly influenced by common global shocks, spillover effects, and shared structural trends. This finding is consistent with the globalized nature of economic activity, financial integration, technological diffusion, and climate-related policies. Accordingly, the presence of cross-sectional dependence justifies the use of second-generation panel unit-root tests and motivates econometric specifications that explicitly account for common factors across countries in the subsequent analysis.

Accordingly, the presence of cross-sectional dependence justifies the use of second-generation panel unit-root tests and supports the application of the PMG-ARDL framework with appropriate controls for common time effects, ensuring consistent estimation of both short-run dynamics and long-run relationships.

The Hausman test was used to determine whether a significant difference exists between the PMG and MG estimators. Under the test, the null hypothesis (H0) posits that the pooled mean group (PMG) estimator is more appropriate, while the alternative hypothesis (H1) suggests that the mean group (MG) estimator is preferred (Hausman 1978).

This study utilized the PMG-ARDL approach to investigate the long-term and short-term effects of financial development, technological innovation, renewable energy consumption, GDP, and population on CO2 emissions, serving as an indicator of environmental degradation. The PMG approach assumes homogeneity in the long-term coefficients across countries, while allowing short-term dynamics to vary. In contrast, the MG approach imposes no restrictions on short-term parameters, permitting greater variability. Notably, the Pool Mean Group (PMG) estimator demonstrated superior efficiency compared to the Mean Group (MG) estimator under the assumption of long-term homogeneity.

To determine the most suitable model between PMG and MG, the Hausman test was conducted (Hausman 1978). The results in table 5 showed no statistically significant difference in the estimated coefficients between the two approaches under the null hypothesis (H0), indicating that the PMG estimator is appropriate.

Table 4. Cross sectional dependence

Variable	CD-test	P-value	Mean ρ	Mean abs ρ
ln (CO_2)	6.662***	0.000	0.09	0.54
ln (FD)	52.125***	0.000	0.70	0.72
ln (TI)	21.737***	0.000	0.29	0.57
ln (REC)	4.784***	0.000	0.81	0.82
ln (GDP)	60.187***	0.000	0.06	0.54
ln (POP)	54.507***	0.000	0.74	0.87
URBAN	64.219***	0.000	0.87	0.87

Notes: Under the null hypothesis of cross-section independence, CD ~ N (0,1) P-values close to zero indicate data are correlated across panel groups. *p<0.1; **p<0.05; ***p<0.01

Table 5. PMG Hausman Specification Test.

Estimator	Stat.	p-Value
Mean Group	8.5275	0.1295
Dynamic Fixed Effects	6.1547	0.2914

Notes: Null hypothesis: Estimator is statistically similar to the PMG estimator

The test did not achieve statistical significance at the 5% level, indicating that the null hypothesis could not be rejected. Consequently, the PMG estimator was considered more reliable.

Co-integration test results:

To examine the existence of a long-run equilibrium relationship among the variables, we first apply the Kao (1999) residual-based panel cointegration test. As reported in Table 6, the ADF statistic is highly significant (ADF = −5.4636, $p < 0.01$), leading to a rejection of the null hypothesis of no cointegration. This result provides initial evidence of a stable long-run relationship among CO_2 emissions, financial development, technological innovation, economic growth, renewable energy consumption, and urbanization.

Table 6. Kao Residual Cointegration Test

Test Statistic	Value	p-value
Kao ADF Statistic	-5.4636	0.0000

Given the presence of cross-sectional dependence and potential heterogeneity across countries, we further validate this finding using the Westerlund panel cointegration test as a robustness check (Table 7). The Westerlund variance ratio statistic is significant at the 5% level, confirming the existence of cointegration for at least a subset of panel units. Taken together, the results from both the Kao and Westerlund tests consistently support the presence of a long-run cointegrating relationship, thereby justifying the subsequent estimation using the PMG-ARDL framework.

Table 7. Westerlund test for cointegration

Test	Statistic	p-value
Variance ratio	-2.0933	0.0182

Notes: Westerlund test. H_0: no cointegration; H_a: some panels are cointegrated. Number of panels = 19; Number of periods = 32. The test specifies panel-specific cointegrating vectors and AR parameters, includes panel means, and excludes a time trend.

4. Results and discussion

4.1 Baseline model

The Pooled Mean Group (PMG-ARDL) estimation results are reported in Table 8, distinguishing between long-run and short-run dynamics. The long-run coefficients provide clear evidence that financial development plays a constructive role in mitigating environmental degradation. The negative and statistically significant coefficient on (ln (FD)) implies that greater financial depth supports decarbonization across G20 economies. This finding is consistent with Paramati et al. (2018), Zafar et al. (2019), and Al-Mulali et al. (2015), suggesting that mature financial systems facilitate access to green financing and incentivize firms to invest in cleaner technologies. However, it stands in contrast to Sehrawat et al. (2015) and Zhang (2011), who documented a positive finance–emissions link in India and China when financial expansion disproportionately supported carbon-intensive sectors. The evidence, therefore, indicates that the environmental effect of finance is contingent on the quality of credit allocation.

These results suggest that well-developed financial systems facilitate investments in environmentally sustainable technologies and promote the adoption of green practices. Such financial infrastructure supports funding for renewable energy projects and environmentally friendly innovations, which, in turn, help mitigate CO2 emissions.

Technological innovation (ln(TI)) also exhibits a negative and statistically significant long-run effect on CO_2 emissions, confirming that innovation facilitates efficiency-enhancing and emission-reducing processes.

Table 8. The result of PMG ARDL

a) Long-run (Pooled) Coefficients

Variable	Model (1)	Model(2)
ln (FD)	-2.839*** (-6.486)	-0.063** (-2.445)
ln (TI)	-0.514** (-1.657)	-0.027** (-2.536)
ln (GDP)	2.305*** (11.611)	0.499*** (12.921)
ln (REC)	-1.988*** (-13.13)	-0.343*** (-11.416)
ln (POP)	-1.980 (-0.978)	
URBAN		0.056*** (9.037)

b) Short-run (Mean-Group) Coefficients

Variable	Model (1)	Model(2)
Cointeq	-0.160*** (-3.426)	-0.353*** (-5.104)
D.ln (FD)	-0.226 (-0.542)	-0.025 (-1.181)
D.ln (TI)	0.155 (1.272)	0.013 (0.443)
D.ln (GDP)	7.069*** (4.364)	0.580*** (5.769)
D.ln (REC)	-0.762*** (-2.709)	-0.113* (-1.767)
D.ln (POP)	2.024 (0.213)	
D.URBAN		0.018 (0.343)
C	32.157*** (3.537)	-1.844*** (-5.189)
Log-Likelihood:	267.603	1419.508

Notes: The model is estimated using the Pooled Mean Group (PMG) estimator with an unrestricted constant. The optimal lag structure, PMG(1,1,1,1,1,1), is selected according to the Akaike Information Criterion (AIC), including one lag of the dependent variable and one lag for each explanatory variable. *p<0.1; **p<0.05; ***p<0.01

This aligns with Ben Abid et al. (2022), Sohag et al. (2015), and Jaffe et al. (2008), who emphasize the role of innovation diffusion in lowering pollution, despite mixed findings in studies such as Yu et al. (2022), which warned of rebound effects under weak regulatory environments. Together, FD and TI results highlight the importance of innovation-oriented financial systems as a combined lever for decarbonization.

Technological change has long been recognized as a pivotal factor in addressing environmental challenges, significantly reducing pollution over time (Weitzman 1998). This reduction can occur through several channels, including transitions in fuel composition, the adoption of high-efficiency technologies, and the implementation of end-of-pipe solutions aimed at limiting environmental damage. Studies on climate change and energy consumption also emphasize the importance of technological progress in improving environmental performance (Yeh and Rubin 2012).

Moreover, research and development (R&D) initiatives have been instrumental in fostering technological innovation, leading to notable declines in CO2 emissions (Jones 2005). This aligns with arguments suggesting that advancements in technology are essential for addressing global environmental issues (Jaffe et al. 2008). While transboundary trade and economic growth can drive higher energy consumption, technological innovations have proven capable of offsetting these effects. For instance, Sohag et al. (2015) demonstrated how advancements in technology ultimately contribute to reduced CO2 emissions, highlighting their transformative potential in achieving sustainable development goals. Technological innovation has historically played a role in reducing environmental impact, recent studies suggest varying effects across different contexts and time periods. Nonetheless, there is consensus that research and development (R&D) and technological advancements are essential for addressing environmental challenges and promoting sustainability.

Economic growth (ln(GDP)) exerts the strongest positive long-run effect, confirming that current G20 growth trajectories remain energy-intensive and emission driven. This finding reflects the environmental cost of economic expansion, often linked to greater energy consumption and industrial activity. The economic growth directly leads to increased CO2 emissions, as a growing economy typically demands more energy resources. This is in line with Genç et al. (2022), Nosheen et al. (2021), and Mikayilov et al. (2018), who also observed that GDP expansion tends to pressure environmental quality in the absence of structural energy transition.

Conversely, renewable energy consumption (ln(REC)) displays the most powerful mitigating effect among all variables, underscoring its central role in long-term sustainability strategies. On the other hand, renewable energy usage exhibits a negative and statistically significant impact on CO2 emissions, underscoring the importance of investing in renewable energy to mitigate environmental degradation. This result is consistent with Al-Mulali and Ozturk (2015), Sinha and Shahbaz (2018), and Liu et al. (2017), who similarly identified renewables as the most direct channel for decarbonization. In relative magnitude, REC remains the dominant long-run driver of emission reduction, followed by FD and TI.

Renewable energy sources have long been recognized for their positive effect on environmental quality by reducing greenhouse gas (GHG) emissions (Bhattacharya et al. 2017). Additionally, investment in renewable energy has been identified as less carbon-intensive compared to traditional energy sources, as reported by the OECD in 2013. Therefore, promoting the adoption of renewable energy can enhance environmental quality and establish a global framework for sustainability.

In the baseline specification (Model 1), the coefficient on population is negative but statistically insignificant, suggesting that aggregate population size does not exert an independent long-run effect on per capita CO_2. This result indicates that demographic scale effects may already be captured by income and structural variables in the model.

To further explore demographic influences, population is replaced with urbanization in Model (2). The long-run coefficient on urbanization is positive and significant, suggesting that most G20 economies remain in a stage where urban expansion increases environmental pressure through infrastructure growth, energy demand, and transport networks. This aligns with Sufyanullah, et al. (2022), Ouyang and Lin (2017) and Wang et al. (2016).

Urbanization, the rapid expansion of cities, has become a hallmark of modern economies and societies. Since 2007, the global urban population has surpassed the rural one, rising from 1.35 billion in 1970 to 4.22 billion in 2018, and is expected to reach 6.6 billion (68% of the world's population) by 2050. This demographic shift has paralleled a sharp increase in CO_2 emissions, as urban areas produce around 60% of global economic output while accounting for nearly 70% of greenhouse gas emissions. Some studies emphasize that urban growth intensifies CO_2 emissions through infrastructure expansion, industrial activity, transportation systems, and higher household energy demand (Wang et al., 2016; Ouyang and Lin 2017). Evidence from emerging economies such as China, ASEAN, and BRICS indicates that urbanization generally worsens emissions due to rapid industrialization and high energy needs, whereas in advanced economies the effect appears weaker or even mitigated by technology and policies (Wang et al. 2022; Huang et al. 2023).

Importantly, the signs and significance of financial development, technological innovation, renewable energy consumption, and GDP remain unchanged, confirming the robustness of the core findings.

The short-run coefficients provide additional insights into adjustment dynamics. The error correction term is negative and highly significant, confirming the existence of a stable long-run equilibrium. Approximately 35% of deviations from equilibrium are corrected each year, indicating a moderate pace of adjustment toward environmental stability.

Short-run GDP effects remain positive and significant, suggesting that growth-driven emission spikes emerge immediately through intensified production and energy consumption. Renewable energy consumption continues to reduce emissions in the short run, although at a weaker magnitude compared to the long run. In contrast, short-term coefficients for FD and TI are statistically insignificant, confirming that their environmental benefits materialize gradually rather than instantaneously. This asymmetry indicates that renewable energy is the only policy lever capable of delivering both immediate and sustained emission reduction effects, whereas financial and technological pathways operate more slowly through capital reallocation and adoption dynamics

The analysis reveals that financial development and technological innovation play crucial roles in reducing CO2 emissions over the long term, while economic growth and renewable energy consumption have significant impacts in both the short and long term. The error correction mechanism highlights the adjustment process towards achieving long-term sustainability goals. These findings underline the importance of promoting financial and technological advancements and prioritizing renewable energy to address environmental challenges effectively.

4.2. Robustness

4.2.1 Robustness Check Using Different Proxies

To validate the above results, Table 9 presents four alternative PMG-ARDL estimations using different proxies for financial development (the Financial Market Index (FMI), the Financial Institutions Index (FI), and Domestic Credit to the Private Sector (DCPS)) and technological innovation (Patents, R&D expenditures).

The findings remain highly consistent across all specifications. Both FMI and FI exhibit negative and statistically significant long-run effects on CO2 emissions, with FI showing the strongest impact among all financial proxies. The result indicates that the maturity and efficiency of financial markets play a vital role in channelling investments toward green technologies and low-carbon projects.

The financial institutions index demonstrates the strongest long-run negative effect among all financial indicators, highlighting the critical role of institutional support in reducing emissions. This confirms that not only financial depth, but also financial institutional strength is instrumental in reducing emissions. The result suggests that well-established financial institutions provide robust frameworks for financing and supporting green initiatives, which significantly reduce environmental degradation over time.

DCPS remains negative but weaker, implying that the effectiveness of credit channels depends on whether lending is directed toward productive or sustainable investments. its impact on emissions reduction is less pronounced compared to broader financial indices.

Similarly, both patents and R&D expenditures serve as effective innovation proxies. R&D displays stronger mitigation effects compared to patents, suggesting that deeper innovation investment is more influential than patent volume alone. This result underscores the need for continuous innovation and investment in green technologies to achieve sustainability goals.

Renewable energy remains consistently negative and highly significant across all specifications, reinforcing its structural importance. GDP continues to be emission-driving across all models, signalling that growth without structural transition remains environmentally costly.

In the short run, renewable energy remains a key factor in reducing emissions, while GDP continues to drive short-term increases in CO2 output. These results highlight the importance of policies promoting renewable energy and innovation while addressing the environmental costs of economic development.

Across all robustness checks, financial development, technological innovation, and renewable energy consistently emerge as reliable long-term mitigation levers. GDP remains an environmental pressure point, while urbanization requires policy intervention to shift from emission-contributing to emission-moderating stages. The results provide robust empirical support for a sustainability strategy built on clean energy expansion, innovation-driven financial intermediation, and institutionally guided development.

Table 9. PMG ARDL Estimation Result

a) Long-run Coefficients

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ln (FMI)	-0.7215***	-0.6710**			-0.0981***	-0.185***		
	(-3.624)	(-2.219)			(-3.448)	(-6.773)		
ln (FI)	-1.5794***	-1.3071***			-0.1094***	-0,123*		
	(-3.942)	(-2.869)			(-1.702)	(-1.854)		
ln (DCPS)			-0.1162*	-0.1166**			-0.096***	-0.122***
			(-1.684)	(-1.96)			(-3.644)	(-4.062)
ln (TI)		-1.1637*		-0.3577	-0.0196**			0.0162
		(-1.769)		(-1.54)	(-2.005)			(-0.925)
ln (R&D)	-0.2123***		-0.1018**			-0.023***	-0.0322***	
	(-3.175)		(-2.343)			(-4.2078)	(-2.857)	
ln (GDP)	1.2355**	1.2637**	0.6187*	2.8947***	0.4949***	0.488***	0.413***	0.4405***
	(2.715)	(1.992)	(1.837)	(8.231)	(13.107)	(13.803)	(10.242)	(8.087)
ln (REC)	-1.4403***	-1.4161***	-1.6047***	-1.816***	-0.3857***	-0.406***	-0.312***	-0.296***
	(-17.291)	(-14.202)	(-26.822)	(-19.384)	(-13.789)	(-14.978)	(-9.951)	(-9.830)
ln (POP)	-9.4094	-10.9114	-4.9271	-3.8626				
	(-1.629)	(-0.997)	(-0.731)	(-1.503)				
URBAN					0.0514***	0.0453***	0.0056*	0.0068**
					(8.473)	(9.0726)	(1.911)	(2.150)

b) Short-run Coefficients

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Cointeq	-0.1886***	-0.1593***	-0.1729***	-0.169***	-0.360***	-0.376***	-0.3195***	-0.321***
	(-3.115)	(-3.202)	(-4.469)	(-4.786)	(-4.814)	(-4.673)	(-5.466)	(-5.839)
D.ln (FMI)	-0.1051	-0.2359			-0.0175	0.0115		
	(-0.379)	(-0.765)			(-0.508)	(-0.375)		
D.ln (FI)	0.3201	0.4759			0.0527	0.0482		
	(0.601)	(0.739)			(0.7129)	(0.585)		
D.ln (DCPS)			-0.1947	-0.2833			-0.000536	0.00337
			(-0.565)	(-0.755)			(-0.0236)	(0.1448)
D.ln (TI)		0.1867		0.1906	0.0154			0.0107
		(1.472)		(1.058)	(0.475)			(0.2819)
D.ln (R&D)	-0.0454		0.0081			-0.0012	-0.000337	
	-1.015		(0.033)			(-0.067)	(-0.0151)	
D.ln (GDP)	7.4327***	7.4502***	7.2796***	6.7773***	0.5503***	0.5678***	0.6609***	0.6184***
	(4.507)	(4.526)	(4.294)	(4.013)	(4.822)	(4.998)	(7.4038)	(6.439)
D.ln (REC)	-0.7273**	-0.7879**	-0.7801**	-0.8121**	-0.0959	-0.0897	-0.1069*	-0.113*
	(-2.199)	(-2.605)	(-2.064)	(-2.174)	(-1.473)	(-1.404)	(-1.732)	(-1.9283)
D.ln (POP)	5.6216	6.5475	2.236	2.6865				
	(0.486)	(0.621)	(0.249)	(0.398)				
D.URBAN					0.0166	0.0247	0.0417	0.0128
					(0.2778)	(0.369)	(0.691)	(0.212)
C	32.0899***	31.2549***	16.4841***	9.0418***	-1.6674***	-1.624***	-0.582***	-0.725***
	(3.179)	(3.246)	(4.527)	(4.74)	(-4.97)	(-4.733)	(-5.436)	(-5.685)
Log Likelihood	2.83.542	283.347	261.229	257.952	1441.588	1439.362	1379.115	1381.532

Notes: Deterministic component: unrestricted constant; lag selection based on AIC; one lag for the dependent variable and all regressors. *p<0.1; **p<0.05; ***p<0.01

4.2.2 Common-Correlated Effects and the Dynamic Common-Correlated Effects

Table 10 reports the estimation results obtained using the Common Correlated Effects (CCE) estimator (Pesaran 2006) and the Dynamic Common Correlated Effects (DCCE) estimator (Chudik and Pesaran 2015), which explicitly control for unobserved common factors and cross-sectional dependence across G20 countries. These estimators therefore provide a robustness check for the PMG-ARDL results by allowing heterogeneous slope coefficients and mitigating bias arising from global shocks, spillovers, and omitted common influences.

Across all model specifications, GDP exhibits a positive and highly significant effect on CO_2 emissions. This finding is robust under both CCE and DCCE frameworks and confirms that economic growth in G20 economies remains strongly carbon-intensive even after controlling for common global factors. The magnitude and stability of the GDP coefficient indicate that scale effects dominate efficiency gains, reinforcing the conclusion that economic expansion continues to exert substantial environmental pressure in the absence of deeper structural transformation.

In contrast, renewable energy consumption consistently shows a negative and statistically significant coefficient across all specifications. This result highlights renewable energy as the most effective and robust channel for mitigating CO_2 emissions, even when cross-sectional dependence and global shocks are accounted for. The persistence of this effect under both static (CCE) and dynamic (DCCE) specifications confirms that renewable energy adoption contributes to emission reduction both structurally and dynamically.

The lagged dependent variable in the DCCE models is positive and statistically significant, indicating strong persistence in CO_2 emissions over time. This dynamic dependence suggests that current emission levels are influenced by past emission trajectories, reflecting inertia in energy systems and production structures. At the same time, the presence of significant adjustment dynamics supports the appropriateness of a dynamic modelling framework.

With respect to financial development indicators, the coefficients are generally negative but statistically insignificant under CCE and DCCE. This contrasts with the significant long-run effects found under PMG-ARDL and suggests that, once common global factors are controlled for, the independent contribution of financial development to emission reduction becomes weaker. This result implies that financial development may operate indirectly through global financial conditions, international capital flows, or coordinated policy environments rather than through purely country-specific channels.

Regarding demographic factors, population size exhibits a positive and significant effect in several specifications, suggesting that population scale continues to place upward pressure on emissions once global common factors are accounted for. By contrast, urbanization is statistically insignificant across all models, indicating that its impact on emissions is not robust after controlling for cross-sectional dependence. This finding supports the view that population scale effects are more influential than population structure effects in explaining emission dynamics in the G20 context under common global shocks.

Overall, the CCE and DCCE results strongly corroborate the main conclusions from the PMG-ARDL analysis. Economic growth remains the dominant driver of emissions, renewable energy consumption is the most reliable mitigation channel, and CO_2 emissions exhibit substantial persistence over time. These findings confirm the robustness of the baseline results and underscore the necessity of coordinated international policies to achieve meaningful emission reductions.

Table 10. The Result of Common-Correlated Effects and the Dynamic Common-Correlated Effects

	The Common-Correlated Effects (CCE)					DCCE	
Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)
l.ln (CO2)						0.121** (2.05)	0.165*** (2.83)
ln (FD)	-0.088* (-1.67)	-0.027 (-0.7)				-0.0649 (-1.29)	
ln (FMI)			-0.030 (-0.49)	-0.0036 (-0.08)			
ln (FI)			-0.042 (-0.33)	-0.065 (-0.62)			
ln (DCPS)					-0.041 (-0.92)		-0.071 (-1.55)
ln (TI)	0.033 (0.62)	-0.017 (-0.46)	0.008 (0.24)		-0.019 (-0.53)	0.004 (0.08)	0.0036 (0.1)
ln (R&D)				-0.006 (-0.14)			
ln (GDP)	0.549*** (4.97)	0.630*** (5.35)	0.631*** (4.69)	0.519*** (4.9)	0.685*** (4.85)	0.488*** (4.24)	0.555*** (3.94)
ln (REC)	-0.248*** (-3.64)	-0.238*** (-2.97)	-0.214*** (-2.63)	-0.192*** (-2.44)	-0.205*** (-3.05)	-0.234*** (-3.94)	-0.187*** (-3.65)
ln (POP)	0.916** (2.05)				1.145** (2.26)	0.932* (1.91)	1.114** (2.29)
ln (URBAN)		0.009 (0.51)	0.011 (0.89)	-0.003 (-0.16)			
Cst	19.865 (1.11)	0.019 (0.01)	1.944 (1.36)	0.852 (0.61)	25.095 (1.47)	26.552* (1.77)	35.831** (2.19)
Fisher	1.64***	3.28***	2.65***	2.00***	1.87***	1.91***	2.01***
R-squared	0.31	0.34	0.33	0.39	0.28	0.3	0.26
R-squared (MG)	0.98	0.97	0.97	0.97	0.98	0.97	0.98
CD Statistic	-1.67*	-2.19**	-2.36**	-2.42**	-1.97**	-1.9*	-1.86*
Nb. Obs.	589	608	608	608	589	570	570

Notes: The table reports CCE and DCCE estimations using alternative proxies for financial development and technological innovation. Only specifications exhibiting statistically significant cross-sectional dependence (Pesaran's CD test) are presented, as the CCE framework is particularly relevant in the presence of common factors.*p<0.1; **p<0.05; ***p<0.01.

4.2.3 Cross-Section Augmented ARDL Model

Table 11 reports the estimation results from the Cross-Section Augmented ARDL (CS-ARDL) model using the Dynamic Common Correlated Effects Mean Group estimator, which controls for unobserved common factors and cross-sectional dependence across G20 countries. This approach, as developed by Chudik et al. (2016), provides a robustness check for the PMG-ARDL results by allowing heterogeneous short-run dynamics and long-run relationships while filtering global shocks and spillover effects.

Table 11. (Dynamic) Common Correlated Effects Estimator - Mean Group (CS-ARDL)

Variable	Coef.	Z	P>z
Short Run Est.			
Cons	-8.075**	-2.01	0.045
LD.ln (CO2)	-0.101*	-1.68	0.093
D.ln (FD)	-0.026	-1.13	0.260
D.ln (TI)	-0.004	-0.12	0.903
D.ln (GDP)	0.861***	9.17	0.000
D.ln (REC)	-0.182***	-2.85	0.004
D.ln (POP)	0.828**	2.42	0.016
Adjust. Term			
lr_ln(CO2)	-1.102***	-18.02	0.000
Long Run Est.			
lr_cons	-8.143*	-1.95	0.066
lr_ln (FD)	-0.025	-1.23	0.217
lr_ln (GDP)	0.834***	7.28	0.000
lr_ln (TI)	-0.007	-0.25	0.804
lr_ln (POP)	0.869**	2.45	0.014
lr_ln (REC)	-0.171***	-2.87	0.004
Observation	570		
Fisher	2.20***		
R-squared	0.48		
R-squared (MG)	0.35		
CD Statistic	1.83*		

*p<0.1; **p<0.05; ***p<0.01

The long-run coefficients indicate that economic growth (ln(GDP)) has a positive and highly significant impact on CO_2 emissions. This finding confirms that economic expansion in G20 economies remains carbon-intensive, even after controlling for global common factors. The magnitude of the GDP elasticity suggests that scale effects dominate technological and structural efficiency gains, consistent with the view that growth continues to exert substantial environmental pressure.

Renewable energy consumption (ln(REC)) exhibits a negative and statistically significant long-run coefficient, confirming its role as the most effective mitigation channel for CO_2 emissions. This result remains robust under CS-ARDL, indicating that the substitution of fossil fuels with renewable energy leads to persistent reductions in emissions, even when global energy and technological trends are accounted for.

The coefficient on population (ln(POP)) is positive and marginally significant, suggesting that population scale exerts upward pressure on emissions once common global factors are controlled for. This supports the scale-effect hypothesis, whereby demographic expansion increases energy demand and emissions, although the effect is weaker than that of GDP.

The short-run estimates reveal that GDP growth significantly increases CO_2 emissions, indicating that growth-driven energy demand affects emissions immediately. Renewable energy consumption continues to reduce emissions in the short run, demonstrating that renewable deployment provides both immediate and long-term environmental benefits.

The lagged dependent variable is negative and significant, and the adjustment term (lr_lco2) is negative and highly significant, confirming the existence of a stable long-run equilibrium relationship. The magnitude of the adjustment coefficient implies a rapid speed of adjustment, indicating that deviations from the long-run equilibrium are corrected quickly, although the coefficient exceeding unity suggests potential overshooting dynamics commonly observed in dynamic CCE models.

The joint F-statistic is highly significant, confirming the overall relevance of the model. The CD test indicates that cross-sectional dependence is adequately controlled, validating the use of the CS-ARDL framework. The R-squared values indicate moderate explanatory power, which is typical for heterogeneous panel models with common factor correction.

Overall, the CS-ARDL results strongly corroborate the PMG-ARDL findings: economic growth remains the primary driver of emissions, renewable energy is the dominant mitigation channel, and demographic scale effects are present but secondary. The insignificance of finance and innovation under CS-ARDL highlights the importance of global common factors in shaping environmental outcomes and suggests that coordinated international financial and technological policies are required to achieve meaningful decarbonization.

4.3 Sensitivity to Sub-Periods

To examine whether the baseline results are sensitive to major global economic and climate policy shifts, we re-estimate the model for two sub-samples: the pre- and post-2008 Global Financial Crisis and the pre- and post-Paris Agreement (2015) periods.

4.3.1 Pre- and Post-2008

The results, reported in Table 12, reveal that financial development exerts a negative and highly significant effect on CO_2 emissions in both sub-periods, confirming its mitigating role across time. Notably, the magnitude of the coefficient becomes substantially larger after 2008, suggesting that financial systems in G20 economies have increasingly supported environmentally sustainable activities in the post-crisis era. This pattern is consistent with the expansion of green finance instruments and tighter environmental disclosure standards following the crisis.

Technological innovation reduces emissions in the pre-2008 period but becomes statistically insignificant after 2008, indicating that innovation effects may have shifted toward indirect or longer-term channels, possibly through global technology diffusion and coordinated policy frameworks.

Economic growth remains positively and strongly associated with CO_2 emissions in both periods, confirming the persistence of carbon-intensive growth patterns. However, the GDP elasticity declines after 2008, implying a gradual weakening of the growth–emissions nexus as energy efficiency and cleaner technologies expand.

Renewable energy consumption exhibits a negative and significant effect in both periods, with a markedly stronger impact after 2008. This finding reflects the rapid scale-up of renewable energy capacity and cost reductions in the post-crisis period, reinforcing renewables as the most effective mitigation channel.

Population size is insignificant before 2008 but becomes negative and significant after 2008, suggesting that demographic scale effects have been

Table 12. Sensitivity to Subperiod Pre- and Post- 2008

	Before 2008		After 2008	
Variable	Coefficient	t-statistics	Coefficient	t-statistics
Long run				
In (FD)	-0.201***	-7.67	-1.246***	-8.13
In (TI)	-0.019***	-3.78	-0.024	-1.22
In (GDP)	1.012***	12.72	0.701***	5.35
In (REC)	-0.051*	-1.73	-0.339***	-18.76
In (POP)	-0.016	-0.16	-1.189***	-5.76
Short run				
Ecm	0.202***	2.52	0.167**	1.98
D.In (FD)	-0.053	-1.05	-0.161	-1.55
D.In (TI)	0.0089	0.31	-0.052	-0.58
D.In (GDP)	0.592***	4.23	0.681***	4.16
D.In (REC)	-0.223***	-2.8	-0.284***	-4.34
D.In (POP)	3.163	1.00	0.892	1.04
_cons	-1.606	-1.12	-2.592*	-1.78
Log Likelihood	843.076		678.841	
Observation	323		247	

*p<0.1; **p<0.05; ***p<0.01

increasingly offset by improvements in energy efficiency, urban infrastructure, and technological adoption in recent years.

Short-run dynamics further show that GDP growth immediately raises emissions, while renewable energy consumption reduces emissions in both sub-periods. The significant error-correction terms confirm the existence of stable long-run relationships and moderate speeds of adjustment toward equilibrium.

4.3.2. Sensitivity to the Paris Agreement (Pre- and Post-2015)

To evaluate whether the determinants of CO_2 emissions changed following the adoption of the Paris Agreement, the sample is divided into pre-2015 and post-2015 periods. The results reported in Table 13 reveal both stability and meaningful evolution in key relationships.

Financial development exerts a negative and statistically significant effect on CO_2 emissions in both periods, indicating that financial systems contribute to environmental improvement before and after the Paris Agreement. However, the magnitude of the coefficient becomes smaller after 2015, suggesting that while green finance continues to play a mitigating role, its marginal impact has weakened in the post-Paris era. This may reflect transitional adjustment costs associated with large-scale restructuring of financial portfolios toward sustainable activities.

Economic growth remains positive and highly significant in both sub-periods, confirming that G20 economies continue to follow growth trajectories that are largely carbon-intensive. Moreover, the GDP elasticity increases after 2015, implying that, despite international climate commitments, economic expansion still translates into higher emissions, and absolute decoupling has not yet been achieved.

Table 13. Sensitivity to the Paris Agreement (Pre- and Post-2015)

a) Long-run (Pooled) Coefficients

	Before 2015		After 2015	
Variable	Coefficient	t-statistics	Coefficient	t-statistics
ln (FD)	-0.073***	-2.524	-0.018*	-1.791
ln (TI)	0.561***	13.701	0.631***	18.198
ln (GDP)	-0.016**	-2.302	-0.021***	-4.725
ln (REC)	-0.154***	-7.656	-0.162***	-7.583
ln (POP)	-0.778	-1.525	-3.232***	-7.413

b) Short-run (Mean-Group) Coefficients

	Before 2015		After 2015	
Variable	Coefficient	t-statistics	Coefficient	t-statistics
COINTEQ	-0.475***	-7.897	-1.088***	-11.117
D.ln (GDP)	0.558***	6.905		
D.ln (REC)	-0.114*	-1.844		
D.ln (POP)	1.014	-0.269		
C	-8.121***	-8.069	-68.646***	-10.9428
Log-Likelihood:	1152.961		394.322	

*P<0.1; **P<0.05; ***P<0.01

Technological innovation consistently exhibits a negative and significant long-run effect on CO_2 emissions in both periods. Importantly, the magnitude of the innovation coefficient becomes larger after 2015, indicating that innovation has become a more powerful channel for emission reduction in the post-Paris era. This finding suggests that climate-oriented innovation policies and increased R&D support following the Paris Agreement have strengthened the environmental benefits of technological progress.

Renewable energy consumption shows a negative and highly significant effect on emissions before and after 2015, with very similar magnitudes across periods. This stability underscores renewable energy as the most reliable and robust mitigation channel, independent of policy regime, and confirms its central role in long-term decarbonization strategies.

Regarding demographic effects, population size is insignificant before 2015 but becomes negative and highly significant after 2015. This indicates that, in the post-Paris era, population growth is increasingly associated with lower emissions, possibly reflecting improvements in energy efficiency, urban infrastructure, and cleaner energy use that offset scale effects.

The error-correction term is negative and highly significant in both periods, confirming a stable long-run equilibrium relationship and faster adjustment toward equilibrium after 2015. In the short run, GDP growth continues to raise emissions, while renewable energy consumption reduces emissions, highlighting their immediate effects on environmental outcomes.

4.3.3. Sensitivity of the ARDL Results to the Exclusion of Major Emitters

To assess whether the baseline results are driven by the two largest emitters, China and the United States, we re-estimate the ARDL model after excluding both countries from the sample (Table 14). Comparing the results with the baseline PMG-ARDL estimates reveals a high degree of consistency. Financial development and renewable energy consumption continue to exert statistically significant negative effects on CO_2 emissions, while economic growth remains positively associated with emissions. Although the coefficient on technological innovation becomes statistically weaker, its sign remains unchanged, indicating that innovation-driven emission reductions are more concentrated in major innovation-intensive economies. The error-correction term remains negative and significant, confirming the existence of a stable long-run relationship. Overall, the exclusion of China and the United States does not alter the qualitative conclusions of the study, demonstrating that the baseline findings are not driven by these two countries.

Table 14. Robustness Analysis: ARDL estimates excluding China and the United States

a) Long Run Equation

Variable	Coefficient	t-Statistic	Prob.
ln (FD)	-0.077**	-2.08	0.038
ln (TI)	-0.025	-1.203	0.229
ln (GDP)	0.463***	5.545	0
ln (REC)	-0.311***	-9.357	0
ln (POP)	-0.716**	-2.009	0.045

b) Short Run Equation

Variable	Coefficient	t-Statistic	Prob.
COINTEQ01	-0.265***	-4.875	0
D(FD)	-0.047**	-2.169	0.031
D.ln(TI)	0.013	0.34	0.734
D.ln(GDP)	0.641***	7.427	0
D.ln(REC)	-0.134**	-1.99	0.047
D.ln(POP)	0.484	1.095	0.274
C	2.976***	4.86	0
Log likelihood	1250.534		

*$P<0.1$; **$P<0.05$; ***$P<0.01$

Conclusion

This study investigates the dynamic relationships between financial development, technological innovation, renewable energy consumption, economic growth, and demographic factors in shaping CO_2 emissions across G20 countries over the period 1990–2021. Employing a PMG-ARDL framework supported by cointegration tests and a wide range of robustness checks, including common correlated effects estimators, sub-period analysis, and exclusion of major emitters, the results confirm the existence of a stable long-run equilibrium relationship among the variables. The findings reveal substantial heterogeneity across countries while highlighting consistent long-run patterns relevant for climate policy in major economies.

The empirical results show that renewable energy consumption is the most effective and robust determinant of emissions reduction, exerting a significant mitigating effect in both the short and long run. In contrast, financial development and technological innovation contribute to decarbonization primarily through long-run structural channels, reflecting the gradual nature of capital reallocation and innovation diffusion. Economic growth remains strongly and positively associated with CO_2 emissions, indicating that scale effects continue to dominate efficiency gains in most G20 economies. Demographic factors also matter: population size generally increases emissions through higher aggregate demand, while urbanization exhibits context-dependent effects that vary with countries' development levels and institutional quality.

From a policy perspective, the results underscore the need for differentiated climate strategies across G20 economies. In high-income countries, policies should focus on accelerating advanced renewable energy deployment, deepening green financial markets, and supporting frontier clean innovation to achieve absolute decoupling between growth and emissions. In middle-income and emerging G20 economies, expanding renewable energy capacity and improving the environmental orientation of financial development are critical for achieving near-term emissions reductions, while technology diffusion and international climate finance play a central supporting role. Across all G20 members, aligning financial systems with environmental objectives and strengthening institutional frameworks remain essential for sustaining long-term decarbonization.

The findings highlight that renewable energy adoption, supported by innovation-oriented financial systems, constitutes the cornerstone of effective climate mitigation in major emitting economies. While economic growth continues to pose environmental challenges, the combined effects of clean energy, financial development, and technological progress offer a viable pathway toward sustainable development. Future research could extend this analysis by incorporating sectoral emissions, nonlinear demographic thresholds, or the role of digital and green financial technologies in enhancing climate resilience.

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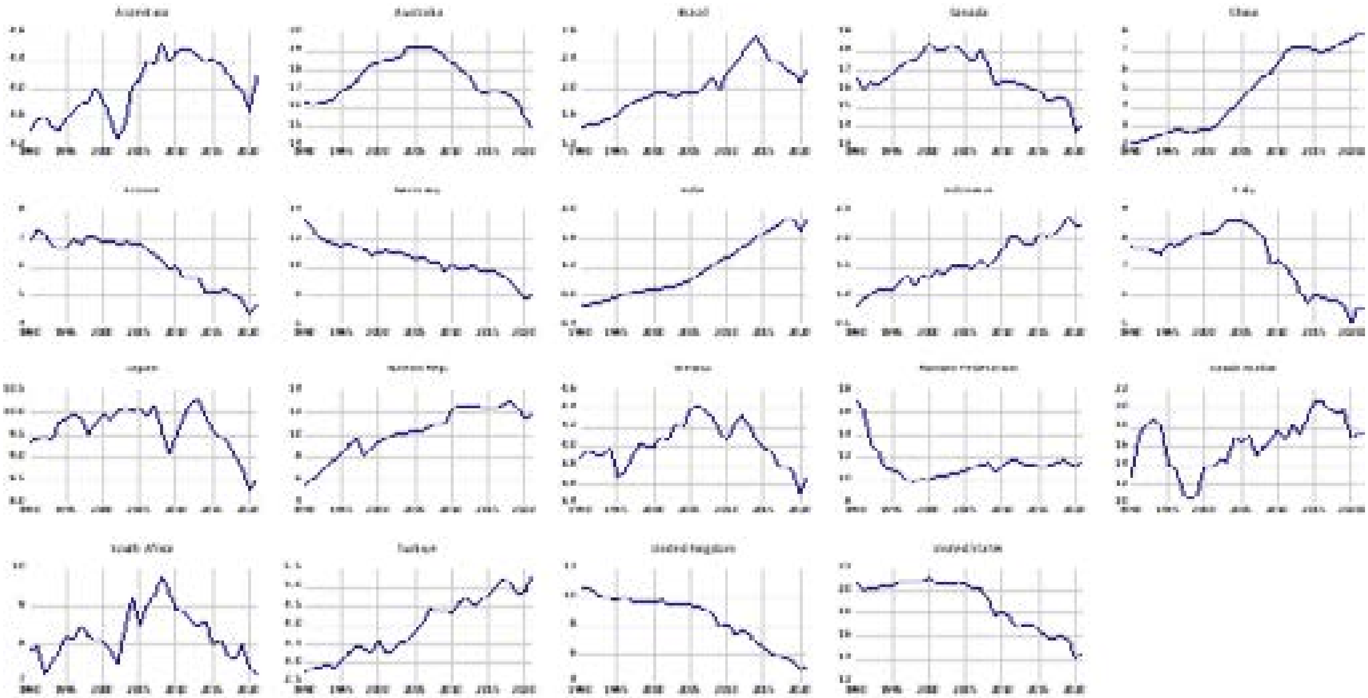
Figure A1. CO_2 emissions across G20 countries

This figure shows the evolution of CO_2 emissions per capita for G20 countries. While several advanced economies exhibit stabilization or declining emission trends, emerging economies display rising trajectories, underscoring the persistence of growth-driven emissions and cross-country divergence in environmental performance.

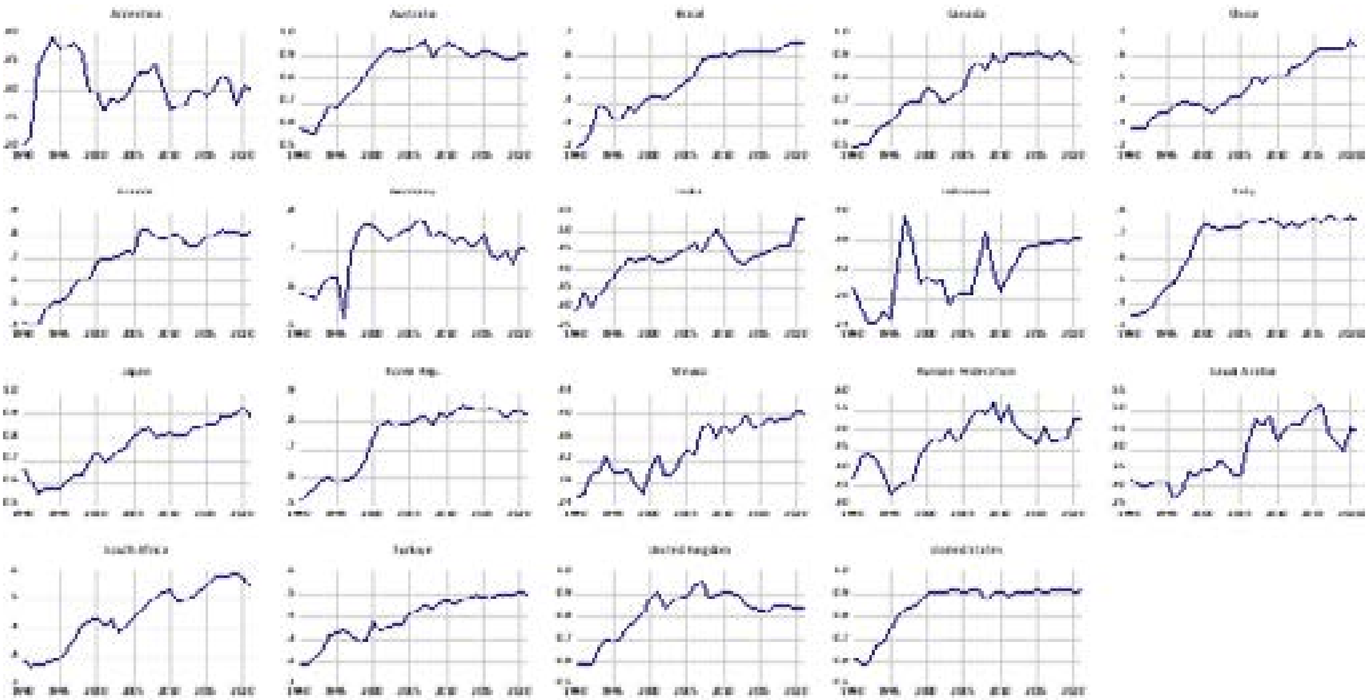


The figure contains 19 country-specific line charts showing CO_2 emissions per capita (metric tons) for G20 countries from 1990 to 2021. The x-axis represents years, and the y-axis represents CO_2 emissions per capita in metric tons. Emission levels and trends vary substantially across countries. The United States has the highest emissions among advanced economies, with a peak at approximately 21 metric tons per capita in the early 2000s before a decline to around 15 metric tons by 2021. Canada and Australia also present high emission levels, with declines after the mid-2000s. Germany, France, Italy, and the United Kingdom show continual downward trends throughout much of the sample period. Among emerging economies, China shows the most increase, rising from below 3 metric tons per capita in the early 1990s to approximately 8 metric tons by 2021. India illustrates a gradual increase from less than 1 metric ton to nearly 2 metric tons per capita. Indonesia and Türkiye also present upward trends over time. Brazil, Mexico, and South Africa display fluctuations around relatively stable levels, while Saudi Arabia and the Russian Federation maintain comparatively high emission levels with notable volatility.

Figure A2. Financial development and technological innovation across G20 countries

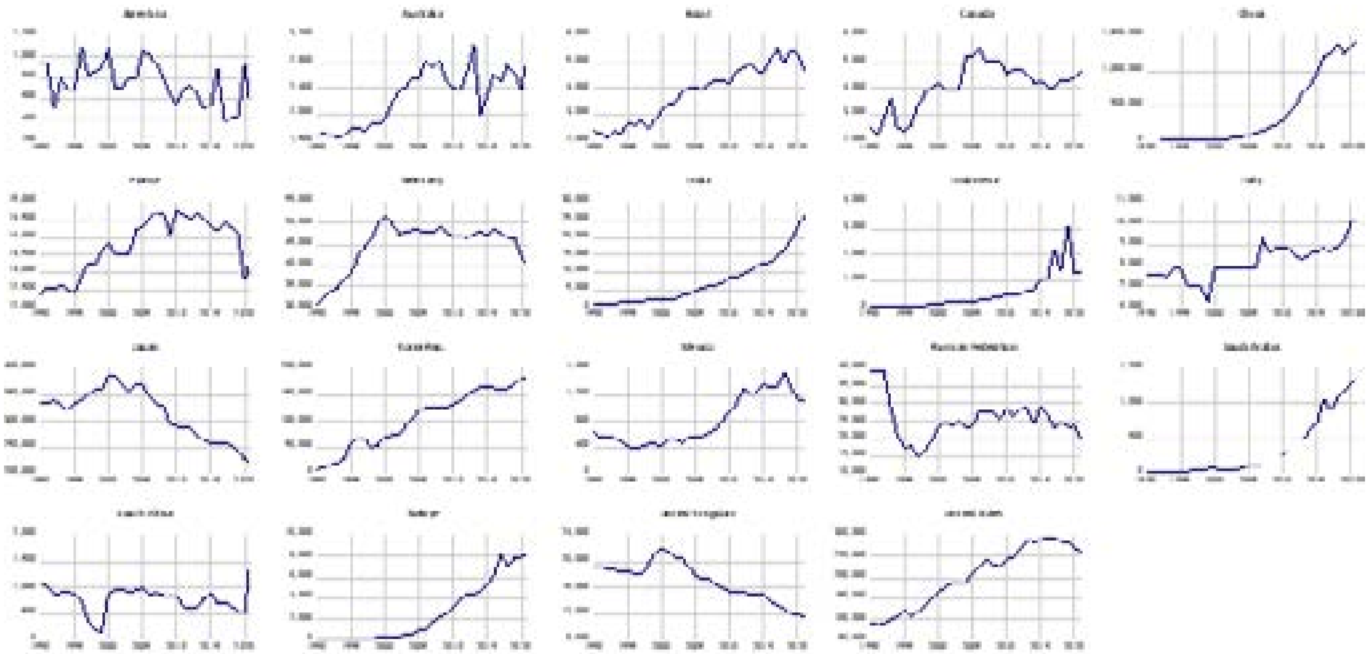
This figure presents country-specific time-series plots of financial development and technological innovation for G20 economies over the study period. The plots illustrate pronounced heterogeneity in financial deepening and innovation intensity, reflecting differences in institutional development, innovation capacity, and economic structure across countries.

Financial development



The figure presents 19 country-specific line charts of the IMF Financial Development Index, measured on a scale from 0 (least developed) to 1 (most developed), over the period 1990–2021. The x-axis represents years, and the y-axis represents the financial development index. Advanced economies generally record higher index values throughout the sample period. The United States maintains values close to 0.9 for most years, while Australia reaches a peak near 1.0 in the late 2000s. Canada, Japan, the United Kingdom, Germany, France, Italy, and Korea also show high levels, with mostly stable or gradually increasing trajectories. Emerging economies begin from lower levels but indicate an improvement over time. China, India, Brazil, Mexico, South Africa, Indonesia, and Türkiye show upward trends, and indicate gradual progress in financial sector development Turkiye records one of the lowest initial values in the sample, while Argentina maintains low index levels throughout the period.]

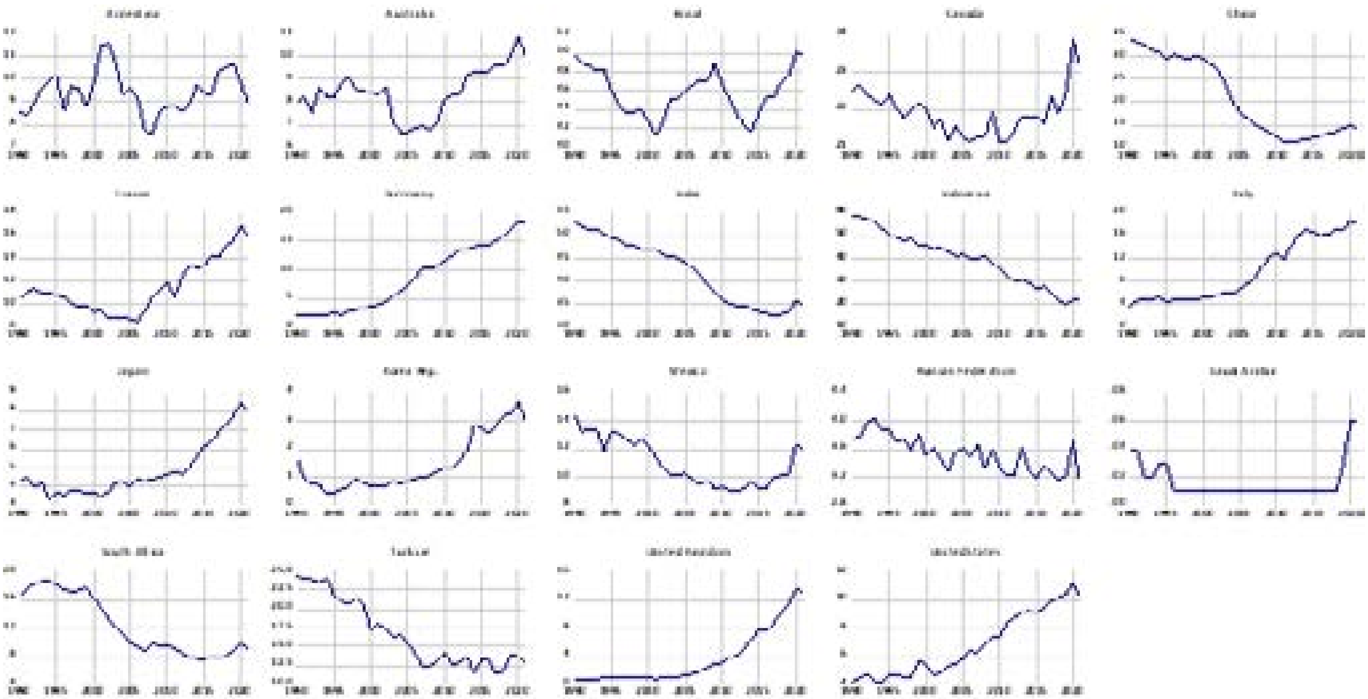
Technological Innovation



The figure presents 19 country-specific line charts of resident patent applications from 1990 to 2021. The x-axis represents years, and the y-axis represents the number of resident patent applications. China has seen the largest increase in patent activity, rising from very low levels in the early 1990s to more than 1.4 million applications by 2021. The United States also records high patent counts and shows a generally upward trend over the sample period. South Korea, and Germany maintain high levels of patent applications compared with most other countries, although their trends are more stable and show slower growth than China's. India shows a strong upward trajectory, particularly after 2005, while Turkiye, Saudi Arabia, and Indonesia also present visible increases during the later years of the sample period. Several countries, including France, the United Kingdom, the Russian Federation, Canada, and Mexico, show fluctuations over time with less long-term growth. Argentina, South Africa, and Saudi Arabia maintain low patent counts throughout much of the period.]

Figure A3. Renewable energy consumption across G20 countries

This figure depicts the share of renewable energy consumption in total final energy use across G20 countries. The plots reveal a gradual but uneven expansion of renewable energy adoption, with more pronounced increases observed in recent years, highlighting the heterogeneous pace of energy transition across countries.



The figure presents 19 country-specific line charts of renewable energy consumption as a percentage of total final energy consumption between 1990 and 2021. The x-axis represents years, and the y-axis represents the share of renewable energy in total final energy consumption. Brazil, India, and Indonesia show the highest renewable energy shares among the other countries. Indonesia begins the period with particularly high values but exhibits a gradual decline over time. Brazil maintains high levels even with fluctuations, while India shows a long-term downward trend followed by stabilization in later years. Several advanced economies, including Germany, France, Italy, Japan, the United Kingdom, and the United States, start from low renewable energy shares and show visible increases, particularly after the late 2000s. Germany, the United Kingdom, Italy, and the United States show some of the strongest upward trends among advanced economies. China exhibits a substantial decline in renewable energy share during the first half of the sample period, followed by stabilization and a small recovery after 2010. South Africa and Turkiye show declining trends over much of the period, while Russia remains relatively stable with moderate fluctuations. Saudi Arabia maintains very low renewable energy shares throughout most of the sample period, with a modest increase toward the end of the period.]