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The Effect of Sustainability Drivers on Economic Growth in G20 Countries: A Quantile Regression Approach

Mehdi Seraj *, Ata Pervar and Huseyin Ozdeser

Department of Economics, Near East University, Nicosia 99138, Turkey
* Correspondence: mehdi.seraj@neu.edu.tr

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Abstract: This study investigates the distributional linkages between core sustainability indicators and economic growth across G20 economies from 2000 to 2024. Employing second-generation panel econometric techniques that account for cross-sectional dependence and slope heterogeneity, we implement the Method of Moments Quantile Regression (MMQR) alongside a Feasible Generalized Least Squares (FGLS) baseline. The results obtained empirically show that Energy Intensity exhibits a positive marginal association with annual real GDP per capita growth that increases continuously up to the upper quantiles (0.537 to 0.968 percentage points), which is due to the dominance of production scale of industry during periods of fast economic development. In contrast, Per Capita CO_2 Emissions have an increasing negative impact on growth from median up to upper quantiles (−0.220 to −0.397 percentage points), which underlines the growing economic costs of environmental damage. Access to Electricity has regime-specific relevance and has statistically significant positive contribution to growth only in moderate and high growth regimes. Renewable Energy Consumption (REC) has a positive marginal impact on growth in low growth regimes (0.084 percentage points at $\tau = 0.05$), while its marginal contribution diminishes and becomes statistically insignificant in the upper quantiles. These distributional asymmetries demonstrate that uniform macroeconomic strategies are inadequate, underscoring the necessity of regime-targeted sustainability policies across the G20.

Keywords: economic growth; sustainability; energy intensity; CO_2 emissions; renewable energy; G20 countries; panel econometrics; quantile regression

1. Introduction

Pursuing sustainable economic growth is still the major goal of all G20 countries, which altogether represent about 85% of world GDP, 75% of global commerce, and almost all consumption of energy and emissions of greenhouse gases [1] Within the post-pandemic period, making a transition towards low-carbon development in line with macroeconomic stability becomes one of the key issues of the policy agenda [2,3]. Sustainability aspects like access to modern electricity (ATE), energy efficiency (EI), use of renewable energy (REC), openness to international trade (TRADE), and carbon dioxide (CO_2) emissions are no longer the external factors to the policies that define the productive potential of national economies [4].

One major reason for conflicting results in the existing body of empirical growth-sustainability studies is the prevalent use of conditional mean models (such as OLS, and standard Fixed Effects). In conditional mean regressions, parameters are assumed to be homogeneous throughout the distribution of growth rates, implying that sustainability determinants have uniform marginal effects, irrespective of the condition—whether the economy is stagnant, growing slowly, or rapidly expanding [5]. Theoretical macroeconomics suggests that such an approach is too narrow because the marginal productivity of energy, integration cost of renewables, and the marginal economic damage caused by the environment are fundamentally different in different stages of the business cycle.

To fill this void, this paper uses the Method of Moments Quantile Regression (MMQR) with individual fixed effects [6], where FGLS is used as a robust model. Evaluating the conditional distribution of annual real GDP per capita growth rates ($Q_\tau(GDP_{it}|X_{it})$ in terms of lower quantiles (τ = 0.05, 0.25), median quantiles (τ= 0.50), and upper quantiles (τ = 0.75, 0.95) will allow addressing the following research questions:

- How do the marginal growth effects of core sustainability determinants (ATE, EI, REC, TRADE, and CO_2) vary across distinct economic growth regimes in the G20 economies?
- What sustainability variables act as key catalysts of economic growth in low-growth regimes, and which determinants exhibit attenuating growth contributions during rapid economic expansions?

The current paper makes three main contributions. The first contribution is in extending from analysis of conditional mean relationships to identification of distributional asymmetries in sustainability determinants under different growth regimes. The second contribution is in applying the robust second-generation panel econometrics method which incorporates explicitly for the presence of cross-sectional dependence, slope heterogeneity and unobserved individual fixed effects. The third contribution is in formulation of policy guidelines targeted at specific regimes depending on the unique structural characteristics of advanced and emerging members of G20 countries. The rest of this paper is organized as follows: Section 2 reviews the literature and provides a summary matrix. Section 3 details data and methodology. Section 4 provides the empirical results and their interpretation.

2. Literature Review

2.1. Access to Electricity (ATE) and Growth: Catalyst vs. Scaling Infrastructure

Electrification theories are usually split into the "growth hypothesis" and "scaling hypothesis." The former argues that electricity availability is a necessary prerequisite for production while the latter claims that electrification is an endogenous outcome of economic development [7]. In empirical research performed in developing countries, one can trace one-directional causation from economic growth to infrastructure investment and not vice versa [7]. However, panel analysis of data in the G20 group and beyond indicates that energy availability drives industrial output and productivity, thereby confirming the growth hypothesis [8].

There is one aspect of disagreement that is yet to be resolved. In the case of rural electrification in developing countries, it is possible that the immediate gains might be small or statistically insignificant because of lack of complementary capital infrastructure. However, in the case of urban electrification, there is a lot of scale effect [9]. Both Best and Burke resolve this contradiction by contending that power access scales with economic growth rather than being a common binding constraint [10].

2.2. Energy Intensity (EI) and Growth: Scale Effects vs. Efficiency Gains

The interaction of EI and economic performance is characterized by the continuous balance between the structural "scale effect" and the technological "technique effect". The neoclassical and green growth approaches predict a negative correlation in which technological advances boost energy efficiency, thereby decreasing energy intensity per unit of production [11–13]. Yet empirical studies show significant non-linearities in relation to income levels. According to [14], the marginal responsiveness of EI to income drops markedly above certain development levels, while Semeniuk [15] notes that increases in aggregate productivity do not necessarily result in reduced energy intensity.

Within the framework of the G20, there is a divergence of industrialization patterns and resource bases. In spite of the rapid convergence of energy intensities in emerging G20 nations due to changes in the industrial structure [16,17] developed countries experience stable divergence of energy intensities [18]. This continuous divergence poses an empirical dilemma: Does energy intensity lead to output through production size during periods of peak economic growth, or is it a measure of inefficiency?

2.3. Renewable Energy (REC) and Growth: Production Stimulus vs. Integration Bottlenecks

There is a divide in the literature concerning the relationship between Renewable Energy Consumption (REC) and growth. On one hand, there is a body of literature that finds a robust positive bidirectional or unidirectional relationship, as investments in clean energy contribute to the development of industrial capabilities and reduce climate-related risks [19–21]. However, another strand finds the potential for short-run friction associated with substantial capital investment, intermittent energy production, and balancing costs that create diminishing marginal returns and short-run growth costs before generating long-term benefits [22,23].

Asymmetric adjustment patterns in the adoption of renewables in G20 countries have been found by researchers [24,25]. Although it is assumed in the literature on energy transitions that renewable energy contributes to growth with the same positive multiplier regardless of the stage of economic development, empirical research finds contradicting evidence.

2.4. Trade Openness and Growth: Propulsive Engine vs. Catalytic Handmaiden

While trade openness has been conventionally considered an engine for growth due to technology transfer and comparative advantage [26], empirical analysis in the context of developed and developing economic blocs suggests a different mechanism at play. Openness to trade is often found to be a catalytic "handmaiden" than an independent driving factor, with intervening variables like finance, institutions, logistics, and gross fixed capital formation playing important roles [27–29]. In the case of integrated economies, the growth gains from trade openness through direct contemporaneous channels get reduced.

2.5. Carbon Emissions (CO_2) and Growth: EKC Turning Points vs. Environmental Penalties

The connection between emissions of carbon and growth of output is embedded in the discussions about the Environmental Kuznets Curve (EKC). Even though some literature shows that there is an inverted U-shape connection between emissions and economic growth because emissions become decoupled at peak income levels [30,31], other researchers state that there is no absolute decoupling of the emissions, taking into account consumption-based trade and carbon lock-in [32,33]. In the G20 group, the cost of environmental degradation becomes increasingly higher due to regulations and carbon pricing.

2.6. Synthesis and Methodological Gap

From the collective literature (Table 1), it emerges that sustainability determinants have non-monotonic and non-static impacts on economies. Contradictions in the findings across studies are due to the wide usage of conditional mean estimators that reduce the regime-dependent dynamics to one parameter. The need to assess the impacts of these links using the quantile distributional approach is key to understanding how the growth impacts of ATE, EI, REC, TRADE, and CO_2 change with economic regimes.

Table 1. Overview of Core Literature on Sustainability Drivers and the Growth Nexus.

Driver	Theoretical Perspectives	Core Empirical Findings	Identified Literature Gap
Access to Electricity (ATE)	• Growth Hypothesis	• Positive long-run relationship in industrial panels [8]	Neglect of threshold effects across different growth and capacity regimes.
	• Scaling Infrastructure Hypothesis	• Weak direct causality in early rural stages [7,9]	
Energy Intensity (EI)	• Neoclassical Technique Effect (Efficiency)	• Reduced intensity at high income [14]	Failure of mean models to distinguish scale-driven energy demand from efficiency gains.
	• Industrial Scale Effect	• Divergence between advanced and emerging G20 panels [18,34]	
Renewable Energy (REC)	• Green Stimulus & Diversification	• Positive growth stimulus [19,21]	Lack of quantile-based evidence on diminishing marginal returns across growth thresholds.
	• Intermittency & Grid Balancing Bottlenecks	• Diminishing returns & integration costs at scale [22,23]	
Trade Openness (TRADE)	• Engine of Growth (Technology Transfer)	• Growth effects mediated by logistics and institutions [28,29]	Underexplored distributional variations during recessions versus economic expansions.
	• Catalytic "Handmaiden" Role	• Lower direct impact in mature open markets [35]	
CO_2 Emissions (CO_2)	• EKC Decoupling Hypothesis	• Evidence of EKC turning points [30,31]	Inability of aggregate mean models to capture rising marginal degradation costs at growth peaks.
	• Environmental Penalty & Regulatory Drag	• Persistent carbon lock-in and damage costs [32,33]	

3. Data and Methodology

3.1. Data

This research uses an annual balanced panel database with the G20 countries from 2000 to 2024. All macroeconomic and sustainability variables are sourced from the World Bank's World Development Indicators (WDI) database (see Table 2). There are two structural reasons that dictate choice of the sampling window:

- The sample period spans 2000 to 2024, representing the full temporal window with complete cross-country coverage across all five indicators for all G20 nations. Indicators were compiled from the World Development Indicators (WDI) and standardized across sources to ensure definition consistency, particularly for renewable energy shares and primary energy intensity following early-2000s reporting reforms.
- Completeness of Observations and Balanced Panel: In order to avoid sample attrition bias and to make sure that second generation panel estimators (such as Cross-sectionally augmented Im, Pesaran and Shin (CIPS) and Covariate-Augmented Dickey-Fuller (CADF) unit root tests, Method of Moments Quantile Regression (MMQR) estimator) are econometrically consistent, only countries with complete data profiles across all variables are included, yielding a balanced panel of 475 observations (N = 19, T = 25) with zero missing values.
- The dependent variable used in this analysis is real GDP per capita growth (GDP). The econometric specification does not follow the traditional aggregate neoclassical growth accounting approach but rather relies on an enhanced macroeconomic production function based on UN Sustainable Development Goals (SDGs).
- Access to Electricity (ATE-SDG 7.1): Constitutes the basic infrastructure requirement standing for the initial access to and modern energy capital needed for productive economic capability.
- Energy Intensity (EI-SDG 7.3): Stands for the energy conversion efficiency on a per unit of GDP basis and captures the technology technique effect and structural industry scale effect.
- Renewable Energy Consumption (REC-SDG 7.2): Constitutes the technological switch towards de-carbonized electricity generation and stands for the green capital investment stimulus and grid limitation.
- Trade Openness (TRADE-SDG 17 / SDG 8): Constitutes the main transmission mechanism for macro-structural effects of technological spillovers and resource allocation and external demand integration.
- Per Capita CO_2 Emissions (CO_2-SDG 13): Constitutes the initial environmental externality, pollution damage and carbon abatement costs associated with industrial growth.

Theoretical Context and Justification for the Choice of Variables:

Instead of employing the standard approach of using an aggregate neoclassical production function (Solow-Swan or Mankiw-Romer-Weil augmented model), our model deliberately uses the sustainability transition growth accounting approach that aligns with the UN's Sustainable Development Goals (Goal 7, Goal 8, Goal 13, and Goal 17). However, while traditional growth models focus on variables like gross fixed capital formation, human capital, and institutional indicators, their deliberate exclusion from our model is justified by the following three main reasons:

- Preservation of a Harmonized, Balanced Panel: The second-generation panel unit root tests (CIPS, CADF) necessitate a continuous and highly balanced panel. Cross-country human capital measures (for example, Barro-Lee) are five-yearly interpolated estimates, while institution databases (Worldwide Governance Indicators, for instance) suffer from break points and missing annual data from the beginning of the 2000s decade. Specifying the test to be limited to World Development Indicators ensures no data manipulation.
- Conventional measures of production and infrastructure are often correlated with primary energy consumption in G20 countries; thus, adding more covariates will likely result in overparameterization. A parsimonious set of structural variables prevents the problem of variance inflation (VIF) and guarantees valid estimation of moment conditions in MMQR.
- Structural Absorption via Individual Fixed Effects: Location scale fixed effect framework automatically controls for time-invariant omitted variables such as structural fundamentals like legal systems, quality of institutions, fixed geographic endowments, and human capital endowments.

The degree of variability for the different variables, as evident from Figure 1, is noticeable. ATE is highly concentrated for extremely high indices (median ~95–100%) with a secondary set of indices for low values. This is representative of the overall adoption of electricity in most of the G20 countries, together with a set of nations with limited electricity accessibility. TRADE has the highest variability, with a tail extending beyond 100%, giving a sense of overall variability in economic conditions. The overall adoption of renewable energy, as depicted by the variable REC, is low (median ~10–15%) with a pronounced right-skewed distribution, with a tail stretching until 50%, which is a potential indication of thresholds in renewable energy accessibility. EI varied minimally with a set of extremely high indices, which is a potential indication of periods with high energy use from peaks observed in overall productivity. Per capita CO_2 emissions had a broadened distribution with a pronounced figure in the upper tail (15–20 tons per capita), which is an overall indication of marked cross-country differences on the environment front. Lastly, annual real GDP per capita growth centers near a median of 2.1%, exhibiting dispersion across both tails (ranging from severe contractions of −11.8% during economic crises to expansion peaks exceeding 10%), which underscores the cyclical heterogeneity across G20 economies over the 2000–2024 period.

Table 2. Data Definition.

Code	Indicator Name	Definition	Unit of Measure	Source
GDP	Real GDP per capita growth	Annual percentage growth rate of real GDP per capita	%	World Bank (WDI)
ATE	Access to electricity	Share of population with access to electricity	% of population	World Bank (WDI)
EI	Energy intensity of primary energy	Energy use relative to economic output	MJ per 2021 USD PPP GDP	World Bank (WDI)
REC	Renewable Energy Consumption	Share of renewables in total final energy consumption	% of final energy use	World Bank (WDI)
TRADE	Trade openness	Total trade relative to GDP	% of GDP	World Bank (WDI)
CO_2	CO_2 emissions per capita	Carbon dioxide emissions stemming from fossil fuel combustion	t CO_2 per capita	World Bank (WDI)

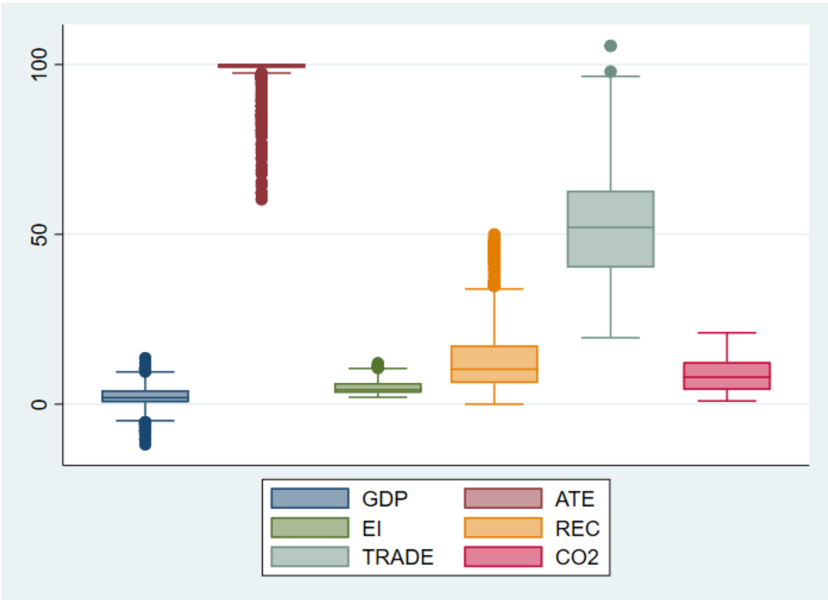

Figure 1. Boxplot.

3.2. Methodology

This research uses a second-generation panel econometric technique to examine the effects of sustainability indicators on economic growth in the G20 economies. The set of economies includes developing, as well as developed economies, which cumulatively represent around 85% of the total economic activity in the globe. In addition, they also contribute around 75% of total world trade. The dependent variable in our empirical specification is the annual real GDP per capita growth rate (GDP_{it}, expressed in %). The vector of explanatory sustainability drivers comprises Access to Electricity (ATE_{it}), Energy Intensity (EI_{it}), Renewable Energy Consumption (REC_{it}), Trade Openness ($TRADE_{it}$), and Per Capita Carbon Dioxide Emissions ($CO_{2_{it}}$). The baseline panel relationship is formulated as follows:

$$GDP_{it} = \alpha_i + \beta_1 ATE_{it} + \beta_2 EI_{it} + \beta_3 REC_{it} + \beta_4 TRADE_{it} + \beta_5 CO_{2_{it}} + \varepsilon_{it}$$

To evaluate parameter heterogeneity across growth states, the conditional quantile model is formulated as:

$$Q\tau(GDPit \mid Xit) = \alpha i(\tau) + \beta(\tau)Xit$$

As G20 nations actively participate in both economic and environmental phenomena, the existence of CD in a cross-section was verified prior to the panel data analysis. It is well established that joint exposure to economic shocks can generate substantial econometric errors. As a result, the Pesaran CD Test [36] is employed in this study. The test statistics involve the average correlation of the correlation coefficients of the error terms among nations, which can be derived from the following equation:

$$CD = \sqrt{\frac{2T}{N(N-1)}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{P}_{ij}}$$

where T denotes the time dimension, N denotes the number of cross-sectional units, and $\hat{P}_{ij}$ represents the pairwise cross-sectional correlation coefficient of the residuals. This diagnostic formally evaluates the presence of contemporaneous cross-sectional correlation induced by unobserved global shocks, confirming the necessity of employing second-generation panel econometric techniques robust to cross-sectional dependence.

After conducting the analysis of cross-sectional dependence, an investigation of slope heterogeneity was performed in order to see if economic structural differences existed among the countries in the model. A test designed by Pesaran-Yamagata [37] evaluated the similarity of response among the panel members with regard to the independent variables. The Test Statistic is given by:

$$\Delta = \sqrt{N}\,\frac{(\bar{S}-k)}{\sqrt{2k}}$$

where, $\bar{S}$ represents the Swamy statistic and k represents the number of independent variables in the model. Confirmation of heterogeneous structures stems from the different sensitivities of G20 countries to sustainability variables, which necessitates the use of flexible methods in panel estimation.

To achieve empirical consistency and prevent spurious regression, the integration properties of the panel series are checked using the second-generation panel unit root tests, which take into account the possibility of cross-section dependence by performing Cross-Sectionally Augmented Dickey Fuller (CADF) test and Cross-Sectionally Augmented IPS (CIPS) test [38]. The CADF test, whose regression equation is defined as:

$$\Delta y_{it} = \alpha_i + \beta_1 y_{it-1} + \gamma_i \bar{y}_{t-1}\delta_i \bar{\Delta} y_t \sum_{k=1}^{P}\theta_{ik}\Delta y_{it_{-k}} + \varepsilon_{it}$$

and at the panel level, the CIPS statistic is calculated as follows:

$$\text{CIPS} = \frac{1}{N}\sum_{i=1}^{n} t_i$$

Since real GDP per capita growth (GDP_{it}) is calculated in terms of an annual percentage rate and the covariates for sustainability have been found to be stationary in levels (integrated of order zero, I(0)), there is no possibility of spurious correlation at the level stage. From an econometric perspective, since cointegration requires that a stationary linear combination must exist among I(1) time series variables, cointegration analysis is not required or even possible since all variables are I(0). The only thing that needs to be done is to prove stationarity at the level stage, which automatically makes the use of static and distributional panel estimators feasible.

In order to test the relationship between sustainability and growth using a robust econometric approach, this paper employs a two-pronged econometric methodology that purposely sets up a comparison between conditional mean estimation and conditional distribution estimation.

First, we perform FGLS estimation, taking into consideration the problem of heteroskedasticity, contemporaneous cross-sectional correlation, and autocorrelation (AR(1)) on the panel data of the G20 countries. The FGLS estimator is:

$$\hat{\beta}_{\text{FGLS}} = (x'\Omega^{-1}x)^{-1}X'\Omega^{-1}Y$$

where Ω is the variance-covariance matrix of the disturbance terms obtained through estimation. Although FGLS results in consistent conditional mean estimates ($E(GDP_{it}|X_{it})$), FGLS is necessarily limited by the underlying assumption of homogeneity of the parameters within different macroeconomic states. To deal with the shortcomings of conditional mean estimation and to identify the regime-specific economic dynamics during the business cycle, the empirical methodology adopted in this study is the Method of Moments Quantile Regression (MMQR) with fixed effects introduced by [6]. The quantile regression framework is established as:

$$Y_{it} = \alpha_i + X'_{it}\beta + (\delta_i + Z'_{it}\gamma)U_{it}$$

where Z is a k-vector of known differentiable transformations of X, and U shows an unobserved random error term. The conditional quantile function $Q_\tau(Y_{it}|X_{it})$ for the quantile $\tau \in (0,1)$ is presented below:

$$Q_\tau(GDP_{it}|X_{it}) = (\alpha_i + \delta_i q(\tau)) + X'_{it}\beta + Z'_{it}\gamma q(\tau)$$

where $q_\tau = F_U^{-1}(\tau)$ is the τ-th quantile of the normalized residual distribution, $(\alpha_i + \delta_i q(\tau))$ is the intercept for that particular quantile. There are definite methodological strengths associated with using the MMQR framework, including the preservation of individual fixed effects along with slope parameters that differ according to the conditional distribution (τ = 0.05, 0.25, 0.50, 0.75, 0.95), thus making it possible to carry out an empirical examination for any asymmetries in the marginal influence of sustainability factors.

Endogeneity problems due to unobserved heterogeneity, time-varying omitted variables, and simultaneity, where economic growth at the same time affects energy consumption, trade, and pollution, represent a significant empirical problem in economic growth and sustainability models. It is important to note that while the fixed-effects MMQR model proposed by Machado and Silva (2019) does not eliminate time-varying omitted variable biases and dynamic reverse causality, the econometric strengths of the MMQR approach in this case include the following:

- Time-Invariant Heterogeneity Control: Through incorporating individual location and scale fixed effects (α_i, δ_i), the model eliminates any time-invariant unobserved heterogeneities specific to each country, including geographic advantages, historical institutional base, and time-invariant industry structure base.
  Moment-Based Estimation: The parameter estimation is done based on conditional moment equations without making any distributional assumptions about the structural error U_{it} which makes it robust to non-normal error distribution and outliers.
- Asymmetries in the Slopes Across Regimes: MMQR, through the construction of the scale function $(\delta_i + Z'_{it}\gamma)q(\tau)$, avoids the strict assumption of parameter pooling of conditional means models.
  In conclusion, the MMQR baseline estimates need to be understood as regime-specific conditional relationships rather than causally identified structural parameters. In order to deal with the issue of simultaneity or contemporaneous feedback (e.g., growth being contemporaneously caused by higher energy consumption and emissions), we perform a formal robustness test in which we estimate an MMQR model with lagged values of the regressors X_{it-1}, making the regressors predetermined with respect to the contemporaneous growth shock.

4. Results and Discussion

4.1. Empirical Results

In Table 3, the results of three cross-sectional dependence tests are displayed. The Pesaran [39], Friedman [40], and Frees [41] tests are all soundly rejecting the hypothesis of “no dependence” at the 1% significance level. The Pesaran CD statistic is significant (20.925, p = 0.00), reporting a high degree of contemporaneous correlation across countries. The result of the Friedman test (167.005, p = 0.00) is a robust joint rejection of cross-sectional independence. The result of the Frees test (3.2786, p = 0.00) is a robust replication of the previous result, independent of the specifics of correlation structure. Taken together, these tests serve as a reminder that there is a high degree of co-movement in the path of the economies of the nations of the G20, largely owing to common worldwide shocks, financial globalization, commodity cycles, and trade/production links. In consequence, cross-sectional dependence needs to be controlled for in the ensuing analysis.

Table 3. Cross Sectional Dependency Tests.

Test	Statistic	*p*-Value
Pesaran	20.925 ***	0.00
Friedman	167.005 ***	0.00
Frees	3.2786 ***	0.00

Note: *** indicates that the estimated parameters are significant at the 1% significance level respectively.

Table 4 reports the results of the second-generation CIPS and CADF panel unit root tests. For all six macroeconomic and sustainability variables (GDP, ATE, EI, REC, TRADE, and CO_2) both test statistics reject the null hypothesis of a unit root at the 1% significance level, establishing that all series are stationary in levels (I(0)). As all the variables are found to be stationary in levels (I(0)), the criteria of spurious regression in non-stationary series are not satisfied and cointegration analysis (which needs non-stationary I(1) variables) becomes redundant. The determination of stationarity in levels of all variables ensures going directly for panel estimation, which justifies the use of FGLS for conditional mean and MMQR for conditional quantile regression.

Table 4. Unit Root Test.

Variable	CIPS	CADF	Order of Integration
GDP	−4.818 ***	−15.492 ***	I(0)
ATE	−3.829 ***	−10.241 ***	I(0)
EI	−3.474 ***	−8.634 ***	I(0)
REC	−4.055 ***	−11.350 ***	I(0)
TRADE	−3.995 ***	−11.054 ***	I(0)
CO_2	−4.136 ***	−11.746 ***	I(0)

Note: *** indicates statistical significance at the 1% level.

The Pesaran-Yamagata tests for homogeneity in the slopes are represented in Table 5. The Δ value of −1.986 with a significant probability of 0.04, along with the adjusted Δ value of −2.499 with a significant probability of 0.01, indicate that the hypothesis of common coefficients is not accepted. The findings indicate that there are significant differences in the marginal effects of ATE, EI, REC, TRADE, and CO_2 on the economic growth in the G20 countries.

Table 5. Heterogeneity slope test.

Δ	*p*-Value	Δ Adj	*p*-Value
−1.986 **	0.04	−2.499 ***	0.01

Note: *** and ** indicate that the estimated parameters are significant at the 1% and 5% significance level respectively.

Table 6 provides the parameter estimates for the MMQR regression, offering clear evidence that distributional asymmetry exists in the effects of sustainability drivers on the real GDP per capita growth at conditional quantiles. Since the dependent variable is measured in terms of annual growth rate (in %), each estimate represents the percentage change in annual growth resulting from a one-unit change in the independent variable:

- Energy Intensity (EI): Exhibits a significant positive marginal effect for all quantiles, increasing from 0.537 percentage points (τ = 0.05) to 0.968 percentage points (τ = 0.95) per 1 MJ/USD increment due to the prevalence of production scale compared to efficiency in periods of rapid production.
- Per Capita CO_2 Emissions: Changes from being statistically insignificant at the bottom end of the distribution (0.050) to having increasingly negative effects beginning at the 25th percentile and above (−0.149 down to −0.397 percentage points for each metric ton of CO_2).
- Access to Electricity (ATE): Demonstrates regime-based statistical significance; its marginal effect is relatively insignificant and statistically insignificant in low growth quantiles (0.015) but becomes positive and statistically significant from the median quantile onwards (0.074 at τ = 0.50 to 0.112 percent point at τ = 0.95).
- Renewable Energy Consumption (REC) and Trade Openness (TRADE): Have positive and significant relationships with economic growth at lower-to-middle regimes (τ = 0.05 to 0.50) but their coefficients become smaller and lose statistical significance at higher quantiles (τ = 0.75 and 0.95). This is not due to neoclassical theory of diminishing marginal return. Instead, it is due to the fact that recovery stimulus from investment in clean energy and trade are more effective at slower-growing economies while faster-growing countries face balancing and logistical saturation.

Table 6. Baseline MMQR Model (Dependent Variable: Annual Real GDP Per Capita Growth).

Quantile	ATE	EI	REC	TRADE	CO_2	Intercept
0.05	0.015	0.537 **	0.084 **	0.048 **	0.050	12.581
0.25	0.058	0.729 ***	0.032 *	0.019 **	−0.149 ***	8.884 **
0.5	0.074 ***	0.797 ***	0.014 *	0.009 **	−0.220 ***	7.569 **
0.75	0.088 ***	0.860 ***	−0.003	−0.001	−0.284 ***	6.368 **
0.95	0.112 ***	0.968 ***	−0.032	−0.017	−0.397 ***	4.284 *

Note: ***, **, and * indicate that the estimated parameters are significant at the 1%, 5%, and 10% significance level respectively.

The FGLS results, which are reported in Table 7, are summarized as follows, with the average effects on GDP, taking into account cross-sectional dependence and heterogeneity. The most influential variable is Energy Intensity (EI), with a large, highly significant positive effect (0.837, z = 10.23, p = 0.00), which means that a one unit increase in EI raises GDP substantially, ceteris paribus. Access to Electricity (ATE) has a positive, significant effect (0.081, z = 3.20). The effect of the Renewable Energy Consumption (REC) variable is positive but relatively small (0.013, z = 2.98). On the other hand, per capita CO_2 emissions have a significant negative impact on growth (−0.212, z = −6.38), which confirms that pollution, with all the inefficiencies that this entails, dampens economic performance. The Trade Openness (TRADE) effect is positive but only marginally significant (0.004, z = 1.70, p = 0.06), providing weak average support for the G20 countries. In summary, the conditional mean benchmark obtained via FGLS largely mirrors the median quantile (τ = 0.50) of the MMQR model: energy intensity exhibits a robust positive association with annual growth, while per capita CO_2 emissions exert a significant negative drag. Meanwhile, electrification and renewable energy display modest positive growth associations, and trade openness yields a marginal, weakly significant average effect.

Table 7. FGLS Conditional Mean Model (Dependent Variable: Annual Real GDP Per Capita Growth).

	Coefficient	Standard Error	z	$p > z$
ATE	0.081 ***	0.025	3.24	0.00
EI	0.837 ***	0.082	10.21	0.00
REC	0.013 ***	0.004	3.25	0.00
TRADE	0.004 *	0.002	2.00	0.06
CO_2	−0.212 ***	0.033	−6.42	0.00
Intercept	8.410 ***	2.689	3.13	0.00

Note: *** and * indicate that the estimated parameters are significant at the 1% and 10% significance level respectively.

One of the key methodological problems in macroeconomic panel regressions is the problem of reverse causality, whereby fast growth in output might simultaneously increase the industrial energy intensity and the level of emissions of pollutants. In order to assess the robustness of our base results, we re-estimate the MMQR model with lagged explanatory variables:

$$Q_\tau\left(GDP_{it}\middle|X_{i,t-1}\right) = \alpha_i(\tau) + \beta(\tau)X_{i,t-1}$$

where $X_{i,t-1} = [ATE_{i,t-1}, EI_{i,t-1}, REC_{i,t-1}, TRADE_{i,t-1}, CO_{2_{i,t-1}}]'$. Since past values of the sustainability factors are predetermined with respect to the contemporaneous output disturbances at time t, the above equation resolves the issue of immediate simultaneity bias. As seen from Table 8, the distributional patterns across all conditional quantiles remain fully robust when predetermined regressors are employed. The past value of Energy Intensity ($EI_{i,t-1}$) has a positive monotonically increasing impact on economic growth ranging from 5th percentile (0.743) to 95th percentile (0.894), confirming that industrial size economies of scale prevail in the case of rapid economic expansion. The negative contribution of past CO_2 emissions ($CO_{2_{i,t-1}}$) increases along the economic growth expansion from 5th to 95th percentile (−0.020 at τ = 0.05 to −0.384 at τ = 0.95). Likewise, the past Access to Energy ($ATE_{i,t-1}$) effect is consistently positive (0.057 to 0.089), whereas Renewable Energy ($REC_{i,t-1}$) and Trade Openness ($TRADE_{i,t-1}$) have positive effects in the lower regimes but decline at upper thresholds. This confirms that the distributional dynamics seen are not due to any contemporaneous endogeneity problem.

Table 8. Robustness MMQR Model with One-Period Lagged Regressors (Dependent Variable: Annual Real GDP Per Capita Growth).

Quantile	ATE_{t-1}	EI_{t-1}	REC_{t-1}	$TRADE_{t-1}$	CO_{2t-1}	Intercept
0.05	0.057	0.743 ***	0.078 **	0.031	−0.020	16.136 ***
0.25	0.072 **	0.813 ***	0.031 *	0.005	−0.188 ***	9.497 ***
0.5	0.077 ***	0.837 ***	0.015	−0.004	−0.245 ***	7.221 ***
0.75	0.081 ***	0.856 ***	0.002	−0.010	−0.291 ***	5.401 *
0.95	0.089 **	0.894 ***	−0.024	−0.025 **	−0.384 ***	1.726

Note: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. Regressors are predetermined via a one-period lag (t − 1) across N = 19 countries and T = 24 periods (N × T = 456 observations).

4.2. Discussion: Distributional Dynamics and G20 Country Heterogeneity

However, the empirical gap between the conditional mean estimates (FGLS) and conditional quantile paths (MMQR) shows that the assessment of sustainability indicators by the panel average ignores important structural differences within the business cycles and country typologies of the G20.

4.2.1. Economic Interpretation of Energy Intensity: Scale vs. Efficiency Dynamics

Based on estimation findings from both the conditional mean benchmark (FGLS: $\beta = 0.837$, $p < 0.01$) and the conditional quantile distribution (MMQR: $\beta = 0.537$ for $\tau = 0.05$ increasing monotonically to $\beta = 0.968$ for $\tau = 0.95$), there is robust empirical evidence for a statistically significant, positive marginal response of annual real GDP per capita growth to increases in primary energy intensity (EI). In terms of energy economics, the high energy intensity level indicates low energy efficiency [11]. Thus, the positive coefficient value on EI should not be confused with the idea that energy inefficiency drives sustainable development. Rather, there are three essential factors that contribute to this finding:

- In production economics, output growth is linked to the scale of industrial capital stock and energy use. In rapidly growing economies, capital intensive manufacturing, infrastructural construction, and heavy industries operate at full capacity. Upgrading the energy efficiency (the technique effect) takes time as it depends on the long capital replacement cycle, which implies that current economic growth will still be tied to the total energy use, which makes the scale effect more relevant in the short and medium run.
- G20 countries consist of the emerging industrial economies (China, India, Russia, South Africa), where industrialization and export-led manufacturing is an important part of GDP. Economic upswings in such economies involve large demand for the basic energy, which results in a high empirical association between the energy intensity and economic performance for the G20 panel.
- Energy intensity is the amount of primary energy used per unit of GDP. In the periods of economic upswing (measured through the upper quantiles, $\tau = 0.75$ and $\tau = 0.95$), energy demand outpaces efficiency retrofits, leading to a larger marginal growth response (0.968 percentage points), compared to lower quantiles ($\tau = 0.05$) where the marginal response is smaller (0.537 percentage points).

Therefore, although high energy intensity is seen as an empirical indicator for production scale in fossil-fuel-based growth patterns, it is, in fact, an unsustainable vulnerability factor and not a driver of sustainability in the long run. The above results clearly indicate the critical need for G20 countries to attain absolute decoupling, that is, moving from scale-related energy intensity to efficient, renewable-based production systems [3,4].

4.2.2. Quantile Dynamics of Electrification, Renewables, Trade, and Emissions

The other sustainability drivers also show distinct distributional disparities in terms of quantiles:

- Access to Electricity (ATE): Access to electricity exhibits regime-contingent significance rather than a uniform linear effect: its marginal effect is statistically not distinguishable from zero at the 5th percentile (0.015), but grows and becomes strongly significant in higher quantiles (0.112). This implies that the gains of electricity access are realized mainly when other factors are available too [8].
- Renewable Energy Consumption (REC): The growth contribution of renewable energy use is declining across the different distribution regimes. The growth contribution marginally contributes positively to the annual growth rate for regimes below the median value (0.084 percentage points at $\tau = 0.05$; 0.014 at $\tau = 0.50$), but fails to remain significant at higher growth percentiles ($\tau = 0.75$, 0.95). This is because of short-run grid balancing and intermittency management as clean energy production scales up within expanding economies [21].
- Trade Openness (TRADE): The trade openness has a limited positive effect concentrated in the lower part of growth distribution ($\beta = 0.048$ at τ 0.05), with minimal direct effects in higher quantiles. Thus, it reaffirms that trade openness works mostly as a "handmaiden" to growth and helps recover and adapt to new conditions in low-growth environments, while the diminishing direct marginal effects become evident in mature trading economies [28,42].
- Per Capita CO_2 Emissions: Carbon emissions show increasing negative impact transitioning from statistically insignificant in the lowest quantile ($\beta = 0.050$ at $\tau = 0.05$) to increasingly strong negative impact in the median and upper quantiles ($\beta = -0.220$ at $\tau = 0.50$; $\beta = -0.397$ at $\tau = 0.95$). This means that while carbon emissions do not constrain economies with excess capacity initially, environmental damage, compliance costs, and health-related productivity losses become serious constraints for rapid growing economies.

4.2.3. Heterogeneous Implications Across G20 Country Typologies

The disparity seen in the quantiles corresponds strongly with the structural difference seen in advanced and emerging member countries [2].

Advanced G20 Countries (USA, Germany, Japan, etc.): Operating around levels of full electrification and high growth quantiles, such countries have the largest marginal costs of CO_2 emissions. Policies should be designed to deal with constraints on renewable power generation and grid management using batteries along with absolute decoupling through strict carbon pricing.

Emerging G20 Countries (China, India, Brazil, South Africa, etc.): Operating across low to medium growth quantiles with a strong energy intensity scale effect, such countries will see significant gains in economic terms from the introduction of renewable power along with international trade links. However, in order not to enter the CO_2 penalty regime at their growth peak, it is necessary for such countries to introduce energy efficiency measures and productive electric power grid management.

5. Conclusions and Policy Recommendations

5.1. Conclusions

This research has empirically investigated the diverse relationship formations between the most significant sustainability factors and economic growth for the G20 countries from the year 2000 through 2024. It has utilized the second-generation panel regression methods that address the cross-sectional dependence on, as well as the slope heterogeneity of, the relationship, applying the FGLS procedure in conjunction with the MMQR approach.

Results indicate regime-dependent and asymmetric relationships between Energy Intensity, CO_2, Access to Electricity, Renewable Energy Consumption and Trade Openness and growth regimes. While Energy Intensity has a positive and increasing marginal effect on growth at higher quantiles, which indicates the prevalence of the industrial size effect in times of economic expansion, per capita CO_2 emissions have an increasing negative effect on growth at higher regimes. Contributions of Access to Electricity to growth become statistically significant only at high growth regimes; on the other hand, Renewable Energy Consumption and Trade Openness make positive contributions at low-to-medium growth regimes. The results supporting the existence of strong cross-sectional dependence, together with slope heterogeneity, thus confirm that G20 nations, despite being globally interlinked, are characterized by distinct economic systems.

5.2. Targeted Policy Recommendations

The empirical evidence proves the insufficiency of a single policy mixture for the G20 countries. Since the effects of energy intensity, electrification, clean energy, and carbon emissions on the economy differ systematically depending on the stage of economic development, policy measures need to be tailored accordingly.

5.2.1. Strategic Roadmap for High-Growth and Advanced Economies (Upper Quantiles)

In economies with fast expansion rates and high-capacity utilization, the first and foremost goal is absolute environmental decoupling to neutralize the strong growth drag imposed by carbon emissions:

- Establish efficient emission trading schemes (ETS) and carbon taxes with a predetermined minimum floor price. Revenues must be reinvested into industrial carbon reduction programs to help cover costs related to regulation compliance.
- In order to compensate for the falling marginal benefits of renewable electricity generation at higher capacities, the policy must focus not only on renewable capacity but also on flexible grids. It entails imposing utility-scale battery energy storage systems (BESS), increasing the number of smart grid connections, and implementing demand side management.
- Due to energy intensity peaking in times of economic boom, governments must establish mandatory energy efficiency standards for heavy industries and accelerate depreciation for investments in energy efficiency technology.

5.2.2. Strategic Roadmap for Low-to-Moderate Growth and Emerging Economies (Lower Quantiles)

For economies facing the process of economic recovery, industrial transformation, or slower economic growth, policy has to capitalize on early high-returns while preventing carbon lock-in:

- Take advantage of the high growth returns from deploying renewable energy by creating green credit facilities, feed-in tariffs, and public-private financing tools for clean energy investments.
- To maximize the developmental return of electrification across lower growth regimes, infrastructure policy must transcend basic household connections and make rural electrification directly conducive to productive industrial activities and agricultural processing as well as SMEs.
- Take advantage of openness to trade as a means of recovery by lowering non-tariff barriers on environmental goods, improving customs logistics and integrating into green technology supply chains in the region.

5.2.3. G20 Multilateral Coordination

Cross-border collaboration is key to harmonizing carbon accounting standards, making possible the transfer of green technology across borders, setting up a fair CBAM system, and raising Just Transition money for workforce relocation from coal-based industrial areas.

5.3. Econometric Limitations and Future Research Directions

Despite providing valuable insights on distributional effects of sustainability drivers in the G20 economies, there exist certain limitations to the methodology used in the present study:

5.3.1. Endogeneity and Causal Identification

Though the fixed effects MMQR estimator controls for any unobserved time-invariant country heterogeneity (α_i, δ_i), and the use of lagged robustness controls X_{it-1} resolves issues regarding contemporaneous reverse causality, the conventional quantile methodology is not able to fully address the problem of dynamic endogeneity or unobserved time-varying shocks in the macroeconomy. Accordingly, the reported coefficients should be interpreted as robust conditional associations across macroeconomic growth regimes rather than structural causal parameters or isolated growth elasticities. Future work needs to expand upon these results through the development of instrumental variable quantile methodologies.

5.3.2. Omitted Variable Bias and Identification Boundaries

One such limitation in econometrics in this case is that the study does not account for traditional time-varying macroeconomic factors that determine economic growth, such as domestic gross fixed capital formation, human capital stock of the labor force, spending on R&D, and dynamic institutional governance indicators. The static part of these structural factors is captured within the individual location (α_i) and scale (δ_i) fixed effects, but there are still omitted time-varying shocks. In the event that unobservable shocks to capital investment are positively correlated with both output booms and energy intensity/carbon dioxide emissions, the coefficient estimates for the primary energy intensity variable may capture elements of capital accumulation cycles in the industry at large, and not only energy consumption effects. On the other hand, if good institutions simultaneously induce green patenting and reduce carbon dioxide emissions without affecting short-term GDP growth, then the negative effect of CO_2 emissions is somewhat overstated in higher quantiles. Consequently, we warn readers against reading into the quantile estimates as ceteris paribus structural growth elasticities in isolation. Rather, they represent the conditional regime-specific trajectories which take into account the macroeconomic realities and the energy transition of the G20 countries as a whole. Future research may consider using high-dimensional panel analysis, factor-augmented quantile regressions, or structural equations modeling to include the indicators of physical capital movement, innovation, and institutional indices over time without sacrificing panel balance.

5.3.3. Directions for Future Research

Future research on this subject can be expanded in the direction of applying dynamic panel quantile regressions using instrumental variables (such as IV-MMQR or structural panel quantile regressions) and using external instruments for macroeconomic variables. The use of time-varying indicators of institutional quality, green financing flows, and detailed sectoral data will add to the research related to G20.

Author Contributions

M.S.: Conceptualization, Investigation, Validation, Formal Analysis, Methodology, Software, Supervision, Visualization, Writing—Review & Editing; A.P.: Conceptualization, Data Curation, Writing—Original Draft; H.O.: Conceptualization. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used Grammarly to check the grammar.

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