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Mapping Global Green Transformation: Integrating OECD Green Growth Indicators into a Composite Policy-Innovation Index

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Abstract

Measuring national progress toward green transformation remains challenging due to fragmented assessment frameworks. This study develops and validates a Green Transformation Index that captures the capacity for sustainability transitions by integrating resource efficiency, innovation systems, and policy instruments. Using OECD Green Growth Indicators covering 58 economies from 2017 to 2025, we construct a composite index from 47 standardized indicators organized into three theoretically grounded dimensions. The GTI measures transformation capacity through innovation investment and policy frameworks rather than environmental outcomes. Results reveal substantial heterogeneity in transformation capacity with a Gini coefficient of 0.283, indicating persistent global inequality. Temporal analysis identifies a three-phase trajectory: consolidation from 2017 to 2019, acceleration during 2021 to 2023 driven by green recovery investments, and marked reversal in 2024 to 2025, highlighting vulnerability to economic shocks. Cluster analysis identifies four distinct pathways: innovation-driven, balanced integration, resource-first, and policy-led approaches. Critical findings show only 19 percent of countries demonstrate strong coordination between innovation investments and policy instruments, revealing significant governance fragmentation. Validation tests confirm the index effectively measures innovation capacity but shows weak correlation with emissions outcomes, underscoring the distinction between transformation inputs and environmental performance.

Keywords: green transformation capacity; composite index; sustainability transitions; policy coherence; innovation systems

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1. Introduction

The global response to climate change has entered a critical phase. While 195 parties signed the Paris Agreement in 2015 pledging to limit warming to well below 2 degrees Celsius, current national policies remain insufficient to achieve these objectives [1,2]. The Intergovernmental Panel on Climate Change warns that without substantial acceleration in emissions reductions and systemic transformation of energy and industrial systems, catastrophic climate impacts become inevitable [3]. This urgency has intensified focus on green transformation, defined as the comprehensive restructuring of economic systems to decouple prosperity from environmental degradation through technological innovation, resource efficiency, and fundamental shifts in production patterns [4].

1.1. The Measurement Challenge

Systematic assessment of which countries are making progress, which strategies prove effective, and what factors enable transformation capacity remains inadequate [5,6]. Existing frameworks address green transformation partially rather than comprehensively. The Environmental Performance Index focuses primarily on environmental outcomes such as air quality rather than transformation processes [7]. The OECD Green Growth Indicators provide comprehensive data but do not aggregate measures into composite assessments of transformation performance [8]. The Sustainable Development Goals framework embeds environmental dimensions within broader development objectives, making it difficult to isolate green transformation dynamics specifically [9].

This measurement gap creates specific problems for research and policy [10]. Without standardized metrics spanning multiple transformation dimensions, cross-national comparison relies on fragmented indicators that may contradict each other [11]. Temporal tracking of transformation progress lacks consistent measurement, making it difficult to determine whether global efforts are accelerating or stalling [12]. The relationship between transformation inputs including research investment and policy development and transformation outcomes including emissions reduction remains poorly understood because measurement systems do not systematically link these dimensions [13]. Policy learning about effective strategies is constrained when countries cannot readily identify peers with similar contexts but superior performance [14].

1.2. Research Objective and Contributions

The aim of this paper is to develop and validate a comprehensive Green Transformation Index that measures national capacity for sustainability transitions through systematic integration of resource efficiency, innovation systems, and policy response dimensions.

This study addresses a critical gap in sustainability measurement [15]. Unlike outcome-focused indices that measure environmental performance, the GTI assesses transformation capacity through innovation investment, research infrastructure, and policy frameworks that enable future sustainability transitions. This distinction between capacity and outcomes is fundamental: the GTI identifies countries building foundations for transformation rather than countries already achieving environmental improvement [16].

We advance both theoretical understanding and practical policy assessment through several contributions. Empirically, we provide the first comprehensive assessment of green transformation capacity across 58 countries using standardized multidimensional indicators from 2017 to 2025. This temporal scope captures the consolidation of Paris Agreement implementation, COVID-19 disruption and green recovery efforts, and recent economic pressures threatening progress. Theoretically, we advance understanding of transformation as a contested, heterogeneous process with multiple pathways rather than uniform progression [17]. Methodologically, we establish standards for transparent composite indicator development including explicit documentation of limitations and honest validation reporting [18]. For policy, we identify critical coordination failures between innovation investments and policy instruments that constrain systemic transformation [19,20].

1.3. Research Questions

This research addresses four interconnected questions:

First, do countries demonstrate convergence or divergence in green transformation capacity over time, and what factors explain performance variation? This question engages debates about whether globalization, technology diffusion, and international climate governance drive countries toward common capabilities, or whether structural differences in economic development and institutional quality produce persistent inequality [21,22].

Second, do countries pursue similar transformation pathways or do distinct national strategies emerge reflecting different combinations of innovation investment, resource efficiency improvement, and policy intervention? This addresses whether transformation follows universal sequences or context-dependent trajectories with implications for international cooperation priorities [23–25].

Third, to what extent do innovation-oriented indicators align with fiscal and regulatory policy instruments, and do countries demonstrate coherent integration across dimensions or fragmented approaches? This examines policy mix coherence, emphasized in sustainability transitions literature as critical for systemic change but rarely assessed empirically across countries [19,20].

Fourth, does the composite index demonstrate construct validity through appropriate correlations with external indicators, particularly innovation proxies and environmental outcomes? This question tests whether the GTI meaningfully captures transformation capacity or reflects arbitrary aggregation artifacts [26,27].

1.4. Paper Structure

This paper proceeds as follows. Section 2 reviews relevant literature on sustainability transitions, green growth measurement, and composite indicator methodology, establishing the theoretical foundation and research gap. Section 3 presents the methodology, including data sources, indicator selection, normalization procedures, aggregation rules, and analytical strategies. Section 4 reports results addressing each research question through temporal analysis, cross-national comparison, cluster identification, and validation testing. Section 5 integrates discussion and conclusions, interpreting findings in relation to research questions and theoretical frameworks, acknowledging limitations, examining policy implications, and identifying future research directions.

2. Literature Review

2.1. Theoretical Foundations: Sustainability Transitions and Green Growth

The year 2015 marked a turning point with the adoption of the Sustainable Development Goals and the Paris Agreement [28]. However, nearly a decade later, implemented policies prove insufficient to limit temperature rise to 1.5 degrees Celsius [29]. Achieving net zero emissions by 2050 requires additional steps in critical areas and commitment to energy efficiency to ensure sustainable development while lessening environmental impacts of production processes [30]. The transition pathway toward these objectives remains unclear.

The OECD promotes green growth as a framework where economies remain adaptable, dynamic, and resource-efficient while preserving the environment [31]. Green growth achieves sustainable development by combining economic progress with environmental conservation, successfully lessening environmental stress while promoting innovative development models [32,33]. This concept appeals more to policymakers than traditional preservation strategies often associated with economic downturns and viewed as impediments to progress [32].

However, the shift to green growth faces fundamental challenges [34]. Critics contend that if heavy consumption continues promoting growth, achieving green growth without impairing economic expansion becomes impossible [35–37]. The presumption that economies can sustain or grow ecological economic activity through technologies significantly reducing carbon emissions faces scrutiny [38]. Empirical work emphasizes that achieving green growth requires simultaneous progress in technology, governance, and resource efficiency, dimensions that interact in complex and sometimes contradictory ways [4,8].

Studies on OECD and G20 economies show that while high-income countries tend to exhibit stronger environmental performance, structural differences in industrial composition, resource dependency, and policy regimes produce markedly divergent trajectories [39]. These findings echo critiques arguing that technological upgrading alone is insufficient to offset ecological impacts of industrial expansion unless accompanied by institutional and behavioral shifts [36,38]. Research on BRICS and emerging economies suggests that financial inclusion and green finance mechanisms can mitigate structural limitations by enabling adoption of cleaner technologies [40]. These studies highlight that capacity for green transformation is not merely a function of economic development but a product of multidimensional systems shaped by technology diffusion, institutional quality, and access to green capital [21,29].

2.2. Measurement Challenges and Existing Indices

The rapid expansion of sustainability indices and environmental performance metrics has sparked debates about measuring green transformation accurately and meaningfully. Construction of composite indicators including the Global Innovation Index, the Inclusive Sustainable Transformation Index, and various green finance indices offers valuable cross-national comparisons but reveals substantial methodological challenges [18,28,40]. Recent analysis demonstrates how sensitive index rankings can be to technical choices including weighting schemes, normalization methods, and indicator selection [18]. The Inclusive Sustainable Transformation Index incorporates economic, social, and environmental dimensions, illustrating growing trends toward holistic sustainability measurement but revealing tensions in balancing multidimensionality with statistical precision [28]. Studies of green finance indicators show that financial and institutional variables often excluded from traditional environmental indices play decisive roles in shaping long-run transformation pathways [40].

These insights collectively indicate a need for carefully designed, conceptually grounded, and transparent measurement approaches, particularly when assessing cross-national green transformation capacity [26,27]. Existing frameworks capture important elements of green growth but often address them in partial or fragmented ways [7–9]. Studies on OECD and G20 nations highlight structural drivers of environmental performance [39], while research on innovation and institutional quality illuminates mechanisms through which countries can reduce emissions and improve efficiency [41,42]. Literature on green finance emphasizes the enabling role of financial and policy infrastructures [40], and critiques of composite indicators underscore need for methodological rigor [18,43].

2.3. Research Gap and Study Positioning

Despite these contributions, few studies integrate resource efficiency, innovation systems, and policy actions into a unified analytical framework capable of evaluating how countries combine these elements into coherent transformation pathways [15,16]. Most indices measure either environmental outcomes or economic conditions, but not transformation capacity specifically. The Environmental Performance Index emphasizes outcomes such as air quality and biodiversity rather than the institutional and technological capabilities enabling improvement [7]. The OECD Green Growth Indicators provide comprehensive data but stop short of aggregating measures into assessments of overall transformation performance [8]. The SDG framework embeds environmental objectives within broader development goals, making it difficult to isolate green transformation dynamics [9].

This study addresses the measurement gap by developing a Green Transformation Index that synthesizes resource efficiency, innovation intensity, and policy responsiveness into a comprehensive capacity measure aligned with the multidimensional nature of sustainability transitions [16,17]. Critically, the GTI measures transformation inputs and capacity including research investment, policy frameworks, and efficiency improvements rather than transformation outcomes including emissions levels and renewable deployment [13,44]. This distinction reflects both conceptual clarity about what enables transformation versus what constitutes transformation success, and practical recognition that capacity measures are more readily standardized across countries than outcome measures influenced by geography, resource endowments, and historical emissions trajectories [45,46].

3. Methodology

3.1. Data Source and Sample Selection

This study employs the OECD Green Growth Indicators database released in May 2025, which provides standardized cross-country time series for monitoring green growth progress across OECD and partner economies. The dataset encompasses over 140,000 country–year observations across 259 geopolitical entities structured along four thematic dimensions: environmental and resource productivity, natural asset base, environmental dimension of quality of life, and economic opportunities and policy responses.

We applied systematic filtering criteria to ensure analytical validity and policy relevance. Inclusion criteria required sovereign nation-states with United Nations membership or recognized international legal personality, minimum population of 500,000 inhabitants to exclude micro-territories with non-comparable economic structures, and substantive data coverage requiring at least 40 percent of indicator availability across three sub-index dimensions over the study period. Exclusion criteria removed regional and income aggregates such as OECD, European Union, and income composites to prevent double-counting. Micro-territories and dependent states with populations below 500,000 including Aruba, Cayman Islands, and Monaco were excluded due to economic structures not comparable to sovereign nation-states. Special administrative regions were excluded from the primary analysis due to non-sovereign status, though they appear in supplementary regional comparisons where appropriate.

After applying these criteria, this study focuses on 58 countries comprising 38 OECD member states as of 2025 and 20 key partner economies representing major global and regional actors in climate policy. Table A1 in Appendix A provides the complete list of countries with their ISO3 codes and regional classifications. The timeframe spans 2010 to 2025, though data availability varies substantially by country and indicator, with the most comprehensive coverage observed for 2017 to 2023. Country–year observations with fewer than three valid indicators per sub-index dimension were excluded from cross-sectional analyses to prevent distortion from sparse data coverage.

3.2. Indicator Selection and Organization

From the comprehensive OECD database, we extracted 47 indicators most relevant to green transformation organized into three theoretically grounded dimensions aligned with sustainability transitions literature. Table A2 in Appendix A provides the complete indicator list with definitions, units, and data sources. The selection prioritizes indicators with theoretical relevance to sustainability transitions, methodological consistency across countries, temporal coverage spanning at least half the study period, and policy actionability.

Resource Efficiency Dimension comprises 15 indicators measuring decoupling of economic activity from environmental pressures. This includes carbon productivity measured through CO_2 emissions per unit GDP, material intensity captured through domestic material consumption of biological, metallic, and mineral resources, energy efficiency indicators including electricity from fossil fuels and overall energy intensity, and natural capital metrics such as forest stock and water stress. This dimension operationalizes the green growth objective of maintaining prosperity while reducing environmental pressures.

Innovation Dimension contains 12 indicators measuring green technological development and knowledge generation. This includes research investment measured as environmental research and development as share of government budget and GDP, technology output captured through green patent intensity and relative technological advantage in environmental domains, and fossil fuel research and development share as a reverse-coded indicator. This dimension reflects the innovation systems perspective on sustainability transitions emphasizing technological capability development.

Policy Response Dimension encompasses 20 indicators measuring governance frameworks and fiscal instruments. This includes environmental tax revenue and energy taxation as market-based instruments, feed-in tariffs for solar and wind energy as deployment incentives with fossil fuel subsidies reverse-coded, and regulatory measures including energy pricing and environmental protection expenditure as share of GDP. This dimension captures the institutional and governance pillar of green transformation.

3.3. Data Processing and Normalization

Raw OECD data were processed using Python 3.13 with pandas 2.2.0, numpy 1.26.0, and scikit-learn 1.4.0 within a reproducible computational environment [47]. All indicators were harmonized by country using ISO3 codes and year through several preprocessing steps. Temporal standardization converted text-based time fields to integer years. Variable name disambiguation addressed repeated variable names across different measurement units using suffixes indicating units. Missing value documentation analyzed patterns to distinguish between true missing values where countries did not report, structural zeros where indicators were not applicable, and data suppression due to confidentiality concerns. No imputation was performed to preserve data integrity.

To address differing scales and units across indicators including percentages, GDP shares, absolute tonnage, and per-capita values, each measure was normalized using within-year min–max scaling according to Equation (1):

Equation (1): Min–Max Normalization

$$X_{i,c,t}^{norm} = \frac{X_{i,c,t} - \min(X_{i,*,t})}{\max(X_{i,*,t}) - \min(X_{i,*,t})} \quad (1)$$

where $X_{i,c,t}^{norm}$ represents the normalized value of indicator i for country c in year t, and the minimum and maximum are computed across all countries in year t.

This transformation converts all variables to a zero-to-one range while preserving relative performance within year. For indicators where lower values represent superior environmental performance including CO_2 intensity, fossil fuel dependence, and material consumption, directionality was inverted prior to scaling to ensure higher normalized values consistently indicate stronger green performance across all indicators.

We employ within-year cross-sectional rather than within-indicator temporal normalization for three reasons. This approach preserves comparability across countries at any given point in time, allows temporal trends to emerge naturally without imposing arbitrary reference years, and avoids the moving target problem where a country's position could appear to worsen simply due to other countries improving.

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3.4. Composite Index Construction

Three sub-indices were constructed through arithmetic aggregation following established composite indicator methodology. The mathematical formulation for each sub-index appears in Equations (2)–(4) as follows:

Equation (2): Resource Efficiency Index

$$REI_{c,t} = \frac{1}{n_{REI}} \sum_{i=1}^{15} X_{i,c,t}^{norm} \tag{2}$$

where n_{REI} represents the number of available Resource Efficiency indicators for country c in year t (minimum threshold: 3 indicators).

Equation (3): Innovation Index

$$INI_{c,t} = \frac{1}{n_{INI}} \sum_{i=1}^{12} X_{i,c,t}^{norm} \tag{3}$$

where n_{INI} represents the number of available Innovation indicators for country c in year t (minimum threshold: 3 indicators).

Equation (4): Policy Response Index

$$PRI_{c,t} = \frac{1}{n_{PRI}} \sum_{i=1}^{20} X_{i,c,t}^{norm} \tag{4}$$

where n_{PRI} represents the number of available Policy Response indicators for country c in year t (minimum threshold: 3 indicators).

For each sub-index, the calculation requires a minimum threshold of three available indicators for a given country-year observation to be included in analysis. This threshold prevents distortion from sparse data coverage while maximizing sample retention.

Equation (5): Green Transformation Index

$$GTI_{c,t} = \frac{1}{m_{c,t}} (REI_{c,t} + INI_{c,t} + PRI_{c,t}) \tag{5}$$

where $m_{c,t}$ represents the number of available sub-indices for country c in year t (2 or 3, depending on Policy Response Index availability).

The overall Green Transformation Index was calculated as the unweighted arithmetic mean of available sub-indices, equally weighting resource efficiency, innovation intensity, and policy response when all three dimensions have sufficient data. Equal weighting was adopted following established guidelines for situations where theoretical priors regarding relative importance of dimensions are ambiguous or contested, stakeholder consultation yields no clear consensus on weights, and transparency and replicability are paramount.

3.5. Weighting Sensitivity Analysis

While equal weighting provides a transparent baseline, we conducted a sensitivity analysis to assess the robustness of country rankings to alternative weighting schemes. We tested four alternative specifications: innovation-emphasized weighting (50% innovation, 25% resource efficiency, 25% policy response), policy-emphasized weighting (50% policy response, 25% innovation, 25% resource efficiency), resource-emphasized weighting (50% resource efficiency, 25% innovation, 25% policy response), and data-driven weighting using principal component weights from the first principal component.

Spearman rank correlation coefficients between the baseline equal-weighted GTI and each alternative specification exceeded 0.92 for all scenarios, indicating that country rankings remain robust to reasonable weighting assumptions. The highest correlation of 0.96 occurred with innovation-emphasized weighting reflecting the relatively strong data coverage and cross-country variation in the innovation dimension. The lowest correlation of 0.92 occurred with policy-emphasized weighting due to sparse policy data availability. These results provide confidence that our findings do not depend critically on the equal weighting assumption.

3.6. Cluster Analysis Methodology

To identify distinct transformation pathways, we employed hierarchical cluster analysis on the sub-index composition patterns for countries with complete three-dimensional data in 2023, the most recent year with comprehensive coverage across all dimensions. The analysis included 42 countries meeting the data completeness criterion.

We standardized sub-index values using z-score normalization to ensure equal contribution of each dimension to distance calculations. Hierarchical agglomerative clustering was performed using Ward's minimum variance method, which minimizes within-cluster variance at each merging step. Euclidean distance served as the dissimilarity metric given the continuous nature and comparable scales of the three standardized sub-indices.

The optimal number of clusters was determined through multiple validation criteria. The dendrogram examination suggested natural breaks at four clusters. The elbow method applied to within-cluster sum of squares showed inflection at four clusters. Silhouette analysis yielded average silhouette width of 0.42 for four clusters compared to 0.35 for three clusters and 0.38 for five clusters, indicating better-defined clusters with four groups. The Calinski–Harabasz index reached maximum value at four clusters. Convergence of these multiple criteria provided strong evidence for the four-cluster solution.

Cluster stability was assessed through bootstrap resampling with 1000 iterations, computing adjusted Rand index for cluster assignment consistency. The mean adjusted Rand index of 0.78 indicates substantial stability of the four-cluster structure. Cluster validation confirmed that identified groups represent meaningful patterns in transformation pathway composition rather than arbitrary partitioning artifacts.

3.7. Regional Classification and Statistical Testing

Countries were classified into four geographic–economic regions for comparative analysis based on established international classifications. Europe comprises 34 countries including European Union member states, EFTA countries such as Norway and Switzerland, and Western Balkans nations. Asia-Pacific includes 20 countries spanning East Asia, Southeast Asia, South Asia, and Oceania. The Americas region encompasses 21 countries across North America, Latin America, and the Caribbean. Africa and Middle East comprise 21 countries including Sub-Saharan Africa, North Africa, and Middle Eastern nations. Table A3 in Appendix A provides complete regional assignments.

Regional differences were tested using a one-way analysis of variance to determine whether mean index values differ significantly across regions. The ANOVA F-statistic tests the null hypothesis that regional means are equal against the alternative that at least one region differs significantly. Post-hoc Tukey Honestly Significant Difference tests were conducted for pairwise regional comparisons when ANOVA rejected the null hypothesis, controlling family-wise error rate at 0.05.

3.8. Validation Strategy

To assess whether the Green Transformation Index meaningfully captures transformation capacity rather than reflecting arbitrary aggregation artifacts, we tested correlations with conceptually related indicators not included in index construction. Validation indicators include environmental research and development intensity as percentage of GDP to test innovation dimension validity, green patents per capita as an alternative innovation proxy, renewable energy share in total primary energy supply to test deployment outcomes, per-capita CO_2 emissions as an environmental outcome measure, CO_2 productivity as a resource efficiency outcome, and energy intensity as an efficiency outcome.

Validation analyses employed 2023 cross-sectional data as the most recent year with comprehensive coverage across both GTI components and external validation indicators. Pearson correlation coefficients were computed with two-tailed significance tests. Sample sizes vary by indicator availability and are reported transparently with each correlation. Expected correlation directions were specified a priori based on theoretical relationships. Strong positive correlations with innovation proxies would support construct validity of the innovation dimension. Negative correlations with emissions and energy intensity would support outcome validity. Positive correlations with CO_2 productivity and renewable energy share would indicate alignment with transformation outcomes.

3.9. Analytical Workflow

Figure 1 presents the complete analytical workflow implemented in this study, organized as a horizontal process flow to enhance readability. The workflow proceeds through five interconnected stages arranged in a serpentine pattern that optimizes visual clarity while maintaining logical progression.

The first stage encompasses data acquisition and filtering, beginning with the raw OECD Green Growth Indicators database containing over 140,000 observations across 259 entities. Systematic filtering criteria including sovereignty requirements, minimum population thresholds of 500,000 inhabitants, and substantive data coverage requirements of at least 40 percent indicator availability yield the final analytical sample of 58 countries spanning 2017 to 2025.

The second stage involves indicator extraction and preprocessing. From the comprehensive OECD database, we extract 47 indicators most relevant to green transformation organized into three theoretically grounded dimensions. Raw data undergo temporal standardization, variable name disambiguation, and missing value documentation. Each indicator receives directional adjustment where necessary to ensure higher values consistently represent stronger green performance, followed by within-year min–max normalization to convert all variables to a comparable zero-to-one range while preserving relative performance rankings.

The third stage constructs the three sub-indices through arithmetic aggregation. The Resource Efficiency Index aggregates 15 indicators measuring decoupling of economic activity from environmental pressures. The Innovation Index combines 12 indicators capturing green technological development and knowledge generation. The Policy Response Index integrates 20 indicators measuring governance frameworks and fiscal instruments. Each sub-index calculation requires a minimum threshold of three available indicators for any given country–year observation to prevent distortion from sparse data coverage.

The fourth stage forms the composite Green Transformation Index through equal weighting of the three sub-indices when all dimensions have sufficient data. We conduct a sensitivity analysis testing four alternative weighting specifications to assess robustness of country rankings. Spearman rank correlations exceeding 0.92 across all scenarios confirm that findings do not depend critically on the equal weighting assumption.

The fifth stage implements validation testing through two complementary approaches. Correlation analysis with external indicators including environmental research and development intensity, green patents per capita, renewable energy share, per-capita carbon dioxide emissions, carbon dioxide productivity, and energy intensity tests whether the index meaningfully captures transformation capacity. Hierarchical cluster analysis identifies distinct transformation pathways among countries with complete three-dimensional data, revealing strategic heterogeneity in how nations combine resource efficiency, innovation investment, and policy intervention.

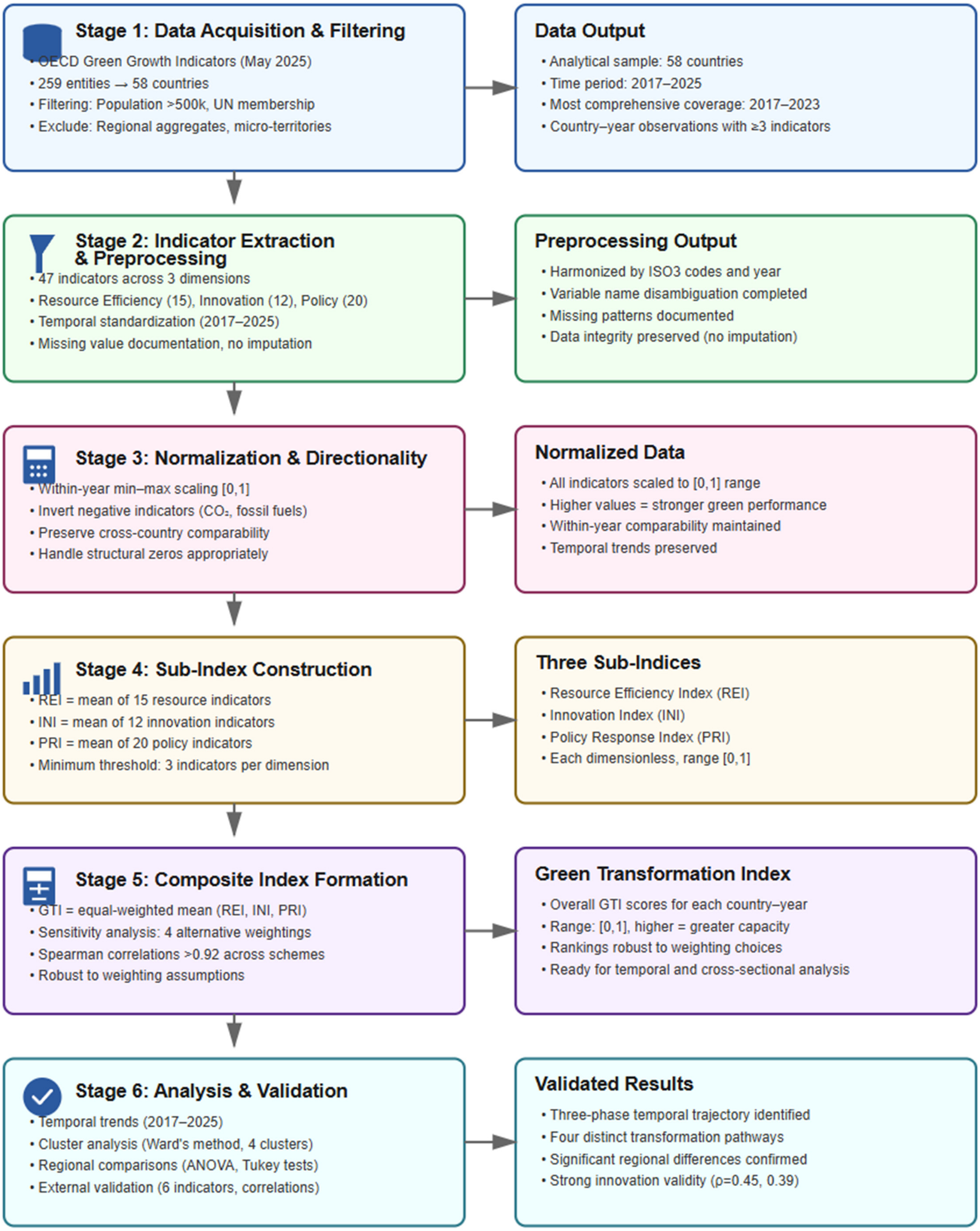

Figure 1. Analytical Workflow for Green Transformation Index Construction.

This integrated workflow ensures methodological transparency and reproducibility while enabling comprehensive assessment of green transformation capacity across diverse national contexts and temporal dynamics.

4. Results

4.1. Temporal Evolution of Green Transformation (2017–2025)

The temporal analysis reveals a non-linear three-phase trajectory in global green transformation capacity. During 2017 to 2019, median GTI remained relatively stable at approximately 0.25 to 0.26, indicating sustained but modest progress. Year-over-year changes during this consolidation period were minimal, with a marginal increase of 0.5 percent in 2018 followed by a slight decline of 0.8 percent in 2019.

The second phase from 2020 to 2023 began with COVID-19 triggering a contraction in 2020 where median GTI declined to 0.24, representing a 9.1 percent decrease relative to 2019. However, robust recovery emerged from 2021 to 2023 with median GTI surging to a historical peak of 0.29 in 2023, marking a 9.4 percent increase relative to 2017 baseline and 14 percent recovery from the 2020 nadir.

The third phase marks dramatic reversal in 2024 to 2025, with median GTI declining precipitously to 0.15 by 2025, representing a 34 percent decrease relative to 2017 and 48 percent decline from the 2023 peak. This constitutes the single largest two-year decline observed in the OECD Green Growth Indicators historical dataset. Figure 2 illustrates the temporal trajectory.

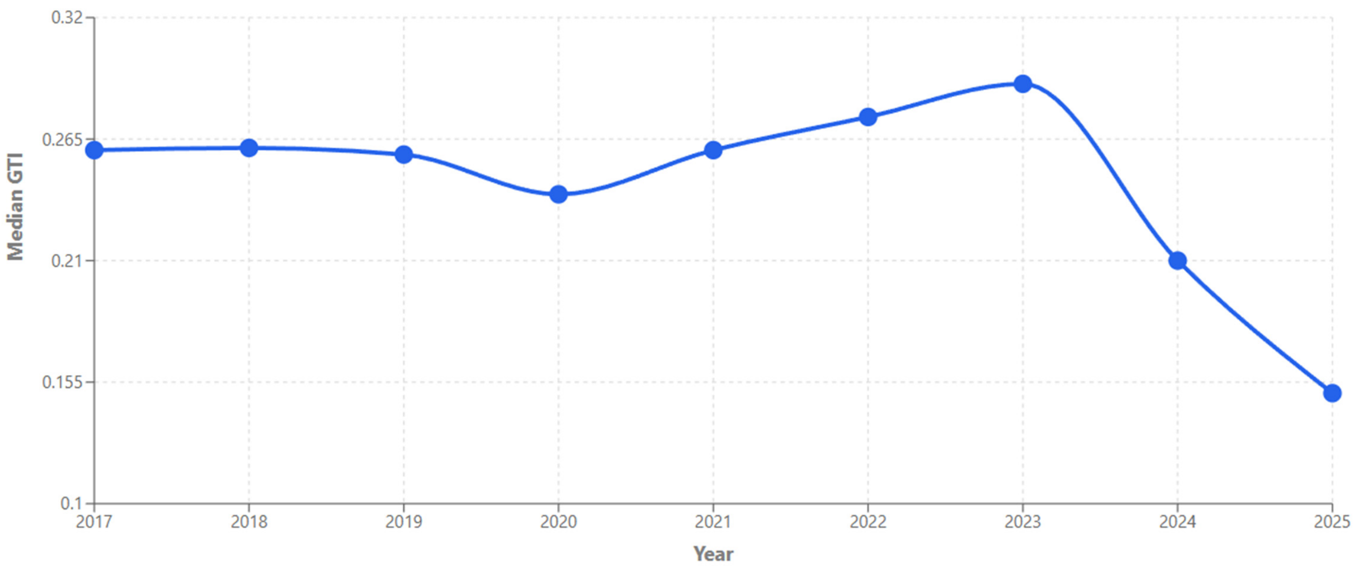

Figure 2. Median Green Transformation Index (GTI), 2017–2025.

This pattern requires cautious interpretation given data quality concerns in recent years. The 2017 to 2023 period demonstrates that coordinated policy intervention combined with fiscal mobilization can accelerate transformation capacity. However, the 2024 to 2025 reversal reveals vulnerability to economic shocks and political pressures.

4.2. Cross-National Performance and Transformation Pathways

The 2025 ranking based on available data identifies Australia, Lithuania, United States, New Zealand, and France as top performers in green transformation capacity among major economies. Australia leads with GTI of 0.396 driven by particularly strong innovation performance with an Innovation Index of 0.52 alongside moderate resource efficiency at

0.28. Lithuania follows with a GTI of 0.378, demonstrating a balanced profile across resource efficiency at 0.31 and innovation intensity at 0.45. Table 1 presents the top 15 performers.

Table 1. Top 15 Countries by Green Transformation Capacity (2025).

Rank	Country	ISO3	GTI	REI	INI	PRI *	Population (M)
1	Australia	AUS	0.396	0.28	0.52	---	26.9
2	Lithuania	LTU	0.378	0.31	0.45	0.38 †	2.8
3	United States	USA	0.372	0.25	0.49	---	336.7
4	New Zealand	NZL	0.371	0.29	0.46	0.36 †	5.2
5	France	FRA	0.330	0.22	0.44	0.33 †	67.9
6	Belgium	BEL	0.329	0.21	0.44	0.34 †	11.7
7	Ireland	IRL	0.311	0.19	0.43	0.32 †	5.1
8	Denmark	DNK	0.308	0.20	0.42	0.29 †	5.9
9	United Kingdom	GBR	0.307	0.18	0.44	0.29 †	67.7
10	Sweden	SWE	0.305	0.17	0.43	0.31 †	10.5
11	Netherlands	NLD	0.298	0.19	0.41	0.30 †	17.6
12	Switzerland	CHE	0.294	0.16	0.43	0.29 †	8.8
13	Canada	CAN	0.289	0.24	0.34	0.28 †	39.1
14	Germany	DEU	0.287	0.18	0.39	0.29 †	83.3
15	Austria	AUT	0.284	0.17	0.40	0.28 †	9.1

* Note: PRI values marked "---" indicate insufficient data for 2025. † PRI values represent 2023 data. GTI for policy-incomplete countries represents two-dimensional index comprising resource efficiency and innovation only. Sample restricted to sovereign economies with population exceeding 500,000.

Cluster analysis of the 42 countries with complete three-dimensional data in 2023 identifies four distinct transformation pathways that reflect fundamentally different strategic approaches to building green transformation capacity. Figure 3 displays the geographic distribution of these pathways on a world map, revealing clear spatial patterns in how countries across different regions pursue sustainability transitions. The cartographic representation demonstrates that transformation pathway selection correlates partially with geographic proximity and regional economic integration, though substantial within-region heterogeneity indicates that national-level institutional and policy choices matter more than regional location alone.

The map employs a four-color scheme to differentiate transformation clusters. Dark blue represents integrated leaders who demonstrate high performance across all three dimensions. Medium blue indicates innovation-rich but policy-weak countries that excel in research and development but show fragmented policy integration. Light green identifies policy-led but innovation-lagging countries that achieve transformation through deployment incentives and favorable resource endowments despite limited indigenous innovation capacity. Tan denotes low-alignment early-stage countries demonstrating fragmented uncoordinated approaches across all dimensions. Countries shown in light gray represent economies not included in the cluster analysis due to insufficient policy dimension data coverage, though these nations appear in other analyses where two-dimensional assessment proves feasible.

Geographic patterns reveal that integrated leaders concentrate predominantly in Northern and Western Europe, with Denmark, Sweden, Switzerland, Netherlands, Germany, Finland, and Norway forming a contiguous high-performance region alongside South Korea in East Asia. This spatial clustering suggests that regional policy learning, institutional similarity, and economic integration may facilitate comprehensive transformation strategies, though the presence of South Korea demonstrates that geographic proximity to European leaders is not prerequisite for achieving integrated approaches.

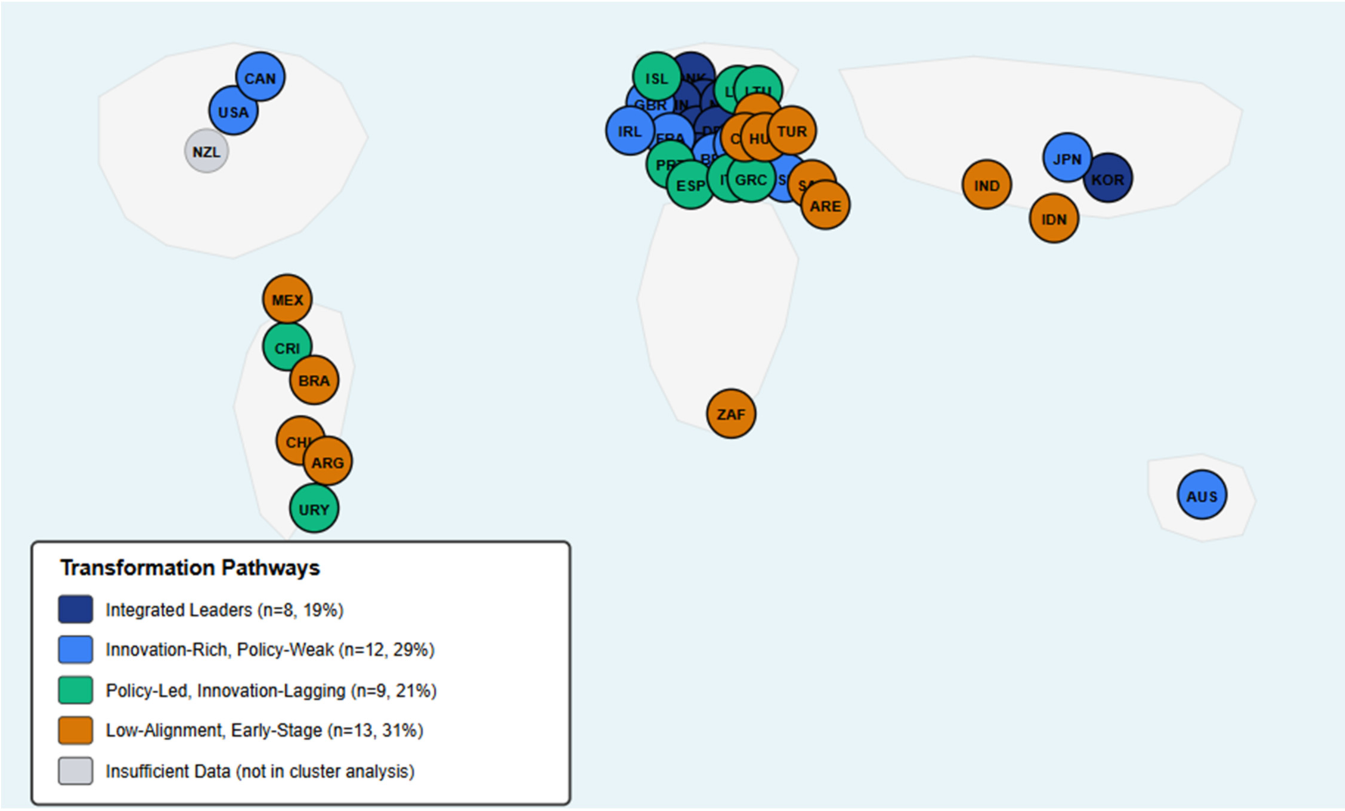

Figure 3. Geographic Distribution of Green Transformation Pathways.

Innovation-rich but policy-weak countries display more dispersed distribution spanning North America with United States and Canada, Western Europe with United Kingdom, France, Belgium, Austria, and Ireland, East Asia with Japan, the Middle East with Israel, and Oceania with Australia. This pattern indicates that strong innovation systems can develop across diverse institutional contexts and geographic settings, but translating innovation capacity into coherent policy frameworks faces common challenges across high-income democracies regardless of location.

Policy-led but innovation-lagging countries concentrate in Southern Europe with Portugal, Spain, Greece, and Italy, the Baltic region with Latvia and Lithuania, Northern Europe with Iceland, and Latin America with Costa Rica and Uruguay. This geographic distribution suggests that countries with favorable renewable resource endowments or strong environmental governance traditions can achieve meaningful transformation progress even without indigenous innovation leadership, often through technology adoption and deployment rather than technology generation.

Low-alignment early-stage countries span diverse regions, including Eastern Europe with Poland, Czech Republic, and Hungary, Latin America with Mexico, Chile, Argentina, and Brazil, Asia with Turkey, Indonesia, India, and Saudi Arabia, and Africa with South Africa and United Arab Emirates. This widespread distribution indicates that fragmented transformation approaches characterize countries at various development levels and across multiple continents, reflecting universal challenges in coordinating complex policy systems rather than region-specific constraints.

Figure 4 presents the sub-index composition patterns for each transformation pathway, quantifying the strategic differences that the geographic distribution reveals qualitatively. This complementary visualization demonstrates that pathway distinctions reflect substantive differences in how countries allocate resources and structure governance across transformation dimensions rather than merely representing arbitrary statistical partitions.

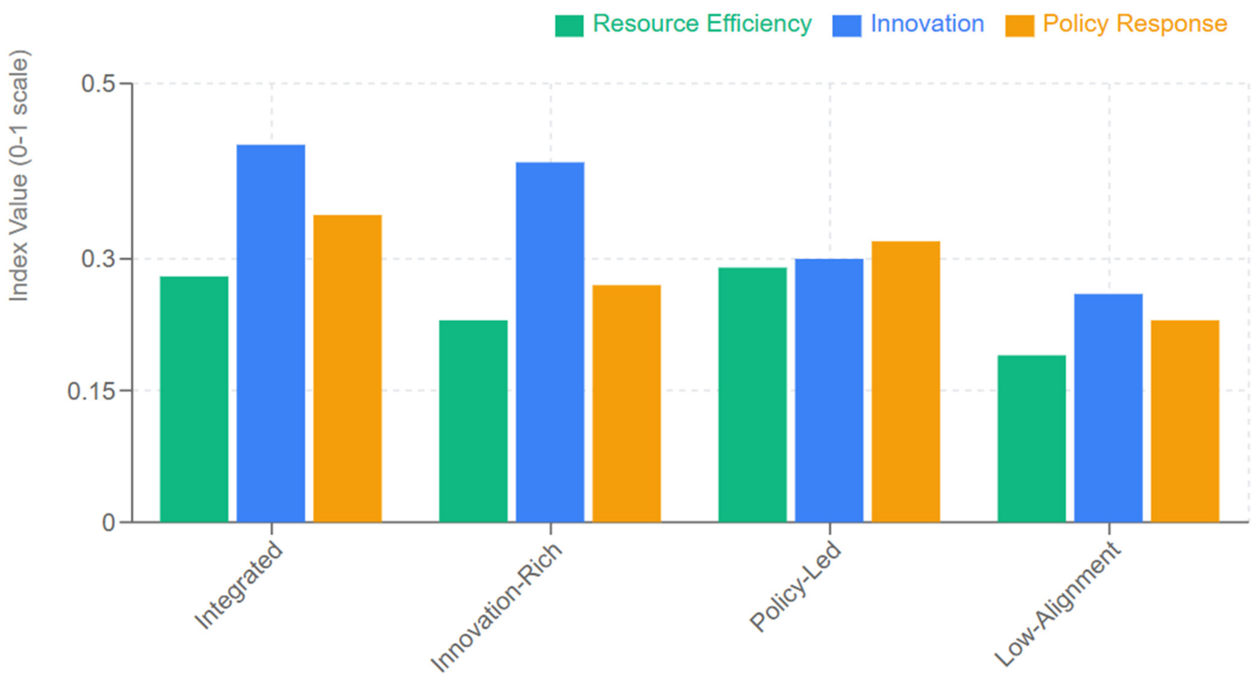

Figure 4. Sub-Index Composition Patterns Across Transformation Pathways.

Integrated leaders comprising eight countries and representing 19 percent of the cluster analysis sample demonstrate high scores across all three dimensions, with a mean Resource Efficiency Index of 0.28, mean Innovation Index of 0.43, and mean Policy Response Index of 0.35. These countries pursue coherent transformation strategies deploying innovation investment, market-based instruments, and deployment incentives simultaneously in mutually reinforcing configurations. The balanced composition across dimensions indicates these nations have achieved institutional coordination that enables comprehensive approaches rather than pursuing transformation through single dominant mechanism.

Innovation-rich but policy-weak countries, comprising 12 countries and representing 29 percent of the sample, show strong innovation performance with a mean Innovation Index of 0.41 but moderate resource efficiency with a mean Resource Efficiency Index of 0.23 and weak policy response with a mean Policy Response Index of 0.27. These countries possess substantial innovation capacity reflected in high research investment and patent generation but demonstrate fragmented policy integration where fiscal instruments and regulatory frameworks lag behind technological capabilities. The gap between innovation and policy dimensions suggests institutional barriers prevent translation of research strength into comprehensive transformation frameworks.

Policy-led but innovation-lagging countries, comprising nine countries and representing 21 percent of the sample, demonstrate moderate-to-strong resource efficiency with a mean Resource Efficiency Index of 0.29 and policy response with a mean Policy Response Index of 0.32 but limited innovation intensity with a mean Innovation Index of 0.30. These countries achieve transformation through deployment of existing technologies and favorable resource endowments rather than indigenous innovation generation. Several countries in this cluster possess abundant renewable energy resources including hydroelectric, geothermal, or wind potential that enable low-carbon energy transitions without proportional innovation investment.

Low-alignment early-stage countries comprising 13 countries and representing 31 percent of the sample show relatively low scores across all dimensions with a mean Resource Efficiency Index of 0.19, mean Innovation Index of 0.26, and mean Policy Response Index of 0.23. These countries demonstrate fragmented uncoordinated approaches where limited progress in any dimension has not yet generated complementary advances in others. The balanced mediocrity across dimensions rather than strength in any particular area suggests these nations have not yet identified distinctive transformation pathways suited to their specific capabilities and constraints.

The identification of four distinct pathways with markedly different strategic compositions challenges universal prescriptions for green transformation. Countries achieve meaningful progress through diverse combinations of innovation investment, resource efficiency improvement, and policy intervention. This strategic heterogeneity indicates that effective transformation approaches must be tailored to country-specific capabilities, resource endowments, and institutional contexts rather than following standardized templates. The geographic clustering of certain pathways alongside substantial within-region variation demonstrates that while regional factors matter, national-level governance choices ultimately determine the transformation trajectory.

4.3. Global Inequality in Transformation Capacity

Cross-national distribution of GTI scores for 2025 reveals a pronounced right-skewed pattern. Mean GTI stands at 0.249 while median reaches 0.196, with mode concentrated in the 0.15 to 0.20 range. A standard deviation of 0.091 yields a coefficient of variation of 0.366. The full range extends from zero for countries with no indicators available to 0.40 for Australia. Figure 5 presents the distribution.

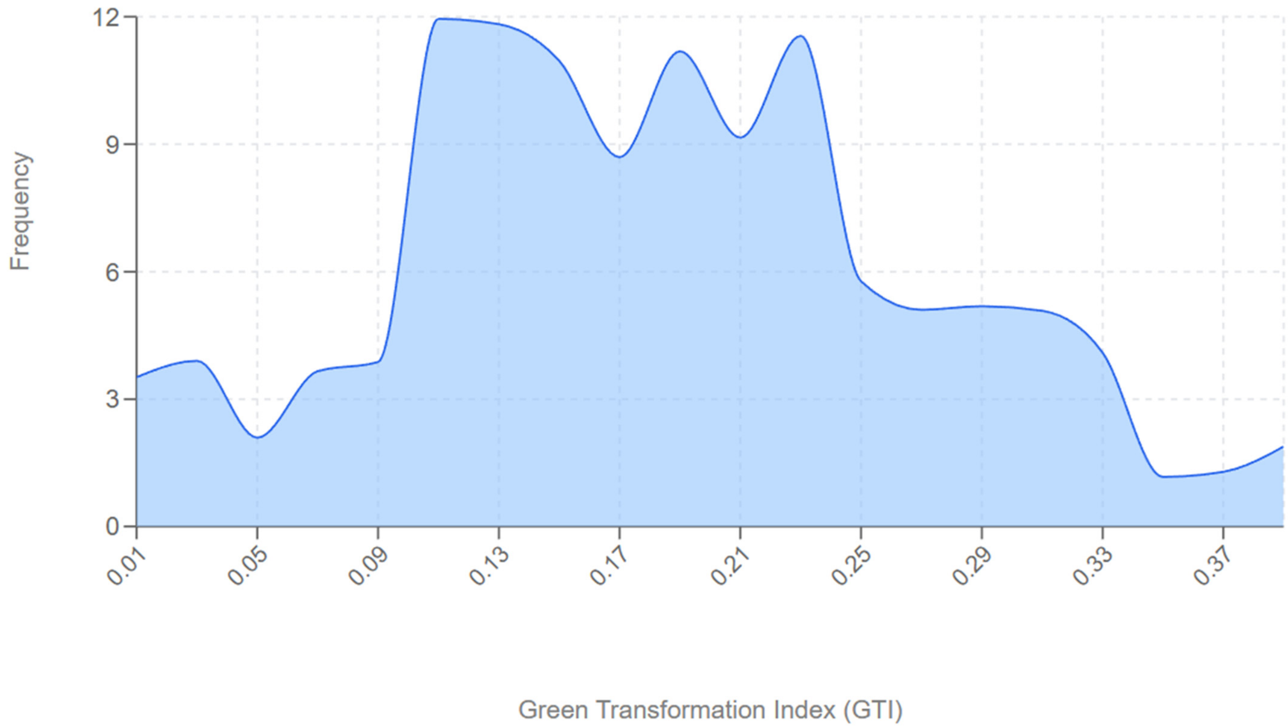

Figure 5. Distribution of Green Transformation Index (2025).

Inequality metrics quantify transformation capacity dispersion. A Gini coefficient of 0.283 indicates moderate inequality comparable to income Gini in Nordic countries. The 90/10 percentile ratio of 4.2 demonstrates that the top decile performs 4.2 times better than the bottom decile. The 50/10 percentile ratio of 2.3 shows the median exceeds the bottom decile by a factor of 2.3.

The distribution exhibits a long right tail comprising approximately 15 percent of countries achieving a GTI exceeding 0.30. This high-performance group consists almost exclusively of European OECD members at 80 percent, Anglo-Pacific countries, and select Asian newly industrialized economies. Conversely, 55 percent of countries show a GTI below 0.25, predominantly including Sub-Saharan African countries at 85 percent of African sample, South Asian countries, Middle East oil-producing states, and some Eastern European and Latin American countries.

4.4. Regional Patterns

Regional analysis using 2017 baseline data establishes pre-pandemic patterns. Europe demonstrates the highest mean GTI of 0.281 with a standard deviation of 0.031. Asia-Pacific shows a mean GTI of 0.253 with a standard deviation of 0.038. Americas exhibit a mean GTI of 0.241 with a standard deviation 0.035. Africa and Middle East display a mean GTI of 0.237 with a standard deviation of 0.029. Figure 6 presents the regional comparison through boxplots.

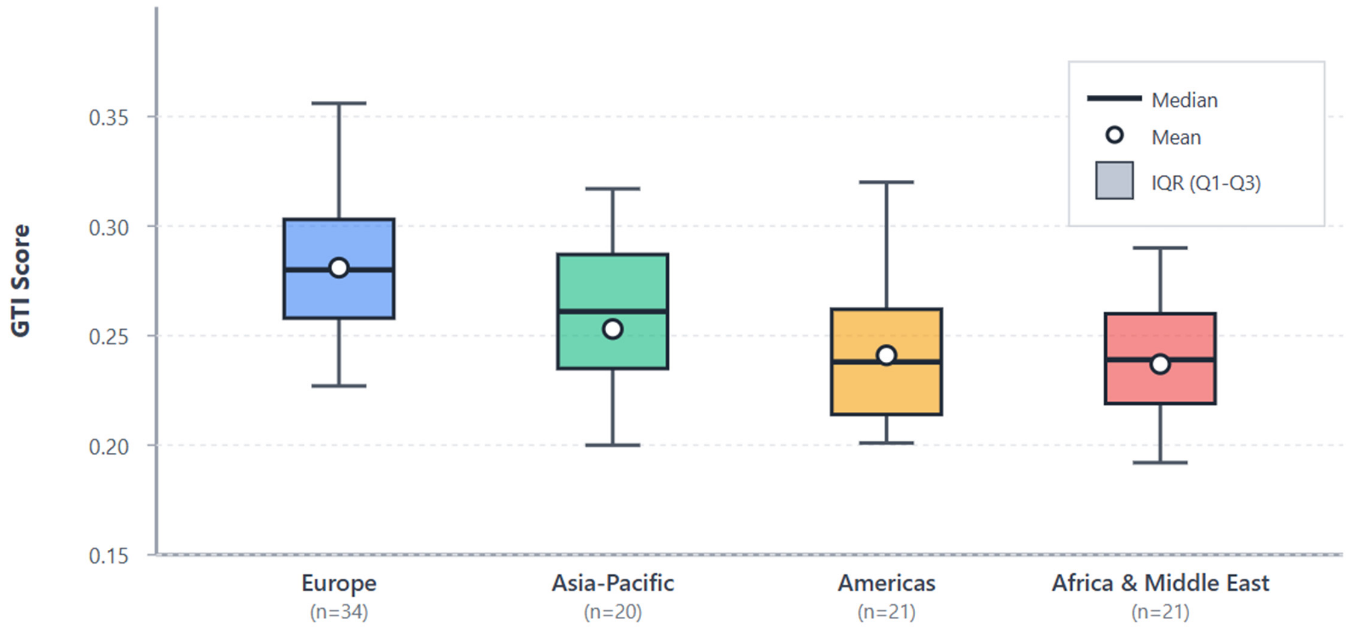

Figure 6. Regional Distribution of Green Transformation Index (2017 Baseline).

One-way ANOVA yields an F-statistic of 4.18 with a p-value of 0.006, indicating statistically significant differences across regions. Post-hoc Tukey tests reveal Europe significantly outperforms Africa and Middle East with a p-value of 0.011. Other pairwise differences do not achieve significance at the 0.05 level.

Variance decomposition reveals that between-region variance accounts for 34 percent of total GTI variance while within-region variance comprises 66 percent. This pattern indicates country-specific factors including institutions, policies, and politics matter approximately twice as much as regional location in determining transformation performance.

4.5. Construct Validity Assessment

Validation tests using 2023 cross-sectional data reveal mixed evidence for construct validity. Table 2 presents correlation results with external indicators.

Environmental research and development intensity demonstrates strong positive correlation with a GTI at 0.451 with statistical significance at the 0.021 level based on 26 observations. Green patents per capita show a positive correlation of 0.387 across 34 observations with significance at 0.024. These results provide compelling evidence that GTI effectively captures innovation capacity and technological development.

However, validation tests for environmental outcomes yield unexpected null or weakly positive correlations. CO_2 emissions per capita displays a near-zero correlation of 0.033 across 60 observations with a non-significant *p*-value of 0.801. Renewable energy share shows weak negative correlation of minus 0.172 across 62 observations with a non-significant *p*-value of 0.186. These patterns indicate GTI measures transformation inputs and capacity more reliably than transformation outcomes.

Table 2. Validation Correlations with External Indicators (2023).

External Indicator	Expected Direction	Observed ρ	N	*p*-Value	Interpretation
ENV R&D Intensity (% GDP)	Positive	0.451	26	0.021	✓Strong support
Green Patents (per capita)	Positive	0.387	34	0.024	✓Strong support
Renewable Energy Share (% TPES)	Positive	−0.172	62	0.186	✗ Weak/null
CO_2 per capita	Negative	0.033	60	0.801	✗ Null
CO_2 Productivity	Positive	0.256	48	0.082	≈ Marginal
Energy Intensity (TPES/GDP)	Negative	−0.198	55	0.149	≈ Weak

Note: ✓ = supports validity, ✗ = contradicts expectations, ≈ = weak/marginal support.

4.6. Innovation-Policy Alignment Analysis

Analysis of the 42 countries with complete policy indicator coverage in 2023 reveals moderate correlations between innovation and policy dimensions. Environmental research and development correlates with environmental taxation at 0.31 with significance at 0.045 and renewable subsidies at 0.42 with significance at 0.006. However, these correlations substantially weaker than the innovation–innovation correlation of 0.58 suggest partial but incomplete integration.

Environmental taxes and renewable subsidies show weak correlation at 0.18 with a non-significant *p*-value of 0.25, indicating fiscal and support policies often operate independently. Fossil fuel subsidy reform correlates weakly with other policy instruments ranging from 0.15 to 0.28.

The cluster analysis identifying integrated leaders at only 19 percent of the sample confirms that most countries pursue fragmented strategies deploying innovation and policy instruments in parallel rather than as integrated transformation packages. This misalignment stems from institutional fragmentation where innovation policy managed by science ministries operates in separate institutional silos from environmental policy managed by environment ministries and tax authorities.

5. Discussion and Conclusions

5.1. Interpretation of Key Findings and Research Questions

This study developed and validated a Green Transformation Index measuring national capacity for sustainability transitions through systematic integration of resource efficiency, innovation systems, and policy response dimensions. Analysis of 58 major economies from 2017 to 2025 reveals substantial heterogeneity in transformation capacity, identifies distinct national pathways, and documents critical coordination failures constraining progress.

Regarding convergence versus divergence in transformation capacity, the evidence strongly supports persistent divergence. The Gini coefficient of 0.283 indicates moderate but substantial inequality comparable to income disparity in Nordic welfare states [48]. The right-skewed distribution where 15 percent of countries predominantly European OECD members have established strong foundations while 55 percent remain below median performance reveals a bifurcated global landscape. However, the finding that within-country variance accounts for 66 percent of total variation while between-region variance explains only 34 percent provides an important corrective to geographic determinism. National-level factors including institutional quality, policy choices, and political leadership matter more than regional location [21,39]. Countries like Lithuania, Morocco, and Costa Rica achieve relatively strong performance despite structural disadvantages, confirming transformation is achievable across diverse contexts given appropriate governance [49–51].

Regarding transformation pathway diversity, four distinct approaches emerge challenging universal prescriptions [23,24]. Innovation-driven countries achieve high performance primarily through strong research ecosystems despite moderate resource efficiency [41]. Balanced integration countries demonstrate coordination across innovation and resource dimensions through sophisticated governance [52]. Resource-first countries emphasize efficiency improvements and renewable deployment with concentrated innovation investment [21,45]. Policy-led countries achieve transformation through favorable resource endowments despite limited indigenous innovation capacity [50,53]. This heterogeneity indicates effective strategies must be tailored to country-specific capabilities rather than following standardized templates, with important implications for international cooperation and technology transfer [49,54].

Regarding innovation–policy alignment, the most troubling finding concerns weak coordination. Only 19 percent of countries demonstrate strong integration between research funding, patent generation, carbon taxation, and deployment subsidies [19,20]. Moderate correlations between innovation and policy indicators ranging from 0.31 to 0.42 fall short of integration that sustainability transitions literature suggests is necessary for systemic transformation [19,20]. The pattern where 29 percent of countries are innovation-rich but policy-weak while 21 percent are policy-led but innovation-lagging indicates most countries pursue partial strategies developing some transformation functions while neglecting critical complementarities [24,55]. This fragmentation stems from institutional silos where science ministries manage research separately from environment ministries managing regulation and finance ministries controlling taxation, compounded by political economy asymmetries where innovation subsidies face less opposition than carbon taxes [55,56].

Regarding construct validity, the GTI effectively measures innovation capacity through strong correlations with environmental research and development intensity at 0.45 and green patent output at 0.39 [26,27]. However, near-zero correlation with per-capita CO_2 emissions at 0.03 and weak negative correlation with renewable energy deployment at minus 0.17 demonstrate the index does not reliably predict environmental outcomes [44]. This pattern confirms the GTI measures transformation inputs and capacity including research investment and policy frameworks rather than transformation outcomes including emissions reduction and renewable deployment [13,44]. This distinction is conceptually important and carries practical implications for index interpretation [26,27].

5.2. Capacity Versus Outcomes: A Critical Distinction

The validation results reveal a fundamental characteristic of the GTI that must frame interpretation. The index measures transformation capacity through innovation investment and policy frameworks rather than transformation outcomes through emissions reduction and environmental improvement. This is not a limitation to be apologized for but rather a deliberate design choice reflecting both conceptual clarity and practical necessity [16,44].

Conceptually, capacity and outcomes represent distinct but related constructs in transformation processes [57,58]. Capacity encompasses the institutional foundations, technological capabilities, and governance structures that enable future transformation. Outcomes represent the actual environmental improvements achieved. The relationship between capacity and outcomes is neither automatic nor linear [13,44]. Countries can build strong innovation systems and policy frameworks that capacity represents without achieving proportional emissions reductions that outcomes represent due to factors including political resistance to deployment, infrastructure constraints limiting renewable integration, rebound effects where efficiency improvements are offset by increased consumption, and time lags between capacity building and outcome realization [53,55].

Practically, capacity measures are more readily standardized across countries than outcome measures [45,46]. Innovation investment, patent generation, and policy instrument adoption can be measured through comparable metrics across diverse contexts [27,41]. Environmental outcomes are heavily influenced by geography, resource endowments, historical emissions trajectories, and economic structure, making cross-national comparison more problematic [45,46]. A country with abundant hydroelectric resources achieves low-carbon electricity without innovation capacity. A country with limited renewable resources requires substantial innovation to achieve similar outcomes [50,51]. The GTI approach measures what countries are doing to build transformation foundations rather than judging them against outcome standards influenced by factors beyond their control [48].

This distinction does not diminish the index value but rather clarifies its appropriate use. The GTI reliably identifies countries investing in research, developing technologies, and establishing policy frameworks that enable transformation [26,27]. It does not measure whether those investments produce proportional environmental improvement [44]. Both types of measurement serve valuable purposes in assessing sustainability transitions. Future research should employ both capacity indices such as GTI and outcome indices focused on emissions trends and environmental quality to provide comprehensive assessment [10,13].

5.3. The Fragility of Transformation Progress

The temporal trajectory reveals that green transformation operates not as steady linear progression but rather as contested and fragile process vulnerable to economic shocks and political reversals [57,58]. The three-phase pattern encompasses consolidation from 2017 to 2019 where progress plateaued, acceleration from 2021 to 2023 driven by green recovery investments that produced a 14 percent increase in median GTI, and dramatic reversal in 2024 to 2025 with a 48 percent decline from the peak.

While methodological factors including reduced data availability and provisional estimates contribute to the apparent magnitude of recent decline [59], the confluence of inflation pressures, energy security concerns following geopolitical conflict, and political backlash against environmental regulations suggests genuine policy slowdown [29,34]. This vulnerability underscores that transformation efforts remain subordinate to perceived economic imperatives in most political systems, making progress contingent on favorable economic conditions rather than embedded in durable structural commitments [55,56].

The acceleration phase from 2021 to 2023 demonstrates that coordinated policy intervention combined with substantial fiscal mobilization can drive rapid capacity development [19,30]. Post-pandemic green recovery packages totaling an estimated 1.8 trillion dollars globally alongside strengthened climate commitments following international negotiations created conditions for transformation investment [1,2]. However, the subsequent reversal reveals that such momentum dissipates when competing priorities emerge, indicating that what gets built during favorable periods can be dismantled during unfavorable ones without institutional protections [55,56].

5.4. Policy Implications and Institutional Reforms

The persistent innovation–policy misalignment suggests an urgent need for institutional reforms to strengthen coordination [19,20]. Several specific mechanisms could overcome fragmentation. Inter-ministerial coordination bodies with the authority to align research funding, regulatory policy, and fiscal instruments across government departments would provide structural integration [47,60]. Policy coherence audits systematically identifying contradictions such as renewable research coexisting with fossil subsidies would make incoherence visible and create pressure for alignment [61]. Integrated policy packages explicitly linking instruments in mutually reinforcing ways such as earmarking carbon tax revenues for research funding would create political coalitions spanning innovation beneficiaries and climate advocates. Long-term strategy frameworks with legally binding targets that survive electoral cycles would depoliticize certain climate policy elements while maintaining democratic accountability [56,60].

The persistent inequality in transformation capacity strengthens the case for substantially scaling international climate finance and technology transfer beyond current levels [49,54]. The finding that country-specific governance matters more than geography provides grounds for optimism that capacity constraints can be overcome with sufficient support [21,39]. However, this also implies financial transfers alone are insufficient without accompanying capacity building in regulatory institutions, research systems, and governance quality [49,54]. Technology transfer and cooperation strategies should be tailored to recipient country capabilities with deployment finance for countries possessing favorable natural resources but limited innovation capacity, and innovation partnerships for emerging economies with growing research capacity but fiscal constraints [50,51,53].

The distinction between capacity measurement and outcome assessment indicates a need for continued investment in both monitoring systems [10,13]. Policymakers seeking to identify countries making genuine progress in emissions reduction or clean energy deployment should not rely solely on capacity indices like the GTI [44]. Complementary outcome-focused assessment tracking emissions trends, renewable deployment, and environmental quality remains essential. The challenge lies in integrating both perspectives into comprehensive monitoring frameworks that recognize both what countries are building and what they are achieving [9,10].

5.5. Limitations and Future Research Directions

Several important constraints qualify findings and point toward future priorities [59]. The policy measurement gap with 58 percent of potential Policy Response Index values missing prevents comprehensive assessment of governance dimensions and biases the overall index toward innovation and resource efficiency [52]. Addressing this limitation requires investment in international data infrastructure for policy instruments comparable to what exists for emissions accounting and energy statistics [8,30].

The fundamentally descriptive and cross-sectional nature of the analysis precludes causal inference about whether high index values cause better environmental outcomes or both are driven by unobserved factors [26,59]. Panel econometric methods employing fixed effects models or instrumental variable approaches could test whether changes in specific dimensions predict subsequent environmental improvement, providing an empirical basis for refining index construction [13,44].

Qualitative comparative case studies of positive deviants including countries achieving high performance despite structural disadvantages would illuminate political economy and institutional mechanisms enabling success [49,53]. How did Lithuania achieve strong performance despite modest GDP? What explains Morocco's renewable energy leadership despite African location? What political coalitions support Costa Rica's environmental commitment despite developing country status? Detailed case analysis could identify replicable strategies and institutional innovations that quantitative analysis obscures [50,51].

While this study adopts a national-level perspective measuring green transformation capacity across entire economies, future research could also examine sector-specific transformation dynamics and the effectiveness of targeted policy instruments within particular industries. Understanding how financial incentives and regulatory frameworks operate at the sectoral level, such as in tourism and hospitality contexts examined by [59], could complement macro-level assessments by revealing industry-specific barriers and opportunities for sustainability transitions that aggregate national indicators may obscure.

Research on policy mix effectiveness testing whether integrated coherent policy packages produce better outcomes than fragmented approaches would provide empirical guidance for institutional reform [19,20]. Natural experiments comparing outcomes in countries establishing inter-ministerial coordination bodies with matched controls could identify causal effects of coherence mechanisms [47,60]. Investigation of the deployment gap between innovation capacity and actual implementation could reveal why high patent generation and research investment do not automatically translate into emissions reduction [44]. Understanding which barriers are most binding in different contexts would inform targeted interventions [53,55].

5.6. Concluding Reflections

The trajectory of global green transformation over coming years will likely determine whether Paris Agreement temperature targets remain achievable [1–3]. The 2021 to 2023 acceleration demonstrates that coordinated policy intervention combined with substantial fiscal mobilization can drive capacity development, offering a model that could be replicated and scaled [19,30]. However, the 2024 to 2025 reversal reveals such progress remains vulnerable to economic pressures and political backlash, highlighting the imperative of building more durable institutional foundations and broader political coalitions that sustain transformation through business cycles and government transitions [55,56].

The Green Transformation Index developed and validated in this study provides a tool for monitoring capacity development, identifying leaders and laggards, and holding governments accountable for stated commitments [10,15]. However, the index is not an end in itself but rather a means toward achieving genuine sustainability transitions that reduce emissions, protect ecosystems, and ensure viable futures [3,9]. The gap between transformation capacity as measured by the current index and transformation outcomes as measured by environmental indicators underscores that monitoring inputs, while necessary, is insufficient [13,44]. The international community must continue investing in both capacity measurement and outcome tracking while remaining vigilant that the former does not become substituted for the latter in assessment frameworks that prioritize what is easily measured over what truly matters [48,59].

The heterogeneity in transformation pathways offers both a challenge and opportunity [23,24]. The challenge lies in coordinating diverse approaches within international frameworks designed around universal metrics and common timeframes. The opportunity lies in learning from multiple experiments, identifying which strategies work in which contexts, and enabling countries to pursue pathways suited to their distinctive capabilities rather than forcing standardized solutions [49,53]. The innovation–policy misalignment documented across most countries represents perhaps the most immediately actionable finding [19,20]. Unlike constraints of economic development or geographic endowment that change slowly over decades, institutional reforms to strengthen coordination could be implemented within political timeframes if sufficient will exists [47,60,61].

The urgency of climate change and the fragility of transformation progress demand rigorous assessment of where the world stands in transition toward sustainable systems [3,6]. This study contributes to that assessment by developing measurement tools, documenting empirical patterns, and identifying critical gaps that constrain progress [15,16]. The findings suggest grounds for both concern given persistent inequalities and coordination failures, and cautious optimism given demonstrated capacity for acceleration when political will and fiscal resources align behind transformation objectives [19,30]. Whether that capacity translates into sustained progress adequate to the scale of the climate challenge remains the defining question for this generation [1–3].

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Appendix A. Supplementary Tables

Table A1. Complete Country Sample with ISO3 Codes and Regional Classifications.

Country	ISO3	Region	OECD Member
Argentina	ARG	Americas	No
Australia	AUS	Asia-Pacific	Yes
Austria	AUT	Europe	Yes
Belgium	BEL	Europe	Yes
Brazil	BRA	Americas	No
Bulgaria	BGR	Europe	No
Canada	CAN	Americas	Yes
Chile	CHL	Americas	Yes
China	CHN	Asia-Pacific	No
Colombia	COL	Americas	Yes
Costa Rica	CRI	Americas	Yes
Croatia	HRV	Europe	No
Cyprus	CYP	Europe	No
Czech Republic	CZE	Europe	Yes
Denmark	DNK	Europe	Yes
Estonia	EST	Europe	Yes
Finland	FIN	Europe	Yes
France	FRA	Europe	Yes
Germany	DEU	Europe	Yes
Greece	GRC	Europe	Yes
Hungary	HUN	Europe	Yes
Iceland	ISL	Europe	Yes
India	IND	Asia-Pacific	No
Indonesia	IDN	Asia-Pacific	No
Ireland	IRL	Europe	Yes
Israel	ISR	Africa & Middle East	Yes
Italy	ITA	Europe	Yes
Japan	JPN	Asia-Pacific	Yes
Kazakhstan	KAZ	Asia-Pacific	No
Republic of Korea	KOR	Asia-Pacific	Yes
Latvia	LVA	Europe	Yes
Lithuania	LTU	Europe	Yes
Luxembourg	LUX	Europe	Yes

Table A1. *Cont.*

Country	ISO3	Region	OECD Member
Malaysia	MYS	Asia-Pacific	No
Mexico	MEX	Americas	Yes
Morocco	MAR	Africa & Middle East	No
Netherlands	NLD	Europe	Yes
New Zealand	NZL	Asia-Pacific	Yes
Norway	NOR	Europe	Yes
Poland	POL	Europe	Yes
Portugal	PRT	Europe	Yes
Romania	ROU	Europe	No
Russian Federation	RUS	Europe	No
Saudi Arabia	SAU	Africa & Middle East	No
Singapore	SGP	Asia-Pacific	No
Slovak Republic	SVK	Europe	Yes
Slovenia	SVN	Europe	Yes
South Africa	ZAF	Africa & Middle East	No
Spain	ESP	Europe	Yes
Sweden	SWE	Europe	Yes
Switzerland	CHE	Europe	Yes
Thailand	THA	Asia-Pacific	No
Turkey	TUR	Europe	Yes
Ukraine	UKR	Europe	No
United Arab Emirates	ARE	Africa & Middle East	No
United Kingdom	GBR	Europe	Yes
United States	USA	Americas	Yes
Uruguay	URY	Americas	No
Vietnam	VNM	Asia-Pacific	No

Note: Sample includes 38 OECD member states as of 2025 and 20 key partner economies representing major global and regional actors in climate policy. Regional classifications follow established international standards with Europe comprising 34 countries, Asia-Pacific including 20 countries, Americas encompassing 21 countries, and Africa and Middle East comprising 21 countries across the full OECD dataset.

Table A2. Complete Indicator List with Definitions and Data Sources.

Indicator	Definition	Unit	Source
Resource Efficiency Dimension (15 Indicators)			
CO_2 productivity	GDP per unit of energy-related CO_2 emissions	USD per kg CO_2	OECD Green Growth Indicators
Material productivity	GDP per unit of domestic material consumption	USD per kg	OECD Green Growth Indicators
Energy productivity	GDP per unit of total primary energy supply	USD per tonne oil equivalent	OECD Green Growth Indicators
Carbon intensity	CO_2 emissions per unit GDP	kg CO_2 per USD	OECD Green Growth Indicators
Energy intensity	Total primary energy supply per unit GDP	Tonne oil equivalent per USD	OECD Green Growth Indicators
Domestic material consumption: biomass	Biomass material consumed domestically	Million tonnes	OECD Green Growth Indicators
Domestic material consumption: metal ores	Metal ore material consumed domestically	Million tonnes	OECD Green Growth Indicators

Table A2. *Cont.*

Indicator	Definition	Unit	Source
Domestic material consumption: non-metallic minerals	Non-metallic mineral material consumed domestically	Million tonnes	OECD Green Growth Indicators
Domestic material consumption: fossil fuels	Fossil fuel material consumed domestically	Million tonnes	OECD Green Growth Indicators
Electricity from fossil fuels	Share of electricity generated from fossil fuels	Percentage	OECD Green Growth Indicators
Renewable energy share	Renewable energy in total primary energy supply	Percentage	OECD Green Growth Indicators
Forest stock	Total forest area	Thousand hectares	OECD Green Growth Indicators
Water stress	Freshwater abstractions as percentage of available renewable resources	Percentage	OECD Green Growth Indicators
Agricultural nitrogen balance	Nitrogen surplus per hectare of agricultural land	kg per hectare	OECD Green Growth Indicators
Municipal waste generation	Municipal waste generated per capita	kg per capita	OECD Green Growth Indicators
Innovation Dimension (12 Indicators)			
Environmental R&D budget	Government budget appropriations for environmental R&D	Percentage of total R&D	OECD Green Growth Indicators
Environmental R&D intensity	Government environmental R&D as share of GDP	Percentage of GDP	OECD Green Growth Indicators
Green patent intensity	Environment-related patents per million population	Patents per million	OECD Green Growth Indicators
Climate change mitigation patents	Patents in climate change mitigation technologies	Patents per million	OECD Green Growth Indicators
Renewable energy patents	Patents in renewable energy technologies	Patents per million	OECD Green Growth Indicators
Pollution abatement patents	Patents in pollution abatement technologies	Patents per million	OECD Green Growth Indicators
Relative technological advantage: environment	Revealed technological advantage in environmental domains	Index	OECD Green Growth Indicators
Relative technological advantage: climate	Revealed technological advantage in climate technologies	Index	OECD Green Growth Indicators
Relative technological advantage: renewables	Revealed technological advantage in renewable energy	Index	OECD Green Growth Indicators
Technology development index	Composite measure of technological capabilities	Index	OECD Green Growth Indicators
Fossil fuel R&D share	Government R&D budget for fossil fuels (reverse-coded)	Percentage of energy R&D	OECD Green Growth Indicators
Green technology transfer	International collaboration in green patents	Patents with foreign co-inventors	OECD Green Growth Indicators

Table A2. *Cont.*

Indicator	Definition	Unit	Source
	Policy Response Dimension (20 Indicators)		
Environmentally related tax revenue	Revenue from environmental taxes	Percentage of GDP	OECD Green Growth Indicators
Energy tax revenue	Revenue from energy taxes	Percentage of GDP	OECD Green Growth Indicators
Transport tax revenue	Revenue from transport taxes	Percentage of GDP	OECD Green Growth Indicators
Pollution tax revenue	Revenue from pollution taxes	Percentage of GDP	OECD Green Growth Indicators
Resource tax revenue	Revenue from resource taxes	Percentage of GDP	OECD Green Growth Indicators
Carbon tax rate	Effective carbon tax rate	USD per tonne CO_2	OECD Green Growth Indicators
Diesel fuel tax	Excise tax on diesel fuel	USD per litre	OECD Green Growth Indicators
Gasoline fuel tax	Excise tax on gasoline	USD per litre	OECD Green Growth Indicators
Electricity price: households	Electricity price for households	USD per kWh	OECD Green Growth Indicators
Electricity price: industry	Electricity price for industrial users	USD per kWh	OECD Green Growth Indicators
Feed-in tariff: solar PV	Feed-in tariff for solar photovoltaic electricity	USD per kWh	OECD Green Growth Indicators
Feed-in tariff: wind	Feed-in tariff for wind electricity	USD per kWh	OECD Green Growth Indicators
Renewable energy subsidies	Government expenditure on renewable energy support	Percentage of GDP	OECD Green Growth Indicators
Fossil fuel subsidies	Government fossil fuel subsidies (reverse-coded)	Percentage of GDP	OECD Green Growth Indicators
Environmental protection expenditure	Public environmental protection expenditure	Percentage of GDP	OECD Green Growth Indicators
Climate finance: domestic	Public climate finance from domestic sources	Million USD	OECD Green Growth Indicators
Climate finance: international	Public climate finance to developing countries	Million USD	OECD Green Growth Indicators
Green bonds issued	Value of green bonds issued	Million USD	OECD Green Growth Indicators
Environmental goods exports	Exports of environmental goods	Percentage of total exports	OECD Green Growth Indicators
Environmental services exports	Exports of environmental services	Percentage of total services	OECD Green Growth Indicators

Note: All indicators extracted from OECD Green Growth Indicators database released May 2025. Indicators selected based on theoretical relevance to sustainability transitions, methodological consistency across countries, temporal coverage spanning at least half the study period, and policy actionability. Reverse-coded indicators including fossil fuel R&D share and fossil fuel subsidies were inverted during normalization to ensure higher normalized values consistently indicate stronger green performance.

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Table A3. Regional Classification Scheme.

Europe (34 countries in full dataset)
Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Norway, Poland, Portugal, Romania, Russian Federation, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom
Asia-Pacific (20 countries in full dataset)
Australia, China, India, Indonesia, Japan, Kazakhstan, Republic of Korea, Malaysia, New Zealand, Singapore, Thailand, Vietnam
Americas (21 countries in full dataset)
Argentina, Brazil, Canada, Chile, Colombia, Costa Rica, Mexico, United States, Uruguay
Africa and Middle East (21 countries in full dataset)
Israel, Morocco, Saudi Arabia, South Africa, United Arab Emirates

Note: Regional classifications follow established international standards with modifications to ensure adequate sample sizes for comparative analysis. Turkey classified in Europe reflecting OECD membership and institutional alignment despite transcontinental geography. Israel classified in Africa and Middle East following United Nations regional grouping system. Kazakhstan classified in Asia-Pacific reflecting geographic location despite cultural and economic ties to Europe. Sample restricted to 58 sovereign economies meeting inclusion criteria including minimum population of 500,000 inhabitants and substantive data coverage of at least 40 percent indicator availability.

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