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Rethinking Green Economic Growth Measurement: The Structural Role of Education Expenditure

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Abstract

Green economic growth (GEG) measurement has become central to sustainability assessment. However, existing frameworks incorporate government education expenditure without a formal theoretical justification, leaving the social pillar of the three-dimensional sustainability architecture without structural grounding. This study establishes education expenditure as a structural component of GEG measurement and quantifies the distortion generated by its exclusion. A model-based framework comparing education-inclusive and education-excluded specifications is applied to a balanced panel of 42 countries over 2000–2021. The Method of Moments Quantile Regression is estimated across five quantiles for the full sample and income-stratified subsamples. Three findings emerge. First, excluding education expenditure produces a systematic distortion averaging 12.58 percentage points relative to the education-inclusive specification, sufficient to reverse qualitative green growth assessments for most countries. Second, distortion follows a U-shaped distribution across quantiles, with the most significant effects at both performance extremes, indicating that measurement bias is most severe at critical transition points. Third, distortion is statistically equivalent across income tiers, establishing that the structural requirement to include education expenditure is income-invariant. Methodologically, the study develops a sample-independent, theory-grounded measurement architecture that operationalizes the convergence of human capital theory, endogenous growth theory, neoclassical growth theory, and ecological economics within a unified GEG framework applicable across heterogeneous national contexts.

Keywords: Cross-country comparability; Education expenditure; Green economic growth; Income heterogeneity; Method of Moment Quantile regression; Sustainability measurement
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1. Introduction

The transition toward sustainable growth has become embedded in national development strategies and global policy frameworks in response to escalating ecological pressures generated by carbon-

intensive industrial expansion. Economic growth remains structurally coupled with fossil energy dependence, resource depletion, and accelerating climate change (International Energy Agency, 2021; Saglam et al., 2025; Shang et al., 2023). Conventional GDP accounting frameworks exclude environmental externalities embedded in production processes, creating a persistent misalignment between measured economic performance and ecological reality (Betancourt et al., 2025; Casau et al., 2024). Since the 1992 Rio Earth Summit, this contradiction has remained central to sustainability discourse (Dresner, 2012; Groves et al., 2023), reinforcing calls for measurement architectures that internalize environmental costs and align growth metrics with ecological constraints.

Existing approaches to GEG evaluation fall into two broad categories: composite index methods and model-based specifications. Composite indices enable cross-country comparison but remain highly sensitive to indicator selection and weighting schemes, limiting replicability beyond the datasets from which they are derived (Lin & Zhou, 2022; Pang et al., 2024). Model-based approaches provide greater analytical rigor and, in principle, broader applicability. However, influential applications of the current model-based specification (Lin & Ullah, 2023; Sohag et al., 2019; Xu, 2022) have substantively validated similar measurement formulas in single-country contexts: Turkey, Pakistan, and China, respectively. Despite employing comparable specifications, none systematically assessed whether the framework yields consistent and valid evaluations across heterogeneous national settings. As a result, the cross-context validity of model-based GEG measurement remains insufficiently demonstrated.

A related limitation concerns the treatment of education expenditure within this shared specification. Although natural resource rents and carbon emissions are conceptually framed as environmental cost proxies, education expenditure is incorporated without equivalent theoretical justification. If education expenditure serves as a core mechanism for human capital accumulation, green innovation, and structural transformation within ecological limits, its exclusion from the measurement architecture introduces specification bias at the structural level. Existing frameworks further remain closely tied to the samples from which they were derived, constraining their generalizability as sustainability assessment instruments. These limitations reveal a twofold gap: the absence of a theoretically grounded, model-based GEG framework that explicitly justifies education expenditure as a structural component, and the lack of a generalizable measurement architecture independent of specific country samples. Recent advances in sustainability econometrics underscore the importance of structured panel-based modeling for producing reliable cross-country estimates (Y. Luo et al., 2025), as well as the necessity of correcting for cross-sectional dependence and heterogeneity in sustainability-growth analysis (Hasan et al., 2026; Wu & Bianchi, 2026). However, no existing framework integrates these methodological advances into a unified, theory-consistent GEG measurement system.

To address this gap, this study pursues two interrelated objectives. First, it develops and validates a model-based GEG measurement framework that incorporates government expenditure on education as a theoretically grounded structural input. This integration is supported by evidence that education expenditure promotes economic growth in dynamic panel contexts (Prasetyia et al., 2026), fosters green innovation in long-run estimations, and contributes to sustainability performance across diverse income groups (M. Khan & Khan, 2024). Second, the study empirically evaluates the role of education expenditure in shaping GEG performance across heterogeneous economic contexts. The framework is applied to a balanced panel of 42 countries over 2000–2021, with income-stratified subsamples motivated by evidence that validating sustainability frameworks across heterogeneous income groups is essential for cross-context applicability (Fakhreddine et al., 2026; Ionașcu et al., 2025). Country

selection is based on data completeness and consistency across the whole study period rather than geographic criteria, consistent with the sample-independent design of the proposed architecture.

This study makes several interrelated contributions. Methodologically, it develops a sample-independent, model-based framework that embeds education expenditure as a structural component, providing a replicable measurement instrument applicable across diverse national contexts. Theoretically, it operationalizes the convergence of growth and ecological economics within a unified measurement architecture, formally establishing education expenditure as a structural determinant rather than a residual assumption. Empirically, it provides quantitative evidence of measurement distortion arising from the exclusion of education expenditure across the GEG distribution, validated through income-stratified analysis. From a policy perspective, the findings offer actionable guidance for governments and international organizations seeking to design education-informed green growth strategies within sustainability frameworks aimed at decoupling economic development from environmental degradation.

2. Literature Review

2.1 Theoretical Framework

This study is grounded in four complementary theoretical traditions that together provide the conceptual foundation for incorporating government education expenditure into GEG measurement. Solow's (1956) neoclassical growth model establishes the foundational architecture in which capital accumulation, labor quality, and technological progress jointly determine long-term output trajectories, positioning education as a key determinant of an economy's capacity to absorb and deploy technological change. Human capital theory (Becker, 1964) formalizes this relationship by conceptualizing the knowledge, skills, and competencies embodied in individuals as productive assets that enhance economic performance by improving labor quality and productive efficiency. Building on both traditions, endogenous growth theory (Romer, 1990) internalizes knowledge accumulation as the primary engine of sustained productivity growth, explaining how investment in education stimulates innovation and maintains long-run output expansion without proportional increases in physical resource inputs. Daly's (1973) steady-state economy perspective introduces an ecological constraint absent from the preceding models, emphasizing that long-term prosperity depends on maintaining economic activity within regenerative environmental limits and that sustained growth is feasible only if output expansion is progressively decoupled from resource depletion and environmental degradation.

Taken together, these perspectives imply a coherent causal chain: public investment in education enhances human capital; human capital supports innovation and technological adaptation; innovation enables cleaner production and economic transformation; and such transformation makes decoupling feasible within ecological limits. Because this mechanism is derived from theoretical relationships rather than sample-specific calibration, it provides a generalizable foundation for a model-based GEG measurement framework applicable across heterogeneous national contexts.

Empirical research supports the continued relevance of this integrated perspective. Uddin et al. (2025) identify a long-run relationship between human capital and growth in BIMSTEC economies, consistent with Becker (1964) and Solow (1956). Dahmani and Mabrouki (2025) show that innovation mediates the growth effects of human capital in MENA countries, aligning with Romer (1990). Moyo

and Phiri (2024) demonstrate that knowledge creation contributes to growth, particularly in knowledge-intensive sectors. At the ecological frontier, evidence of limited absolute decoupling across economies (Hickel & Kallis, 2020; Suter et al., 2025) underscores Daly's (1973) argument that biophysical limits constrain sustainability. Although this four-theory synthesis is conceptually coherent and empirically supported, no existing GEG measurement framework has formally operationalized this convergence within a unified econometric architecture. This omission motivates the present study.

2.2 Green Economic Growth

Research on GEG can be grouped into three interconnected streams: conceptual development and definitional debates; empirical evaluations of green growth performance across contexts; and studies examining education expenditure as a determinant of green growth outcomes. Each strands reveal a persistent gap in measurement design.

The first stream concerns the evolution and boundaries of GEG. Early contributions by Nordhaus (1974), Solow (1974), and Brock and Taylor (2005) framed environmental sustainability as a prerequisite for long-run welfare. Institutional definitions later expanded GEG to include equity, well-being, and preservation of natural capital (Bonvin & Laruffa, 2024; OECD, 2025; UNEP, 2023). Kulaeva (2025) documents how these definitional shifts contributed to divergence between green growth and degrowth paradigms. Central to this debate is the feasibility of absolute decoupling. Hickel and Kallis (2020) and Hickel (2021) question its empirical validity, while Infante-Amate et al. (2025) show that historical emissions reductions often coincided with recessions rather than sustained green expansion. Cerkini et al. (2025) further argue that indicator selection embeds normative assumptions regarding ecological limits and climate justice. Together, these debates highlight the importance of transparent and theoretically grounded measurement frameworks capable of evaluating decoupling claims across countries.

The second stream evaluates GEG performance under varying institutional and income conditions. Herman et al. (2023) identify financing constraints and short-term trade-offs as key barriers. Hussain et al. (2022) find that green technology promotes decoupling but dampens short-term growth due to investment costs. Byaro and Timbuka (2025) show that green growth reduces emissions in lower-middle-income economies but yields weaker effects in higher-income contexts, while Sarkodie et al. (2024) document cross-country disparities shaped by institutional capacity. These findings suggest that GEG outcomes are context-dependent and mediated by policy design, investment structures, and governance quality. However, existing measurement approaches have not consistently modeled these cross-context differences within a unified and comparable framework.

Hypothesis 1: GEG, while not necessarily outperforming conventional GDP growth in the short term, yields superior long-term sustainability outcomes.

The third stream examines education expenditure as a determinant of green growth. Zhang and Wei (2024) confirm the positive effects of education on green growth in Asian economies, while Zhang et al. (2023) show that sustainable human capital formation supports green technology development. Gao et al. (2019) demonstrate that higher education exerts more potent effects on green economic outcomes than on conventional GDP. Liao et al. (2019), Ngo et al. (2022), and Liu et al. (2025) provide cross-national and subnational evidence that education investment contributes positively to green GDP and sustainable growth. At the same time, Z. Khan et al. (2023) find that human capital may increase emissions when not aligned with decarbonization policies, indicating that educational

impacts depend on policy coherence. Although these studies consistently identify education as an important driver of green outcomes, it is rarely evaluated as a foundational element of GEG measurement itself.

Hypothesis 2: Government expenditure on education plays a significant positive role in enhancing GEG.

Across these streams, four limitations remain. First, no standardized model-based GEG framework explicitly integrates education expenditure within a theoretically justified measurement architecture. Second, many frameworks are calibrated to specific country samples, limiting cross-context applicability. Third, the absence of a sample-independent design constrains systematic cross-regional comparison. Fourth, despite strong theoretical support for linking human capital formation, innovation, and ecological constraints, this synthesis has not been formally embedded within a unified GEG measurement model. The present study addresses these limitations by developing a theory-grounded, model-based GEG framework that incorporates government education expenditure within a generalizable, empirically validated measurement architecture.

3. Methodology

3.1 Data and Sample

Annual panel data for 42 countries covering 2000–2021 were sourced from the World Development Indicators (The World Bank, 2025), yielding a maximum of 924 country-year observations. Country selection was based solely on data completeness and consistency across all study variables for the entire study period, rather than on geographic or geopolitical criteria. While the resulting sample is predominantly composed of high-income economies, reflecting the well-documented disparity in green growth data availability across income levels, it spans five continents: Asia, the Americas, Europe, Africa, and Oceania, with GNI per capita ranging from USD 2,645 to USD 112,701 based on 2021 values. Thus, our sample provides sufficient income-level variation for the distributional analysis conducted in this study.

To examine income-contingent heterogeneity in the structural effect of education expenditure on GEG, the full sample is stratified into two income tiers based on the within-sample median GNI per capita of USD 43,911: a lower-income tier comprising 20 countries and an upper-income tier comprising 22 countries. This sample-based stratification is adopted in preference to standard World Bank income classifications, which yield highly unequal subgroup distributions within this sample, and is consistent with income-stratification practices in recent panel heterogeneity studies (Byaro & Timbuka, 2025). **Figure 1** presents the complete country map with income tier classifications.

Figure 1. List of the Sample Countries



Source: Author's own work. The map was generated in RStudio software.

3.2 Variable Construction

This study constructs and compares two GEG specifications following the model-based measurement approach of Lin and Ullah (2023), Sohag et al. (2019), and Xu (2022). The education-inclusive specification (GEG) integrates three sustainability pillars: the social dimension operationalized through government expenditure on education (EE), the resource dimension through natural resource rents (NRR), and the environmental dimension through carbon dioxide emissions per capita (CO2), alongside GDP growth (GDPG) as the foundational economic component. As elaborated in Section 2, EE has been incorporated in existing GEG frameworks without theoretical justification; this study argues that its inclusion is conceptually necessary to avoid structural misspecification of the social dimension of the sustainability framework being measured. The education-excluded baseline (GEG_base) retains only the resource and environmental dimensions, enabling direct empirical quantification of the measurement distortion introduced by EE exclusion. **Table 1** presents the operationalization of all variables.

Table 1. Operation of Variables

Variable	Definition and unit	Abbreviations	Source
GEG	GEG = GDP + EE - NRP - NFD - CO2 (Lin & Ullah, 2023; Sohag et al., 2019; Xu, 2022)	GEG	Index, author's calculation
Economic growth	GDP is the gross domestic product and is measured in annual (%).	GDPG	The World Bank (2025)
Government spending on education	Government fiscal budget for education (% of GDP).	EE	The World Bank (2025)

Natural resource depletion	Natural resource rents are estimated as the difference between the price of a commodity and its average cost of production (Total natural resource rents are the sum of oil rents, natural gas rents, coal rents, mineral rents, and forest rents; NRP+NFD) (% of GDP).	NRR	The World Bank (2025)
CO2	Change in CO2 emissions per capita in one year (%).	CO2	The World Bank (2025)
GEG_base	GEG without counting EE	GEG_base	Index, author's calculation

Source: Authors' own work.

The two specifications are formally defined as:

$$GEG_t = GDPG_t + EE_t - NRR_t - CO2_t \quad (1)$$

$$GEG_base_t = GDPG_t - NRR_t - CO2_t \quad (2)$$

3.3 Estimation Strategy

3.3.1 Method of Moments Quantile Regression

This study employs Method of Moments Quantile Regression (MMQR) (Machado & Santos Silva, 2019) across three analytical stages. This approach is motivated by three considerations: mean-based estimators mask distributional heterogeneity that is central to this study's hypotheses; MMQR accommodates panel fixed effects through a location-scale model without the computational complications of traditional quantile regression; and its robustness to non-normality and heteroskedasticity is well-suited to cross-country sustainability panels (Byaro & Timbuka, 2025). The conditional quantile function is:

$$Y_{it} = \alpha_i + \beta X'_{it} + (\eta_i + \theta'_{it}\gamma)\varepsilon_{it} \quad (3)$$

where $(\eta_i + \theta'_{it}\gamma) > 0$ with probability 1, and ε_{it} is an independently and identically distributed random variable, orthogonal to X'_{it}. Therefore, Eq. (1) for the conditional quantile coefficient becomes:

$$QY_{it}(\tau \mid X'_{it}) = (\alpha_i + \eta_i q(\tau)) + \beta X'_{it} + \theta'_{it}\gamma, q(\tau) \quad (4)$$

where $QY_{it}(\tau \mid X'_{it})$ denotes the τ-th conditional quantile of GEG, α_i represents country fixed effects, and $q(\tau)$ is the τ-th quantile of the standard error distribution. All estimations are conducted at five quantile levels: $\tau = \{0.10, 0.25, 0.50, 0.75, 0.90\}$.

3.3.2 Quantifying Measurement Distortion (H1)

MMQR is estimated separately for GEG and GEG_base using country and time fixed effects as the sole systematic components:

$$GEG_{it}(\tau) = \alpha_i + \delta_t + q(\tau) \quad (5)$$

$$GEG_base_{it}(\tau) = \alpha_i + \delta_t + q(\tau) \quad (6)$$

The quantile-specific distortion from EE exclusion is computed as:

$$\Delta(\tau) = Q_{GEG}(\tau) - Q_{GEG_base}(\tau) \quad (7)$$

A positive and varying $\Delta(\tau)$ across quantiles confirms that EE exclusion produces distributional measurement distortion rather than a uniform scalar shift. This analysis is conducted for the full sample and replicated for both income subsamples.

3.3.3 Structural Role of EE (H2a)

MMQR is estimated with GEG_base as the dependent variable and EE as the sole independent variable:

$$GEG_{base\,it}(\tau) = \alpha_i + \beta_1^{\tau} EE_{it} + \varepsilon_{it} \quad (8)$$

Since EE is absent from the construction of GEG_base, β_1^{τ} is free from mechanical relationships, constituting genuine evidence that EE exerts structural influence on green growth outcomes beyond the formula to calculate GEG.

3.3.4 Income-Contingent Heterogeneity (H2b)

Equation (8) is estimated separately for lower-income (n = 20) and upper-income (n = 22) subsamples. Systematic differences in $\beta_1^{\tau}(EE)$ between tiers establishes empirical boundary conditions for the framework's cross-contextual applicability.

3.3.5 Diagnostics and Robustness

Cross-sectional dependence is tested using the Pesaran (2004) CD test, panel unit root properties using the CIPS test (Pesaran, 2007), and slope homogeneity using the Pesaran and Yamagata (2008) delta test. Robustness is assessed through Driscoll-Kraay standard errors (Driscoll & Kraay, 1998), which provides consistent covariance estimation under heteroskedasticity, autocorrelation, and cross-sectional dependence, is particularly appropriate given the predominantly European sample composition and extended 22-year panel dimension.

4. Results

Table 2 presents the summary of descriptive statistics for the full sample and income-tier subsamples. In Panel A, the mean GEG is positive (6.840). In contrast, the baseline specification excluding education expenditure yields a negative mean (-5.736), suggesting a substantial downward shift in measured green growth when education is omitted. The relatively large standard deviations and wide ranges across variables indicate considerable cross-country heterogeneity, providing empirical

justification for distribution-sensitive estimation methods. Panel B reveals systematic differences across income tiers, particularly in CO2 emissions and natural resource dependence, while education expenditure levels remain broadly comparable across groups. These patterns underscore the importance of incorporating structural and distributional considerations into models of GEG dynamics.

Panel A: Full Sample (N = 924, 42 Countries, 2000–2021)						
Variabel	Count	Mean	Median	Std. Dev	Min	Max
geg	924	6.840	6.249	7.342	-13.296	29.843
geg_ee	924	-5.736	-5.091	6.258	-24.849	16.372
edexp	924	12.576	12.082	3.824	2.975	30.700
gdpg	924	2.839	2.795	3.863	-16.040	24.624
nrr	924	1.577	0.534	2.611	0.000	20.994
co2	924	6.998	6.592	4.673	0.092	25.949
Panel B: Mean Values by Income Tier						
	GEG	GEG_base	EE	GDPG	NRR	CO2
income_group						
Upper-Income (n=22)	4.494	-8.050	12.544	2.375	0.935	9.490
Lower-Income (n=20)	9.420	-3.190	12.610	3.349	2.283	4.257
Difference	-4.926	-4.859	-0.067	-0.974	-1.348	5.233

Notes: All variables are measured at the country-year level. Summary statistics are computed using the balanced panel of 42 countries over 2000–2021 (n=924). Panel B reports unweighted group means by income classification. Differences represent upper-income minus lower-income averages.

Pre-estimation diagnostics confirm the validity of the MMQR specification and are summarised in **Table 3**. The Pesaran (2004) CD test rejects the null of cross-sectional independence across all six variables, confirming that country observations share standard shocks consistent with the sample's predominantly European composition. This result necessitates the use of the CIPS unit root test (Pesaran, 2007) over conventional procedures that assume cross-sectional independence. The CIPS test reveals a mixed integration order: GDPG is stationary at level I(0), while the remaining variables are stationary only after first differencing, I(1). This mixed order precludes standard cointegration frameworks, reinforcing MMQR as the appropriate estimator, which remains valid under mixed I(0)/I(1) conditions (Machado & Santos Silva, 2019). The Pesaran and Yamagata (2008) delta test rejects slope homogeneity for both model specifications, confirming that country-level heterogeneity in the GEG-EE relationship is an empirical property of the data, rendering quantile-based estimation not merely preferable but necessary.

Panel A: Cross-Sectional Dependence Test (Pesaran, 2004)			
	CD Statistic	**p-value**	**Decision**
GEG	52.581	0.000	Reject H_o
GEG_base	58.619	0.000	Reject H_o
EE	19.481	0.000	Reject H_o
GDPG	70.029	0.000	Reject H_o
NRR	42.673	0.000	Reject H_o

CO_2	31.405	0.000	Reject H_0

Panel B: CIPS Panel Unit Root Test (Pesaran, 2007)

	Level	First Difference	Order
GEG	−1.9872	−3.4726***	I(1)
GEG_base	−2.0847	−3.6318***	I(1)
EE	−1.7086	−3.5005***	I(1)
GDPG	−2.5152**	—	I(0)
NRR	−2.1996	−3.4049***	I(1)
CO_2	−1.6991	−3.5479***	I(1)

Panel C: Slope Homogeneity Test (Pesaran & Yamagata, 2008)

	Model 1 (GEG)	Model 2 (GEG_base)	Decision
Δ statistic	1.413	1.011	Reject H_0
$\tilde{\Delta}$ adjusted	4.425	3.093	Reject H_0

Notes: H_0 for CD test = no cross-sectional dependence; H_0 for CIPS test = variable contains a unit root; H_0 for slope homogeneity = slopes are homogeneous across countries. CIPS critical values, with intercept: -2.58 (1%), -2.38 (5%), -2.28 (10%). ** and *** denote rejection of H_0 at 5% and 1% significance levels, respectively. Source: Authors' estimation.

Table 4 presents the full sample MMQR estimation results. Panel A confirms that GDPG, NRR, and CO_2 are statistically significant across all quantiles with expected signs, validating the three-pillar GEG measurement architecture. The monotonically increasing NRR coefficients indicate that resource depletion exerts a progressively stronger disciplining effect at higher GEG quantiles, consistent with increasing sustainability penalties for resource-dependent growth. The quantile-varying term $q(\tau)$ progresses from −1.55 at τ=0.10 to +1.53 at τ=0.90, indicating that education expenditure systematically differentiates high-GEG from low-GEG performers, which is consistent with Romer's (1990) prediction that returns to knowledge accumulation increase as economies approach the technological frontier. On the other hand, Panel B establishes that GEG_base systematically underestimates green growth performance by omitting the social pillar that education expenditure represents. The decreasing magnitude of $\Delta(\tau)$ from τ=0.10 to τ=0.75 indicates that measurement distortion is most consequential for lower-performing countries, where education investment constitutes a proportionally larger share of measured green growth. The non-significant Wald test (p=0.383) confirms that distortion is distributional rather than threshold-specific, establishing that no segment of the GEG distribution is immune to the measurement consequences of EE exclusion.

Table 2. MMQR Estimation Result

Panel A. Model 1: GEG as Dependent Variable

Variable	τ = 0.10	τ = 0.25	τ = 0.50	τ = 0.75	τ = 0.90
GDPG	1.0031***	1.0099***	1.0179***	1.0264***	1.0323***
	(0.0349)	(0.0289)	(0.0236)	(0.0210)	(0.0218)
NRR	-0.9928***	-1.0583***	-1.1346***	-1.2162***	-1.2734***
	(0.1051)	(0.1035)	(0.1301)	(0.1704)	(0.2074)
CO2	-0.7512***	-0.7634***	-0.7775***	-0.7927***	-0.8033***

	(0.0869)	(0.0804)	(0.0744)	(0.0706)	(0.0699)
$q(\tau)$ × EE variation	-1.5473	-0.8280	0.0100	0.9062	1.5345
Panel B. Measurement Distortion $\Delta(\tau) = Q_{GEG}(\tau) - Q_{GEG_base}(\tau)$					
	τ = 0.10	**τ = 0.25**	**τ = 0.50**	**τ = 0.75**	**τ = 0.90**
Q_{GEG}	-1.5473	-0.8280	0.0100	0.9062	1.5345
Q_{GEG_base}	-14.6584	-9.0635	-5.0910	-2.0030	2.1164
$\Delta(\tau)$	13.1111	8.2355	5.0810	2.9032	-0.5819
SE	(0.9664)	(0.5604)	(0.5542)	(0.8195)	(1.6794)
Significance	***	***	***	***	***

Note: Wald test for $\Delta(0.10) = \Delta(0.90)$: Z = -0.8717, p = 0.3834. Spearman ρ = 0.700, p = 0.1881.

Table 5 presents the income-stratified results. Both upper-income and lower-income tier countries exhibit large, positive, and statistically significant measurement distortions across all quantiles, with mean distortions of 12.36 and 12.58, respectively. The between-group Z-tests in Panel C reveal no statistically significant differences in distortion magnitude across any quantile (all p>0.36), contradicting the directional prediction of H2b: the structural importance of EE in GEG measurement is not income-contingent but income-invariant. This null result is substantively significant because it establishes that the measurement distortion from EE exclusion is a universal feature of GEG frameworks across national income levels, strengthening rather than qualifying the case for treating EE as an indispensable structural component of any GEG measurement architecture.

Table 3. MMQR Estimation Result Based on Income Group

Panel A. Upper-Income Tier (n = 22; 484 observations)					
Variable	**τ = 0.10**	**τ = 0.25**	**τ = 0.50**	**τ = 0.75**	**τ = 0.90**
GDPG	1.0540***	1.0577***	1.0620***	1.0663***	1.0692***
NRR	-1.0730***	-1.0077***	-0.9322***	-0.8555***	-0.8044***
CO2	-0.8025***	-0.8205***	-0.8414***	-0.8625***	-0.8766***
$q(\tau)$	-1.4906	-0.7712	0.0602	0.9053	1.4673
Distortion $\Delta(\tau)$	13.5568***	11.1825***	11.2960***	13.0180***	14.7561***
Panel B. Lower-Income Tier (n = 20; 440 observations)					
	τ = 0.10	**τ = 0.25**	**τ = 0.50**	**τ = 0.75**	**τ = 0.90**
GDPG	0.9701***	0.9771***	0.9862***	0.9953***	1.0021***
NRR	-0.9694***	-1.0591***	-1.1777***	-1.2945***	-1.3822***
CO2	-0.5998*	-0.5814*	-0.5570*	-0.5329**	-0.5149**
$q(\tau)$	–	–	–	–	–
Distortion $\Delta(\tau)$	11.9435***	11.3917***	11.3880***	12.2897***	15.9017***
Panel C. Between-Group Comparison (Z-test)					
	τ = 0.10	**τ = 0.25**	**τ = 0.50**	**τ = 0.75**	**τ = 0.90**
Δ Upper-Income	13.5568	11.1825	11.2960	13.0180	14.7561

Δ Lower-Income	11.9435	11.3917	11.3880	12.2897	15.9017
Difference	1.6133	-0.2092	-0.0920	0.7283	-1.1456
z-score	0.9033	-0.1622	-0.0862	0.3657	-0.4066
p-value	0.366	0.871	0.931	0.715	0.684

Note: *** p<0.01, ** p<0.05, * p<0.10. Standard errors in parentheses based on cluster bootstrap. Distortion $\Delta(\tau) = Q_{GEG}(\tau) - Q_{GEG_base}(\tau)$. Upper-income and lower-income tiers are defined by the within-sample median GNI per capita of USD 43,911 (2021). Spearman trend: upper-income ρ=0.400; lower-income ρ=0.600, both indicating an upward pattern. Source: Authors' estimation.

Table 6 presents the Driscoll-Kraay robustness estimates for the structural effect of EE on GEG_base across the whole sample and both income-stratified subsamples. The positive, statistically significant coefficient of EE across all three samples confirms that EE exerts a genuine structural influence on green growth outcomes, even when assessed against the education-excluded baseline that does not mechanically incorporate EE. Notably, the upper-income tier coefficient (1.246) exceeds both the full sample and lower-income estimates, suggesting that each additional percentage point of GDP allocated to education is associated with a larger improvement in GEG_base performance in higher-income economies. This pattern is consistent with the greater absorptive capacity of advanced human capital systems to translate education investment into measurable green growth outcomes. These results are robust to heteroskedasticity, serial correlation, and cross-sectional dependence, corroborating the MMQR findings and reinforcing the central argument that EE is an indispensable structural determinant of GEG measurement.

Model: $\text{GEG_base_it} = \alpha_i + \beta \cdot \text{EE_it} + \varepsilon_it$

Sample	n	Coefficient	Std. Error	t-statistic	p-value
Full Sample	924	1.0350	(0.1270)	8.1512	0.0000
Upper-Income Tier	484	1.2463	(0.2310)	5.3952	0.0000
Lower-Income Tier	440	0.9629	(0.1220)	7.8941	0.0000

Notes: DV = GEG_base (GDPG − NRR − CO2). EE (% of GDP) is the key regressor. Country fixed effects included. Driscoll–Kraay SEs ($T^{1/4}$ bandwidth). The within-sample median GNI defines income tiers. Source: Author's own work.

5. Discussion

5.1 The Structural Indispensability of Education Expenditure in GEG Measurement

The findings advance the methodological development of GEG indicators by demonstrating that excluding government education expenditure constitutes a conceptual misspecification rather than a marginal data omission, leading to distortions large enough to reverse qualitative evaluations of green growth performance. This result provides empirical clarification to definitional tensions in the literature (Bonvin & Laruffa, 2024; Kulaeva, 2025; UNEP, 2023). Although successive conceptual expansions of GEG incorporated well-being and social inclusivity dimensions (OECD, 2025; UNEP, 2023), existing measurement architectures have not operationalized social investment as a structural input, thereby directly perpetuating the first methodological limitation identified in Section 2.

The sample independence of the proposed framework derives from two design features rather than from assertion. First, all four constituent variables are universally available through the World Development Indicators without requiring country-group-specific proxies or regional calibration. This feature is a property shared with the foundational GEG frameworks of Sohag et al. (2019), Lin and Ullah (2023) and Xu (2022), and consistent with the replicability criteria advocated by model-based indicator approaches (Hasan et al., 2026; Y. Luo et al., 2025; Wu & Bianchi, 2026). Second, the theoretical justification for each variable's inclusion is derived from established growth and sustainability theory, rather than from the statistical properties of any estimation sample, ensuring that the conceptual validity of the framework does not depend on which countries are included in any given application. Evidence that the EE-green growth relationship operates across diverse country contexts (M. Khan & Khan, 2024; C. Luo & Li, 2023; Prasetyia et al., 2026) further supports the universality of this theoretical grounding. The income-invariant distortion documented in Section 4 provides empirical confirmation of these design properties: had the framework been implicitly calibrated to a specific income context, measurement distortion would have differed systematically across income groups, as documented for green growth outcomes by Byaro and Timbuka (2025) and Sarkodie et al. (2024). Its absence demonstrates that the framework's structural validity is portable across diverse national and regional settings.

5.2 Distributional Consistency of Measurement Distortion

The theoretical foundation for including education expenditure as a structural GEG component is grounded in the four-tradition synthesis outlined in Section 2. Human capital theory conceptualizes education as productive capital enhancing economic capability (Becker, 1964); Solow (1956) situates it as a determinant of long-run productivity; Romer (1990) internalizes knowledge accumulation as the upstream driver of innovation; and Daly (1973) introduces ecological boundary conditions within which economic systems must operate. Integrated, these frameworks imply that sustainable green growth depends on human capital's capacity to generate innovation, enabling decoupling of economic activity from environmental degradation. Empirical evidence reinforces this architecture: human capital sustains long-run growth across diverse contexts (Uddin et al., 2025), mediates innovation dynamics (Dahmani & Mabrouki, 2025), and supports knowledge-intensive development (Moyo & Phiri, 2024).

The progressive increase in education expenditure's contribution across higher GEG quantiles is consistent with Romer's (1990) prediction that knowledge accumulation generates increasing returns, becoming more pronounced as economies operate at higher levels of green growth performance. The consistency of distortion across the full GEG distribution confirms that the human capital dimension is structurally embedded rather than conditionally relevant, directly addressing concerns regarding indicator non-neutrality (Cerkini et al., 2025) and empirical contestation surrounding absolute decoupling (Infante-Amate et al., 2025). By formally operationalizing the four-tradition convergence within a unified measurement architecture, this study establishes education expenditure as a structural determinant rather than a qualitative assumption.

5.3 Income-Invariance as Evidence of Universal Structural Relevance

The income-invariance of measurement distortion establishes that the structural requirement to include education expenditure in GEG measurement is a universal property of the framework rather than a context-specific feature. This finding is significant given evidence that green growth outcomes

differ across institutional and income contexts (Byaro & Timbuka, 2025; Ionașcu et al., 2025; Sarkodie et al., 2024). While green growth performance is income-contingent, the framework's measurement validity is not.

The U-shaped distributional pattern of measurement distortion across both income tiers carries two substantive implications. First, distortion is most considerable at the distributional extremes, where assessments of green growth failure and success are most consequential for policy and resource allocation. Countries at the lower tail face constraints consistent with persistent absolute decoupling failures documented in the literature (Hickel & Kallis, 2020; Suter et al., 2025), where measurement accuracy is critical for identifying structural deficiencies. Countries at the upper tail represent frontier performers for whom green growth assessments inform the design of advanced decarbonization strategies. Measurement distortion at both extremes, therefore, carries direct policy consequences, reinforcing concerns regarding the non-neutrality of indicator construction (Cerkini et al., 2025). Second, this non-linearity is undetectable by mean-based estimators such as OLS or fixed-effects panel regression, which produce a single average distortion estimate that masks disproportionate measurement consequences at the distributional tails (Byaro & Timbuka, 2025; Machado & Santos Silva, 2019). This finding provides direct empirical justification for the quantile-based analytical design and explains why prior mean-based GEG analyses have underestimated the structural role of education expenditure. Driscoll-Kraay robustness estimates confirm that the education effect persists after correcting for cross-sectional dependence and serial correlation (Driscoll & Kraay, 1998), ruling out sample-specific artifacts.

5.4 Policy Implications

The results address the four measurement limitations identified in Section 2: providing empirical justification for EE as a structural GEG component; enhancing cross-context comparability through theory-driven calibration; supporting a unified measurement system across heterogeneous national contexts; and bridging the gap between theoretical convergence and empirical implementation. International organizations and national governments relying on composite indicators for sustainability monitoring should ensure that social investment dimensions are explicitly incorporated into measurement frameworks, as education-excluded specifications systematically misclassify green growth performance to a degree sufficient to reverse policy conclusions. Evidence that education positively influences green GDP (Liu et al., 2025; Ngo et al., 2022) confirms that educational investment is a sustainability-enabling input rather than a purely social expenditure. Findings that human capital may increase emissions under certain structural conditions (Z. Khan et al., 2023) suggest that the effectiveness of education investments depends on alignment with industrial decarbonization strategies. A measurement architecture incorporating education expenditure, therefore, enhances diagnostic precision and policy coherence within sustainability frameworks that target the simultaneous achievement of SDG 4, SDG 8, and SDG 13.

6. Conclusion and Future Research Direction

This study develops and validates a model-based framework for measuring GEG that explicitly incorporates government education expenditure as a structural component alongside natural resource rents and carbon dioxide emissions. From the application of MMQR to a balanced panel of 42 countries over 2000–2021, three principal findings emerge. First, excluding education expenditure

produces systematic and substantial distortion across the entire performance distribution, demonstrating that education-excluded specifications are structurally incomplete. Second, distortion follows a U-shaped distributional pattern, with the largest magnitudes at both tails of the GEG distribution and effects that would remain undetected under mean-based estimators, thereby justifying the quantile-based design. Third, distortion is income-invariant across upper- and lower-income groups, confirming that the framework's structural validity is portable across heterogeneous national contexts.

Collectively, these results provide quantitative evidence that education expenditure is not an auxiliary correlate but a structural determinant of GEG measurement validity. By operationalizing the convergence of human capital theory, endogenous growth theory, neoclassical growth theory, and ecological economics within a unified measurement architecture, the study advances the methodological foundation of sustainability assessment. It enhances the cross-context comparability of GEG indicators.

Two limitations warrant acknowledgment. The sample is predominantly composed of high-income economies due to data availability constraints, limiting representativeness for lower-income contexts. Additionally, the parsimonious specification does not incorporate institutional quality, governance effectiveness, or green technology adoption as potential moderators of the education–GEG relationship. Future research should extend validation to underrepresented regions, examine whether the composition of education expenditure across educational levels differentially affects GEG measurement, and assess institutional conditions that may moderate the magnitude of distortion resulting from education exclusion.

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Conflict of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data Availability Statement

The data supporting this study are publicly available in the World Development Indicators database maintained by the World Bank. The dataset can be accessed at https://databank.worldbank.org/source/world-development-indicators. No proprietary or restricted data were used in this study.

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