IJE | INDONESIAN JOURNAL OF ENERGY
P-ISSN: 2549-1016 | E-ISSN: 2549-760X
available online at www.ije-pyc.org

Published by: The Purnomo Yusgiantoro Center

Measuring Sustainability at the Climate–Energy Nexus

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Article History

Received 30 December 2025
Accepted 2 June 2026
Available 31 August 2026

Abstract

Balancing climate change mitigation, secure and affordable energy supply, and sustained economic activity remains a major sustainability challenge. This study introduces the Climate–Energy Sustainability Index (CESI), a composite indicator that captures six normalized dimensions: adjusted net savings, carbon emissions per capita, carbon intensity of energy use, renewable energy share, energy use per capita, and climate stability measured through temperature anomalies. CESI employs geometric-mean aggregation to enforce non-substitutability across dimensions and to penalize unbalanced development paths. Mathematically, the index remains within a fixed range. The direction of the normalized component scores is preserved. It also shows conditional scale invariance under the given normalization framework. The index is applied to 76 countries over the period 1990–2023. The results reveal substantial cross-country and regional heterogeneity in climate–energy sustainability outcomes. The global average CESI shows a gradual long-term increase, although the trajectory is non-linear and marked by periodic fluctuations. Cross-country dispersion changed over time. It increased from 1993 to 2013 but declined by 2023. This shows a recent reduction in dispersion, rather than consistent long-term convergence. Europe shows the strongest regional performance. Its performance is also more consistent over time. South America performs relatively well, but its results vary more over time. Africa, Asia, and Oceania show weaker progress, with some variation across the years. At the country level, Italy, Panama, Chile, the United Kingdom, and Japan emerge as the top performers in 2023. Tuvalu, Trinidad and Tobago, and several African and small-island states remain at the lower end of the distribution. Scatter-plot analysis indicates that no single factor determines CESI performance. Adjusted net savings and renewable energy share show weak positive relationships with CESI, suggesting that greater savings or renewable deployment alone does not guarantee better sustainability outcomes. Energy use per capita, carbon intensity, and per capita CO_2 emissions display weak negative associations. Climate–energy sustainability depends on the combined interaction of cleaner energy structure, efficient energy use, and lower carbon dependence rather than improvement in any single indicator. CESI captures observed sustainability outcomes rather than policy effort or transition readiness. As a result, similar index values may reflect different development pathways.

Keywords:
Climate Energy Sustainability Index (CESI), climate policy, composite sustainability index, energy efficiency, renewable energy

1. Introduction

Sustainability has emerged as one of the most critical global challenges of the twenty-first century, driven by the dual imperative of mitigating climate change and ensuring equitable access to secure

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and affordable energy. The climate–energy nexus lies at the center of this challenge, as energy systems constitute the largest source of greenhouse gas emissions, while climate instability increasingly threatens the resilience of energy infrastructure and long-term economic development pathways. Addressing these interconnected risks requires integrated analytical approaches that simultaneously consider environmental, economic, and social dimensions of sustainability.

Recent trends in renewable energy deployment reflect both significant progress and continuing urgency. In 2024, global renewable energy capacity expanded by a record 15.1 percent, reaching 4,448 GW, with approximately 585 GW added within a single year, largely driven by solar and wind technologies. However, achieving the global commitment to triple renewable energy capacity by 2030 will require sustained acceleration, with annual growth rates of around 16.6 percent (IRENA, 2025). These developments underscore substantial cross-country disparities in energy transitions and sustainability performance.

At the same time, rising global temperatures and uneven climate impacts indicate that sustainability progress remains highly unequal across countries. This raises a key question: which countries perform best at the climate–energy interface, and how can such performance be systematically assessed? Existing individual indicators offer only partial insights. For example, higher adjusted net savings per capita does not necessarily indicate sustainability if it is accompanied by rising emissions or resource depletion. Similarly, low per-capita carbon emissions alone cannot ensure sustainability when energy systems are inefficient, or climate vulnerability is high. Other commonly used indicators—such as carbon intensity, renewable energy share, energy consumption, and temperature anomalies—also provide fragmented and sometimes misleading signals when considered in isolation.

Composite indices, including those developed by the World Energy Council (2024), Environmental Performance Index (Wendling et al., 2020), Sustainable Development Index (Hickel, 2020), and ND-GAIN Country Index (University of Notre Dame, 2024), have improved sustainability assessment by combining multiple dimensions into a single framework. However, important gaps remain. Most existing indices either emphasize specific domains (such as environmental performance or climate vulnerability) or allow a high degree of compensability, where strong performance in one dimension can offset weak performance in another. This can mask critical imbalances in the climate–energy nexus. In addition, these indices generally rely on additive or weakly constrained aggregation methods, which do not adequately penalize uneven development paths. They also tend to treat indicators as largely independent, limiting their ability to reflect the tightly interconnected and non-linear relationships between economic activity, energy use, emissions, and climate stability. Existing frameworks do not explicitly enforce the idea that sustainability requires simultaneous progress across multiple dimensions.

There are both synergies and trade-offs in achieving sustainability goals. For instance, Ekeinde et al. (2025) show that renewable energy supports resilience and reduces emissions. However, it also involves governance challenges and environmental trade-offs. Similarly, Tian et al. (2024) note that renewable energy may conflict with broader sustainability goals. Institutional challenges are emphasized by Nasiritousi et al. (2020), who identify weak coordination in climate–energy governance. In contrast, Segers et al. (2024) advocate holistic and multi-actor approaches to address sustainability issues. Empirical studies such as Fortea et al. (2024) highlight the role of policy shifts and energy crises in shaping sustainability in the EU. García-Arango et al. (2023) stress the importance of integrating environmental indicators into economic growth strategies. Gu et al. (2024) show that technological innovation and cleaner energy help moderate transport emissions despite continued growth. Zhang et al. (2025) find that climate risk reduces energy security. They also emphasize that energy transition and efficiency improvements can enhance resilience.

Decomposition-based studies using the Kaya identity and LMDI provide important insights into emission drivers. Yamaji et al. (1993) and Tavakoli (2017) identify population and economic growth as the main contributors to CO_2 emissions. They also show that declining energy and carbon intensity can offset some of these effects. Similar findings are reported by Karnik (2025) and Khusna &

Kurniawan (2021) in different regional contexts. Kaika (2023) further demonstrates that technological progress and structural changes can help decouple economic growth from emissions. However, Overland et al. (2021) note that ASEAN countries still rely heavily on fossil fuels, which limits mitigation efforts.

Measurement issues are widely discussed in literature. Stevens et al. (2023) show that differences in index construction can significantly affect sustainability rankings. Choi (2019) also finds that aggregation methods influence vulnerability assessments. To address these issues, Zhang & Wu (2022) propose the Environmental Human Index, which combines human development and environmental performance. Hickel (2020) introduces the Sustainable Development Index, which incorporates ecological impacts.

Wang et al. (2024) contribute by analyzing SDG interlinkages and developing the Comprehensive Environmental Sustainability Index. Their findings reveal trade-offs between economic and environmental goals and highlight environmental degradation trends. García-Arango et al. (2023) further emphasize the need for long-term policy alignment. Finally, Wu & Qiao (2026) show that environmental challenges are driven by complex and nonlinear interactions. They stress the need for integrated and multi-factor policy approaches.

Existing sustainability indices provide useful assessments of different aspects of sustainability. However, the performance across the six dimensions considered in this study (i.e., economic savings, emissions, carbon intensity, renewable energy share, energy use, and climate stability) is not sufficiently assessed together in a single framework. A country may perform well in one dimension, such as renewable energy or economic savings, while showing poor performance in other dimensions. Such differences may be overlooked when individual dimensions are assessed separately or when strong performance in one area offsets weak performance in another. Therefore, a composite measure is needed to assess these six dimensions together. To address this gap, the Climate–Energy Sustainability Index (CESI) is developed as a complementary and more targeted framework for the climate–energy nexus. The study further applies CESI to cross-country data to compare sustainability performance over time, identify regional patterns and disparities, and examine the combined performance of economic savings, energy use, emissions, and climate stability.

2. Methods and Materials

The composite Climate–Energy Sustainability Index (CESI) is constructed as the geometric mean of six normalized indicators representing key dimensions of sustainability: adjusted net savings (% of GNI), carbon emissions per capita, carbon intensity of energy use, renewable energy share, energy use per capita, and temperature anomalies. To ensure comparability across heterogeneous indicators, each variable is transformed into a unit-free score bounded within the interval $[0,1]$. The normalization process follows a threshold-based approach (see Table 1), where lower and upper bounds are defined using a combination of sustainability benchmarks, policy targets, and observed global ranges.

Formally, the CESI is defined in Eq. (1). Each $S_i(x)$ denotes the normalized score of one sustainability component. The multiplicative structure ensures that no dimension can compensate for extreme underperformance in another. If one component performs poorly, the entire CESI value decreases immediately. The sixth root prevents any single factor from dominating the composite index. CESI increases only when improvement occurs simultaneously across several domains. It declines when one or more indicators move away from sustainability targets.

$$CESI(x) = [S_{ANS}(x) * S_{CO2}(x) * S_{CI}(x) * S_R(x) * S_E(x) * S_T(x)]^{\frac{1}{6}} \quad (1)$$

The threshold and normalization values were selected from empirical observations, international sustainability benchmarks, and researcher-defined assumptions. Some values were based on the observed international range of the indicators. Other values were selected to represent desirable or transition-oriented conditions. The upper values were used as practical normalization ceilings, not as theoretical maximums. Therefore, these thresholds are treated as operational benchmarks for the proposed sustainability framework. They are not considered universal policy thresholds set by any single international institution.

Table 1. Benchmark and normalization values used in the proposed sustainability index.

Variable	Threshold / Normalization Value	Explanation
ANS_{target}	10% of GNI	10% of GNI is used as a positive adjusted-net-savings benchmark. It indicates a relatively strong level of net capital accumulation. The GNI and ANS data was obtained from the World Bank (2025a).
ANS_{MAX}	45% of GNI	High-saving economies can record high adjusted-net-savings levels. Therefore, 45% of GNI is used as a practical normalization ceiling. It is not treated as a theoretical maximum. The data was obtained from the World Bank (2025a).
$CO_{2_{target}}$	5 tCO_2 per capita	The 5 tCO_2 per capita level is adopted as a transition-oriented emissions benchmark. It represents a relatively lower emission level than that found in many high-emission economies. The value is used for normalization. Supporting data was obtained from international climate and Energy sources.
$CO_{2_{max}}$	24 tCO_2 per capita	High-emission economies can show very high per capita emissions. Hence, 24 tCO_2 per capita is used as a practical normalization ceiling. Values above this level are placed at the upper end of the normalization scale. Data was obtained from Our World in Data (Ritchie & Roser, 2020).
CI_{target}	0.3 kg CO_2 per kWh	The 0.30 kg CO_2/kWh level represents a low-carbon electricity benchmark. It is consistent with the general direction of electricity-sector decarbonization. Supporting information was obtained from the International Energy Agency.
CI_{max}	0.66 kg CO_2 per kWh	A value of 0.66 kg CO_2/kWh is used as a high-carbon normalization benchmark. It represents a carbon-intensive energy system. It is used as a practical ceiling, not as a theoretical maximum. Data was obtained from websites of the World Bank (2025b) and Our World in Data (Ritchie & Roser, 2020).
R_{target}	50% of total final energy consumption	A renewable share of 50% is used as an ambitious energy-transition benchmark. It represents a substantial shift towards renewable energy. Supporting information was obtained from the International Energy Agency and United Nations sources.
R_{max}	97% of total final energy consumption	Near-complete renewable-energy penetration is represented by 97%. This level is used as a practical upper normalization ceiling. It is not a theoretical maximum, since 100% is the upper limit. Supporting data was obtained from the World Bank (2025d) and Our World in Data (Ritchie & Roser, 2020).
E_{target}	1,000 kgOE per capita	The 1,000 $kgOE$ per capita level is used as an energy-availability benchmark. It represents a moderate level of energy use for socioeconomic development. Supporting information was obtained from international energy and climate sources.
E_{max}	9,000 kgOE per capita	A value of 9,000 kgOE per capita is used as a high-energy-use normalization ceiling. Very high energy consumption is

		observed in some energy-intensive economies. Data was derived from websites of the World Bank (2025c) and Our World in Data (Ritchie & Roser, 2020).
$T_{threshold}$	0.5	The midpoint of the normalized scale is set at 0.50. It provides a simple boundary between relatively lower and higher sustainability performance. This threshold was defined as a methodological choice in the present framework.

Each raw variable is normalized to a score in the interval [0,1]. For adjusted net savings per capita, sustainability is assessed relative to the threshold ANS_{target}. The scoring function in Eq. (2) assigns a score of zero when adjusted net savings are zero or negative and provides a threshold-based transformation for positive values. The score is defined in Eq. (2). The score is bounded between 0 and 1 according to the specified thresholds. Therefore, the resulting score is interpreted as a normalized sustainability score within the adopted threshold framework rather than as a direct monotonic measure of adjusted net savings.

$$S_{ANS}(x) = \begin{cases} 0, & if\ x \le 0 \\ 1 - \dfrac{x}{ANS_{target}}, & if\ 0 < x < ANS_{target} \\ \dfrac{x - ANS_{target}}{ANS_{max} - ANS_{target}}, & if\ ANS_{target} \le x < ANS_{max} \\ 1, & if\ x \ge ANS_{max} \end{cases} \tag{2}$$

Carbon emissions are normalized using a continuous decreasing transformation in Eq. (3). Lower emissions yield higher scores, while avoiding the artificial assignment of perfect scores for low-emission countries. Higher values of $S_{CO_2}(t)$ indicate lower emissions relative to sustainability benchmarks.

$$S_{CO_2}(x) = \begin{cases} 1, & if\ x \le 0 \\ 1 - \dfrac{x}{CO_{2max}}, & if\ 0 < x < CO_{2target} \\ \dfrac{CO_{2max} - x}{CO_{2max} - CO_{2target}}, & if\ CO_{2target} \le x < CO_{2max} \\ 0, & if\ x \ge CO_{2max} \end{cases} \tag{3}$$

Carbon intensity of energy use is normalized in a similar way. The score is in Eq. (4). Lower carbon intensity implies a higher sustainability score.

$$S_{CI}(x) = \begin{cases} 1, & if\ x \le 0 \\ 1 - \dfrac{x}{CI_{max}}, & if\ 0 < x < CI_{target} \\ \dfrac{CI_{max} - x}{CI_{max} - CI_{target}}, & if\ CI_{target} \le x < CI_{max} \\ 0, & if\ x \ge CI_{max} \end{cases} \tag{4}$$

The share of renewable energy is normalized using the specified target and upper threshold in Eq. (5). This ensures continuous improvement without assigning a maximum score prematurely.

$$S_R(x) = \begin{cases} 0, & if\ x \leq 0 \\ \dfrac{x}{R_{target}}, & if\ 0 < x < R_{target} \\ \dfrac{x - R_{target}}{R_{max} - R_{target}}, & if\ R_{target} \leq x < R_{max} \\ 1, & if\ x \geq R_{max} \end{cases} \quad (5)$$

Energy use per capita is normalized against optimal and maximum tolerable thresholds in Eq. (6). Lower energy consumption relative to the upper bound yields higher sustainability scores while preserving variation across countries.

$$S_E(x) = \begin{cases} 1, & if\ x \leq 0 \\ 1 - \dfrac{x}{E_{max}}, & if\ 0 < x < E_{target} \\ \dfrac{E_{max} - x}{E_{max} - E_{target}}, & if\ E_{target} \leq x < E_{max} \\ 0, & if\ x \geq E_{max} \end{cases} \quad (6)$$

The temperature anomaly component reflects climate stability. It applies a nonlinear penalty based on a rational function when temperature anomalies increase. The score is defined in Eq. (7). The parameter $\gamma > 0$ determines the sensitivity of the score to temperature anomalies. In the implementation, negative temperature anomalies are treated as zero. Higher temperature anomalies therefore reduce the score continuously without discrete jumps. In this study, $\gamma = 2$ is used as a calibration parameter to control the sensitivity of the score to temperature anomalies. The rational functional form provides a smooth and bounded response to increasing temperature anomalies. Robustness is examined using alternative values of γ, such as 1–3, which do not materially affect the overall results. Together, these transformations generate six normalized indicators bounded between 0 and 1, allowing direct comparability across components.

$$S_T(x) = \frac{1}{1 + \gamma\,(T(x)\,)} \qquad x \geq 0 \quad (7)$$

The CESI satisfies several key mathematical properties that ensure its consistency and interpretability. Each component sustainability score $S_i(t), for\ i = 1, \dots\dots, 6$ is constructed using normalized piecewise functions such that $0 \leq CESI\ (t) \leq 1$. CESI is defined as the geometric mean of these six components (see Eq. (8)).

$$CESI\ (t) = \left(\prod_{i=1}^{6} S_i(t)\right)^{1/6} \quad (8)$$

Since the product of non-negative numbers bounded above by one also lies in [0,1], it follows Eq. (9). The transformation $x \mapsto x^{1/6}$ is continuous and strictly increasing on$[0, \infty]$, and it maps the interval [0,1] into itself. Therefore, $0 \leq CESI\ (t) \leq 1$. The boundary cases follow directly. If $S_j(t) = 0$, for any component j, then $\prod_{i=1}^{6} S_i(t) = 0$ and hence $CESI(t) = 0$. Conversely, $CESI(t) = 0$, implies that at least one factor $S_j(t)$ must equal zero. Similarly, $CESI(t) = 1$ occurs if and only if $S_i(t), for\ i = 1, \dots\dots, 6$. When all component scores satisfy $0 < S_i(t) < 1$, the index also satisfies $0 < CESI(t) < 1$.

$$0 \leq \prod_{i=1}^{6} S_i(t) \leq 1 \quad (9)$$

CESI is strictly increasing in each component score on the domain $[0,1]^6$. Suppose that all component scores are fixed except for one component $S_j(t)$, which increases from $S_j(t)$ to $S_j'(t)$ such that $S_j'(t) > S_j(t)$. Let Eq. (10) define $P(t)$ and $P'(t)$.

$$P(t) = \prod_{i=1}^{6} S_i(t), \quad P'(t) = \prod_{i=1}^{6} S_i'(t) \tag{10}$$

Since all other factors remain unchanged and $S_j'(t) > S_j(t)$, it follows that $P'(t) > P(t)$. Applying the strictly increasing transformation $x^{1/6}$ yields Eq. (11). Thus, an improvement in any single sustainability dimension leads to a strict increase in the overall index, holding all other dimensions constant.

$$CESI'(t) = \left(P'(t)\right)^{1/6} > \left(P\ (t)\right)^{1/6} = CESI\ (t) \tag{11}$$

CESI also exhibits conditional scale invariance with respect to raw indicators normalized using ratio-based or distance-based transformations. Let each component score be defined as $S_i(t) = f_i(X_i(t))$. Consider a raw indicator $X_j(t)$ replaced by $kX_j(t)$, where $k > 0$, without crossing any normalization thresholds. For ratio-based normalization in Eq. (12) and for distance-based normalization in Eq. (13), the normalized score remains unchanged, so $S_j'\ (t) = S_j\ (t)$. Since all other component scores are unaffected, the product $\prod_{i=1}^{6} S_i(t)$ remains the same, and consequently, $CESI'(t) = CESI\ (t)$. Hence, CESI is invariant under any positive proportional scaling of raw indicators that does not alter their location within the normalization intervals.

$$\frac{kX_j(t)}{kX_{j,\ target}} = \frac{X_j(t)}{X_{j,\ target}} \tag{12}$$

$$\frac{kX_{j,max} - kX_j(t)}{kX_{j,max} - kX_{j,\ target}} = \frac{X_{j,max} - X_j(t)}{X_{j,max} - X_{j,\ target}} \tag{13}$$

The dataset includes indicators from the World Bank. These indicators cover adjusted net savings as a percentage of GNI, carbon intensity, renewable energy consumption, and per capita energy use. The dataset also incorporates data from Our World in Data. This includes CO_2 emissions per capita and the global temperature anomaly. The final sample consists of 76 major countries. These countries represent six regions across the world. All variables were converted into consistent measurement units. A detailed summary of all data sources and indicator definitions is provided in Table 2.

Table 2. Data sources for CESI components.

Component	Description	Unit	Data Source
ANS	Adjusted savings: net national savings (% of GNI)	% of GNI	World Bank (2025a)
CO_{2pc}	CO_2, Emissions per capita	Metric tons per person	Ritchie & Roser (2020)
CI	Carbon Intensity (CO_2 emissions per energy use)	kg CO_2 per kWh	World Bank (2025b)
R	Renewable Energy Consumption	% of total final energy consumption	World Bank (2025d)
E_{pc}	Per Capita Energy Use	MJ/person	World Bank (2025c)
T	Global Temperature Anomaly (relative to pre-industrial)	°C	Ritchie et al. (2024)

3. Results and Discussions

3.1 Global Trend

During the study period, the global average CESI exhibits a non-linear but overall improving trend, marked by short-term fluctuations and gradual long-term gains. The index begins at a relatively low level in the early 1990s, with a slight decline around 1991 followed by a modest recovery through the mid-1990s, although variability remains due to uneven progress across countries. From the late 1990s to the mid-2000s, CESI shows a gradual upward trajectory with minor dips, reflecting incremental improvements driven by expanding renewable energy adoption and early climate policy efforts. A notable surge occurs between 2005 and 2007, when the index reaches its highest level, indicating a period of strong global progress in emissions management and energy efficiency.

After this peak, the index experiences a mild decline and then fluctuates within a relatively stable range during 2010–2014, suggesting mixed sustainability performance across regions. A moderate recovery is observed between 2015 and 2018, followed by renewed fluctuations and a slight downward tendency toward 2020. In the post-2020 period, CESI continues to oscillate without a clear upward trend, indicating that global sustainability progress remains fragile and sensitive to external shocks, energy market dynamics, and uneven policy implementation (see Figure 1).

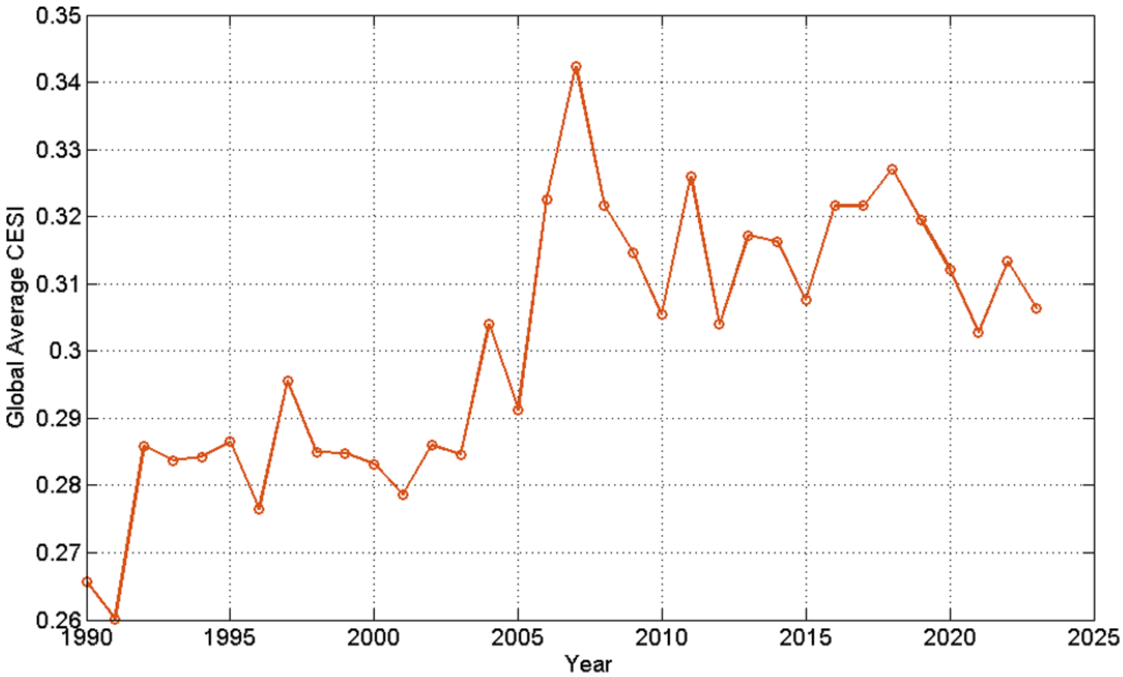

Figure 1. Global trend of the Climate–Energy Sustainability Index (CESI), 1990–2023.

3.2 Country Patterns

Over the past three decades, cross-country variability has not declined consistently; instead, variance increased slightly from 0.0295 in 1993 to 0.0319 in 2013 before falling to 0.0230 in 2023, suggesting only a moderate reduction in dispersion in recent years rather than a long-term contraction. The central tendency shows mixed dynamics: the median CESI remained relatively stable between 1993 (0.3083) and 2003 (0.3077), increased substantially by 2013 (0.3390), and further improved to 0.3597 in 2023, indicating that the typical country has experienced gradual improvement rather than stagnation. Similarly, the global average rose from 0.2837 in 1993 to 0.3172 in 2013 but declined slightly to 0.3063 in 2023, reflecting recent setbacks or uneven progress across countries.

By 2023, the distribution does not exhibit a clear high-threshold clustering as previously suggested; instead, it shows a broad and continuous spread of performance levels. Only a small group of countries, led by Italy (0.5721), Panama (0.5579), Chile (0.5439), and the United Kingdom (0.5250), form a relatively high-performing cluster, though none exceed a CESI value of 0.60. A large middle group spans approximately 0.30 to 0.45, comprising a mix of developed, emerging, and developing economies, indicating substantial heterogeneity in sustainability transitions. The lower tail includes countries with CESI values below 0.25, such as Tuvalu (0.0053), Trinidad and Tobago (0.0177), and several African and small island states, reflecting persistent structural challenges related to energy access, economic capacity, and climate vulnerability (see Table 3).

Table 3. Trends in the CESI and country rankings, 1993–2023.

Country	CESI in 1993 (Rank)	CESI in 2003 (Rank)	CESI in 2013 (Rank)	CESI in 2023 (Rank)
Italy (ITA)	0.3464 (29)	0.3594 (25)	0.5872 (4)	0.5721 (1)
Panama (PAN)	0.4112 (18)	0.3247 (36)	0.6171 (3)	0.5579 (2)
Chile (CHL)	0.5859 (3)	0.3570 (27)	0.3294 (42)	0.5439 (3)
United Kingdom (GBR)	0.3462 (30)	0.3132 (38)	0.4912 (13)	0.5250 (4)
Japan (JPN)	0.3001 (40)	0.3570 (28)	0.4391 (19)	0.4771 (5)
Spain (ESP)	0.2557 (49)	0.3780 (22)	0.5284 (9)	0.4766 (6)
Paraguay (PRY)	0.3099 (37)	0.3549 (29)	0.3589 (35)	0.4763 (7)
Argentina (ARG)	0.3832 (26)	0.4305 (15)	0.5018 (11)	0.4619 (8)
Mexico (MEX)	0.4919 (8)	0.4988 (8)	0.5285 (8)	0.4580 (9)
France (FRA)	0.3080 (39)	0.3021 (39)	0.4647 (15)	0.4497 (10)
Czechia (CZE)	0.3596 (28)	0.4111 (18)	0.4931 (12)	0.4446 (11)
Uganda (UGA)	0.0511 (62)	0.0480 (62)	0.0482 (64)	0.4337 (12)
Colombia (COL)	0.4059 (19)	0.4496 (12)	0.4564 (16)	0.4264 (13)
Austria (AUT)	0.5181 (5)	0.4397 (13)	0.4220 (24)	0.4263 (14)
Suriname (SUR)	0.4958 (7)	0.6538 (2)	0.5534 (6)	0.4262 (15)
Germany (DEU)	0.2582 (48)	0.3613 (24)	0.3399 (38)	0.4250 (16)
Uruguay (URY)	0.4023 (20)	0.3587 (26)	0.3227 (43)	0.4194 (17)
Sweden (SWE)	0.5891 (2)	0.5097 (7)	0.5269 (10)	0.4190 (18)
Hungary (HUN)	0.0539 (61)	0.4831 (9)	0.3804 (28)	0.4157 (19)
China (CHN)	0.4400 (13)	0.6088 (3)	0.4652 (14)	0.3969 (20)
New Zealand (NZL)	0.4484 (10)	0.4343 (14)	0.4079 (25)	0.3942 (21)
Nicaragua (NIC)	0.0448 (68)	0.2712 (45)	0.1990 (59)	0.3915 (22)
Guatemala (GTM)	0.4304 (15)	0.3985 (19)	0.4459 (17)	0.3859 (23)
Samoa (WSM)	0.0366 (71)	0.1637 (58)	0.3740 (30)	0.3840 (24)
Netherlands (NLD)	0.2355 (52)	0.2402 (49)	0.2977 (49)	0.3832 (25)
United States (USA)	0.2701 (45)	0.2577 (46)	0.3191 (44)	0.3825 (26)
Honduras (HND)	0.3173 (35)	0.3473 (31)	0.1596 (60)	0.3801 (27)
Cote d'Ivoire (CIV)	0.0445 (69)	0.0415 (69)	0.0430 (67)	0.3761 (28)
Costa Rica (CRI)	0.1823 (56)	0.2753 (43)	0.5511 (7)	0.3751 (29)
Pakistan (PAK)	0.3255 (34)	0.1340 (59)	0.3969 (27)	0.3726 (30)
Romania (ROU)	0.0583 (59)	0.0610 (60)	0.5583 (5)	0.3713 (31)
Canada (CAN)	0.4326 (14)	0.2834 (40)	0.3349 (40)	0.3665 (32)
Nigeria (NGA)	0.2982 (41)	0.2778 (42)	0.3992 (26)	0.3654 (33)
Ghana (GHA)	0.0481 (64)	0.0376 (72)	0.4257 (23)	0.3648 (34)
El Salvador (SLV)	0.2904 (42)	0.2805 (41)	0.4439 (18)	0.3640 (35)

Malaysia (MYS)	0.4463 (11)	0.2048 (53)	0.2687 (51)	0.3624 (36)
Ethiopia (ETH)	0.0493 (63)	0.0463 (65)	0.4309 (22)	0.3606 (37)
Thailand (THA)	0.4304 (16)	0.4209 (16)	0.3698 (31)	0.3598 (38)
India (IND)	0.1679 (57)	0.3474 (30)	0.3660 (33)	0.3596 (39)
Australia (AUS)	0.4006 (22)	0.3184 (37)	0.2256 (56)	0.3559 (40)
Ecuador (ECU)	0.4258 (17)	0.4163 (17)	0.3381 (39)	0.3492 (41)
Kiribati (KIR)	0.3086 (38)	0.1770 (56)	0.3601 (34)	0.3438 (42)
Philippines (PHL)	0.2791 (44)	0.3752 (23)	0.3681 (32)	0.3404 (43)
Bangladesh (BGD)	0.1976 (55)	0.2055 (52)	0.3577 (36)	0.3364 (44)
Dominican Republic (DOM)	0.2456 (51)	0.3399 (33)	0.3009 (48)	0.3207 (45)
Indonesia (IDN)	0.2868 (43)	0.0478 (63)	0.2309 (55)	0.3185 (46)
Vanuatu (VUT)	0.2550 (50)	0.2213 (50)	0.2709 (50)	0.3157 (47)
Angola (AGO)	0.0455 (67)	0.3937 (20)	0.4323 (21)	0.3133 (48)
Peru (PER)	0.4015 (21)	0.2525 (47)	0.3317 (41)	0.3053 (49)
Iraq (IRQ)	0.3272 (33)	0.1978 (55)	0.3742 (29)	0.3036 (50)
Solomon Islands (SLB)	0.0303 (72)	0.1656 (57)	0.2386 (53)	0.3031 (51)
Morocco (MAR)	0.3165 (36)	0.3296 (35)	0.3069 (47)	0.2958 (52)
Belgium (BEL)	0.2688 (47)	0.2504 (48)	0.1582 (61)	0.2878 (53)
Sudan (SDN)	0.3915 (24)	0.2714 (44)	0.2388 (52)	0.2635 (54)
Jamaica (JAM)	0.5814 (4)	0.3454 (32)	0.3123 (46)	0.2619 (55)
Haiti (HTI)	0.0479 (65)	0.3388 (34)	0.3459 (37)	0.2486 (56)
Tonga (TON)	0.1992 (54)	0.2098 (51)	0.2030 (58)	0.2402 (57)
Poland (POL)	0.5133 (6)	0.5305 (6)	0.4351 (20)	0.2213 (58)
Algeria (DZA)	0.2103 (53)	0.2032 (54)	0.2334 (54)	0.2212 (59)
Fiji (FJI)	0.3339 (32)	0.4532 (11)	0.3139 (45)	0.1905 (60)
Bolivia (BOL)	0.0467 (66)	0.3811 (21)	0.2214 (57)	0.1106 (61)
Saudi Arabia (SAU)	0.0007 (76)	0.0401 (70)	0.0386 (72)	0.0923 (62)
Brazil (BRA)	0.3420 (31)	0.7433 (1)	0.7518 (1)	0.0736 (63)
Portugal (PRT)	0.4452 (12)	0.5942 (4)	0.6553 (2)	0.0666 (64)
Greece (GRC)	0.0564 (60)	0.0514 (61)	0.0611 (62)	0.0626 (65)
Papua New Guinea (PNG)	0.0735 (58)	0.0377 (71)	0.0420 (70)	0.0587 (66)
South Africa (ZAF)	0.6923 (1)	0.5583 (5)	0.0569 (63)	0.0473 (67)
Mozambique (MOZ)	0.2700 (46)	0.4564 (10)	0.0470 (65)	0.0430 (68)
Kenya (KEN)	0.3984 (23)	0.0467 (64)	0.0443 (66)	0.0414 (69)
Madagascar (MDG)	0.3906 (25)	0.0428 (68)	0.0416 (71)	0.0407 (70)
Cameroon (CMR)	0.4850 (9)	0.0462 (66)	0.0430 (68)	0.0406 (71)
Marshall Islands (MHL)	0.0433 (70)	0.0439 (67)	0.0425 (69)	0.0404 (72)
Nauru (NRU)	0.0078 (73)	0.0078 (73)	0.0273 (73)	0.0365 (73)
Palau (PLW)	0.0074 (74)	0.0071 (74)	0.0068 (74)	0.0319 (74)
Trinidad and Tobago (TTO)	0.3664 (27)	0.0038 (75)	0.0035 (76)	0.0177 (75)
Tuvalu (TUV)	0.0009 (75)	0.0008 (76)	0.0041 (75)	0.0053 (76)

The 2023 CESI rankings do not show a clear dominance of Western European countries; instead, they reveal a more geographically diverse pattern of sustainability performance. While some European economies such as Italy (rank 1, 0.5721), the United Kingdom (rank 4, 0.5250), Spain (rank 6, 0.4766), France (rank 10, 0.4497), and Germany (rank 16, 0.4250) remain strong performers, the top positions are shared with Latin American and other middle-income countries, including Panama (rank

2, 0.5579), Chile (rank 3, 0.5439), Paraguay (rank 7, 0.4763), and Argentina (rank 8, 0.4619). This indicates that high CESI performance is not confined to advanced economies but can also emerge in countries with favorable energy structures, relatively lower emissions, and increasing renewable energy shares. Long-term trajectories further highlight significant upward mobility across diverse regions.

For instance, Italy improved markedly from rank 29 in 1993 to rank 1 in 2023, while the United Kingdom advanced from rank 30 to rank 4, reflecting sustained policy efforts and energy transition. Even more striking are cases such as Uganda (rank 62 to 12), Côte d'Ivoire (rank 69 to 28), and Romania (rank 59 to 31), which demonstrate that substantial gains are possible from very low initial baselines, often driven by improvements in energy access, efficiency, and structural transformation. At the same time, several traditionally high-performing or resource-rich economies experienced pronounced declines. South Africa, the global leader in 1993 (rank 1, 0.6923), dropped sharply to rank 67 (0.0473) by 2023, while Brazil fell from rank 31 in 1993 and peak global leadership in 2003–2013 to rank 63 (0.0736) in 2023. Similarly, Portugal, which ranked among the top performers in 2003 and 2013, declined dramatically to rank 64 (0.0666) by 2023. These reversals suggest that earlier advantages, often linked to specific energy structures such as hydropower, have diminished in relative importance as global sustainability standards have tightened, particularly regarding emissions and energy intensity.

Large emerging economies exhibit more gradual but constrained improvements. India moved from rank 57 in 1993 to rank 39 in 2023, while China declined slightly in ranking despite moderate performance (rank 20 in 2023), indicating that rapid economic growth and rising energy demand continue to offset gains from renewable expansion and efficiency improvements. Finally, the lower tail of the distribution is dominated by structurally constrained economies and fossil-fuel-dependent states. Countries such as Saudi Arabia (rank 62, 0.0923) and Trinidad and Tobago (rank 75, 0.0177) remain among the weakest performers due to persistently high per capita emissions, heavy reliance on fossil fuels, and limited diversification of energy systems. Extremely low scores are also observed in small island states such as Tuvalu (rank 76, 0.0053) and Nauru (rank 73, 0.0365), reflecting structural vulnerabilities related to scale, resource constraints, and climate exposure.

3.3 Continental Trend

Europe exhibits a relatively strong and generally upward trajectory. Its CESI increased from around 0.30 in the early 1990s to peaks above 0.42–0.44 during the late 2000s and again around 2019–2021. However, the increase was not smooth, with noticeable short-term fluctuations. South America also performs relatively strongly. Its position varies across regions over time, with CESI values typically ranging between 0.38 and 0.47. A pronounced peak was observed around 2011, followed by greater volatility and a decline after 2019. A partial recovery was observed thereafter. North America shows a stable mid-to-high performance, fluctuating within a narrower band of approximately 0.32–0.36, indicating incremental but limited progress over time. Asia follows a similar but slightly lower trajectory, generally ranging between 0.27 and 0.35, with gradual improvement after the mid-2000s but continued variability reflecting structural pressures from industrial growth and rising energy demand. Africa displays moderate but uneven performance, typically between 0.29 and 0.36, with visible fluctuations indicating inconsistent progress across countries. Oceania remains the lowest-performing region, although it shows gradual improvement from around 0.13 in the early 1990s to about 0.20–0.22 in recent years, suggesting slow but steady gains from a low base (see Figure 2).

Europe shows the most consistent improvement, with its average rank declining (improving) from 35 in 1993 to 23 in 2013, before slightly worsening to 26 in 2023, confirming its sustained leadership despite minor recent setbacks. South America emerges as one of the strongest-performing regions overall, achieving the best average rank in 2003 (20) and maintaining a relatively favorable position at 28 in 2023, although this reflects some loss of earlier advantage. In contrast, Africa records a clear deterioration in relative standing, with its average rank rising (worsening) from 42 in 1993 to above 50 in both 2013 and 2023, indicating that progress in the region has lagged behind global improvements. North America exhibits moderate fluctuations, moving from 34 in 1993 to 37 in 2003, then improving slightly to 34 by 2023, suggesting incremental but limited gains in relative performance. Asia remains relatively stable over time, with average ranks hovering between 36 and 41, reflecting heterogeneous country-level transitions and mixed sustainability outcomes. Oceania consistently records the highest (worst) average ranks across all years, remaining above 53 throughout the period, highlighting persistent structural and scale-related constraints that limit its relative sustainability performance (see Figure 3).

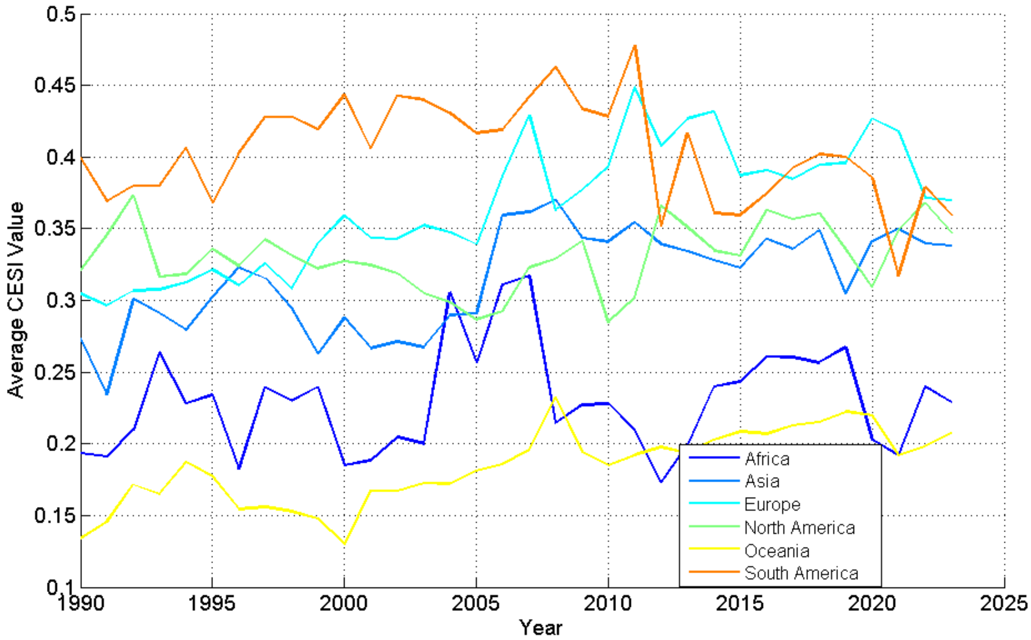

Figure 2. Continental trends in the Climate–Energy Sustainability Index (CESI), 1990–2023.

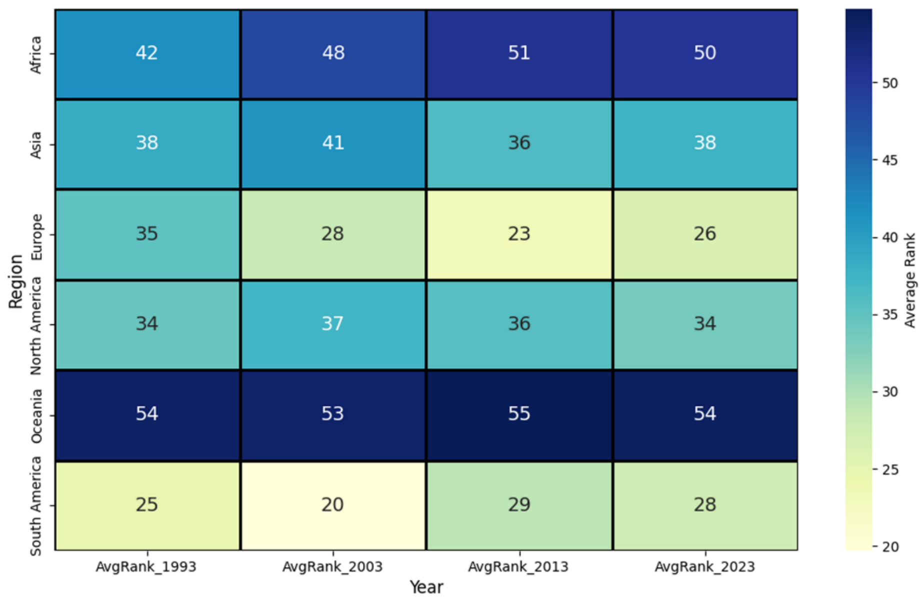

Figure 3. Continental average CESI rank over time (1993–2023).

3.4 Bivariate Relationship

Now, how different factors respond to CESI is examined using a set of scatter plots. Specifically, CESI is analyzed in relation to adjusted net national savings (% of GNI), renewable energy consumption share, per-capita energy use, CO_2 intensity of energy use, and CO_2 emissions per capita, allowing a comparative assessment of how sustainability performance aligns with savings behavior, energy structure, and emission characteristics across countries. For each country, the scatter plots use the average values of CESI and the corresponding explanatory factors over the period 1990–2023. Thus, each country is shown by one point, representing its average CESI and the average value of the respective factors during the study period.

The upward-sloping trend line, combined with a low coefficient of determination ($R^2 = 0.15$), suggests that higher savings are associated with modest improvements in sustainability outcomes, but the explanatory power remains limited. Countries with relatively high CESI scores, such as Suriname, Sweden, Chile, and Panama, tend to lie in the mid-to-high savings range, indicating that economic capacity can support better sustainability performance when aligned with appropriate policies and energy structures. However, the wide dispersion of points shows that savings alone is not a decisive factor. For example, Saudi Arabia exhibits relatively high savings levels but records one of the lowest CESI values, reflecting the dominance of fossil-fuel-based development and limited diversification of the energy system. Similarly, some countries with moderate savings achieve only average CESI outcomes, highlighting inefficiencies in translating financial resources into sustainability gains. In contrast, several developing and emerging economies, including India, China, and Indonesia, cluster in the middle range of both variables, suggesting a partial linkage between growth and sustainability alongside ongoing structural constraints. Additionally, countries with very low or negative savings, such as Côte d'Ivoire, tend to record low CESI values, reinforcing the idea that insufficient economic resources can hinder sustainability progress (see Figure 4).

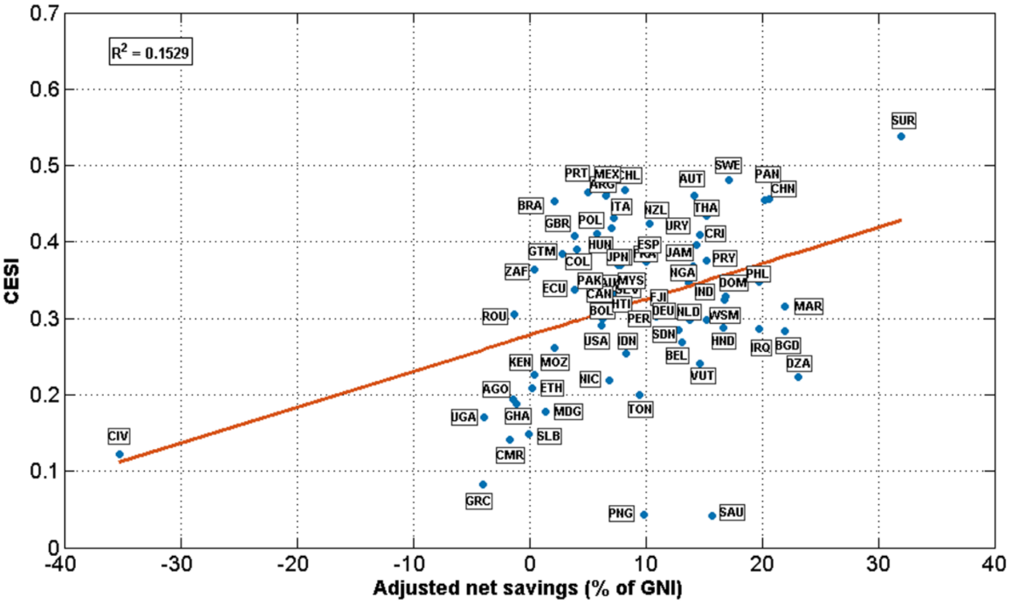

Figure 4. Relationship between average CESI and adjusted net savings (% of GNI) over the period 1990–2023.

Renewable energy consumption shows a positive but weak relationship with the Climate–Energy Sustainability Index (CESI). The fitted trend line is only slightly upward, and the very low explanatory power ($R^2 = 0.0115$) shows that renewable energy share alone explains almost none of the cross-country variations in sustainability performance. Several countries with relatively high CESI values, such as Suriname, Sweden, Chile, Panama, and Portugal, are spread across a broad range of renewable shares, indicating that strong sustainability outcomes can occur under quite different energy structures when supported by favorable performance in other CESI components. At the same time, some countries with very high renewable shares still record only modest or low CESI values. Ethiopia, Uganda, Mozambique, and Côte d'Ivoire, for example, combine high renewable shares with comparatively weak CESI performance, suggesting that a large renewable share does not automatically imply broader climate and energy sustainability, especially where traditional biomass dominates energy use or where economic and institutional constraints remain significant. Fossil-fuel-dependent economies such as Saudi Arabia and Trinidad and Tobago remain clustered at very low renewable shares and low CESI levels, reflecting limited progress in energy transition. Several emerging economies, including India, China, and Indonesia, lie in the middle range of both variables, indicating gradual progress but also persistent pressures from rising energy demand and emissions (see Figure 5).

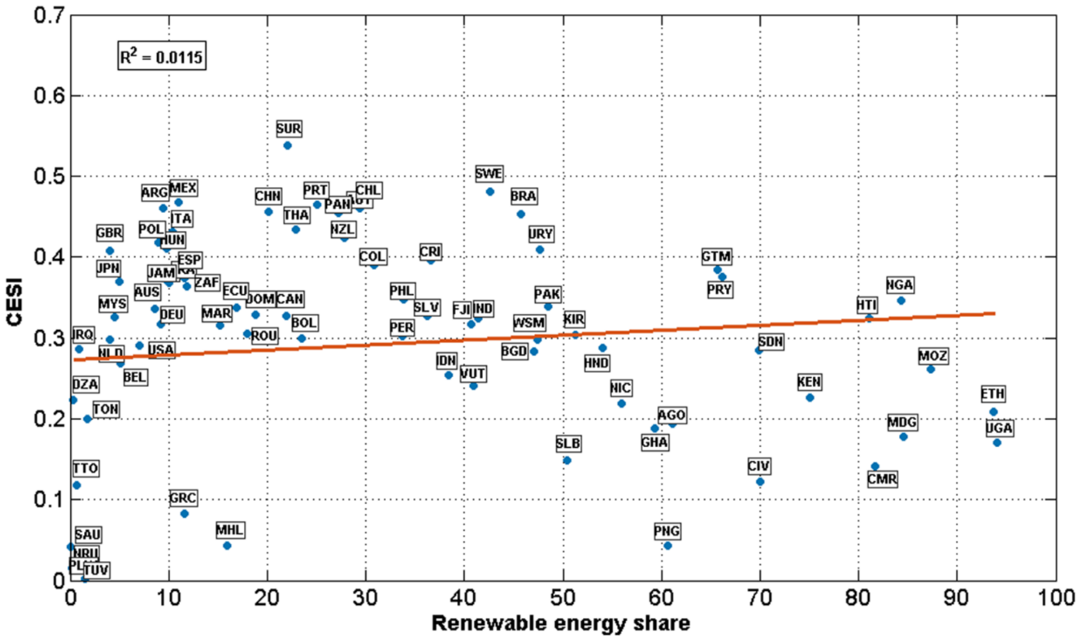

Figure 5. Relationship between average CESI and renewable energy consumption share over the period 1990–2023.

However, the nearly flat fitted line and the extremely low explanatory power ($R^2 = 0.0004$) indicate that per capita energy use alone explains very little of the cross-country variation in sustainability performance. This weak relationship arises because energy use per capita includes both renewable and non-renewable energy sources. As shown earlier, renewable energy contributes positively to CESI, while fossil-fuel-based energy tends to reduce sustainability through higher emissions and carbon intensity. Since these opposing effects are combined in the total energy-use measure, the overall relationship appears only slightly negative. Countries such as Saudi Arabia and Trinidad and Tobago combine very high energy use with low CESI, while several low-energy-use countries also record weak CESI values, indicating that the sustainability impact depends more on energy composition and efficiency than on the absolute level of energy consumption (see Figure 6).

Carbon dioxide (CO_2) intensity of energy use shows a weak negative relationship with CESI, as indicated by the downward-sloping trend line and the low explanatory power ($R^2 = 0.0286$). Countries with relatively lower CO_2 intensity, such as Suriname, Sweden, and Panama, generally achieve higher CESI values, reflecting cleaner energy systems and lower carbon dependence. By contrast, economies with relatively high CO_2 intensity, including Saudi Arabia, Angola, and Algeria, tend to record lower CESI values. However, the wide dispersion of observations suggests that CO_2 intensity alone does not determine sustainability performance. Renewable energy expansion, energy efficiency, and broader structural factors also influence CESI outcomes. Overall, higher carbon intensity tends to weaken climate–energy sustainability, but its effect remains moderate rather than decisive (see Figure 7).

Per capita CO_2 emissions show a very weak negative relationship with CESI, as indicated by the nearly flat downward trend and very low explanatory power ($R^2 = 0.0010$). Countries with relatively low or moderate per capita emissions, such as Suriname, Sweden, and Panama, generally achieve higher CESI values. In contrast, high-emission economies such as Saudi Arabia, Trinidad and Tobago, and the United States tend to record lower CESI scores, reflecting more carbon-intensive consumption patterns. However, the wide dispersion of points shows that per capita emissions alone explain little of the variation in sustainability performance. Renewable energy use, energy efficiency, and broader structural conditions also shape CESI outcomes (see Figure 8).

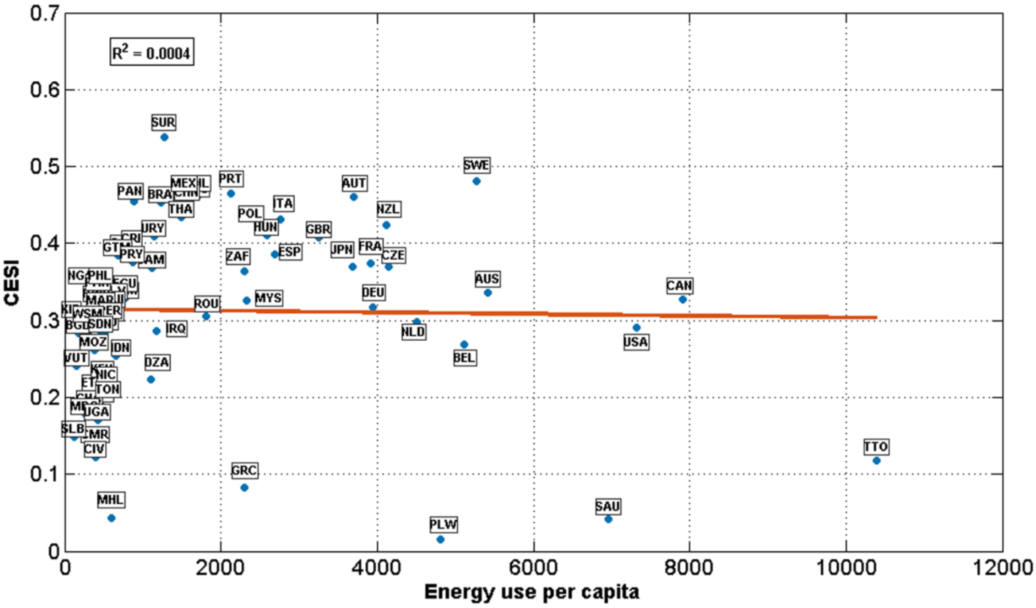

Figure 6. Relationship between average CESI and energy use per capita over the period 1990–2023.

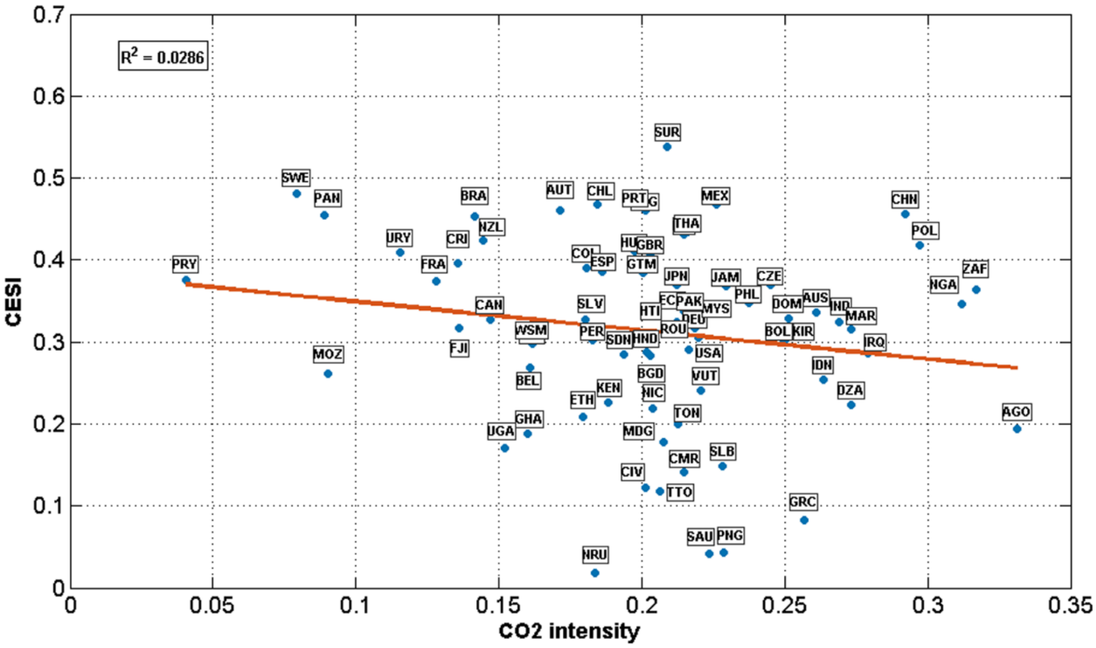

Figure 7. Relationship between average CESI and CO_2 intensity over the period 1990–2023.

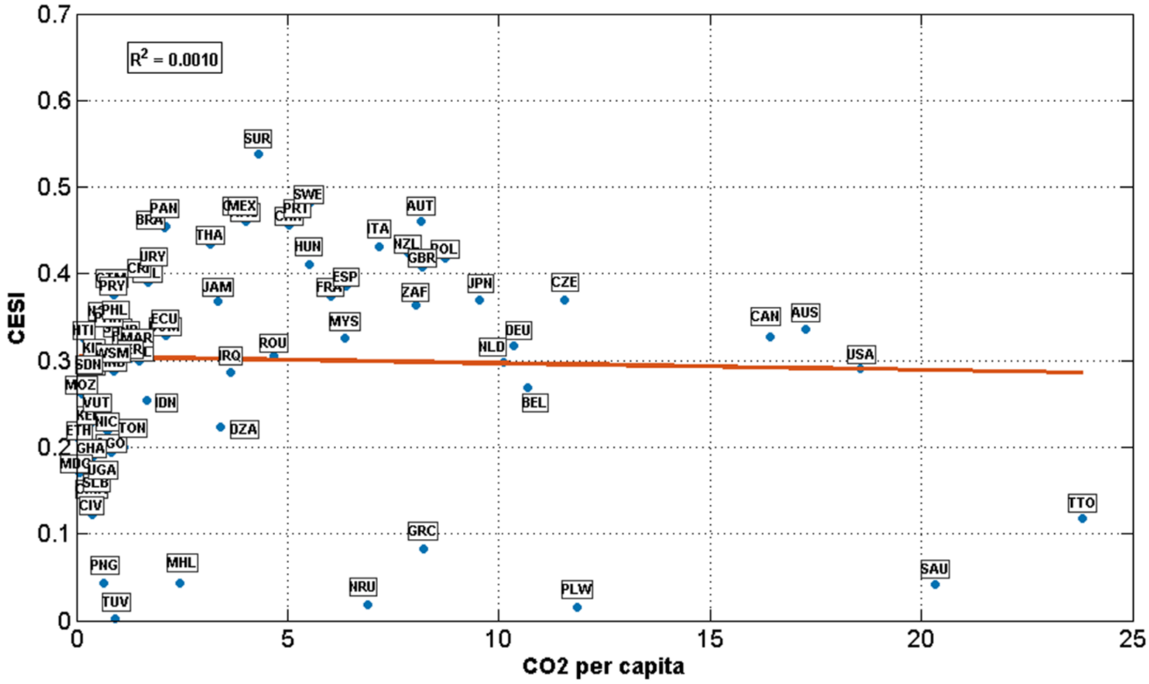

Figure 8. Relationship between average CESI and CO_2 emissions per capita over the period 1990–2023.

4. Conclusions

This study proposes and applies the Climate–Energy Sustainability Index (CESI) as an integrated framework for evaluating sustainability performance at the climate–energy nexus. CESI combines economic capacity, energy structure, carbon intensity, consumption patterns, and climate stability into a single composite measure that captures the multidimensional and non-substitutable nature of sustainability. Mathematically, the index remains within a fixed range. The direction of the normalized component scores is preserved. It also shows conditional scale invariance under the given normalization framework, supporting the consistency and interpretability of the index.

Empirical results for 76 countries over the period 1990–2023 reveal substantial heterogeneity in climate–energy sustainability outcomes. The global average CESI shows a gradual long-term increase, although the trajectory is non-linear and marked by periodic fluctuations. Cross-country dispersion shows mixed dynamics, with variance increasing from 0.0295 in 1993 to 0.0319 in 2013 before declining to 0.0230 in 2023. Thus, the results indicate a recent reduction in dispersion rather than a consistent long-term convergence. However, the decline in the average CESI after 2013 suggests that recent progress has not been uniform across countries.

Regional analysis highlights substantial differences in sustainability pathways. Europe records the strongest and most consistent performance, with regional CESI values generally remaining above those of other regions after the mid-2000s, reflecting long-term policy coordination, energy efficiency improvements, and sustained decarbonization efforts. South America also performs relatively strongly, though with greater volatility in recent years. North America remains moderate, while Africa and Asia show gradual but uneven improvement. Oceania records the weakest overall regional performance throughout the study period. Continental average ranking patterns further reinforce these differences: Europe improved from an average rank of 35.13 in 1993 to 26.33 in 2023, while South America remained comparatively strong despite some loss of momentum. Africa and Oceania continued to occupy relatively weaker positions.

At the country level, the 2023 CESI distribution confirms substantial heterogeneity. Italy, Panama, Chile, the United Kingdom, and Japan emerged as the top five performers. Several countries, including Uganda, Romania, and Hungary, recorded notable long-term gains. In contrast, some countries that ranked highly in earlier years, such as Brazil, Portugal, and South Africa, experienced pronounced declines by 2023. Tuvalu, Trinidad and Tobago, and several African and small-island countries are at the lower end of the CESI distribution. Weak performance across several dimensions limits their overall sustainability outcomes.

The scatter-plot analysis shows that no single variable determines CESI performance. Adjusted net savings and renewable energy share have weak positive relationships with CESI. Greater renewable energy use and higher savings alone may not lead to better sustainability outcomes. Energy use per capita shows a slight negative relationship. This is expected because total energy use includes both renewable and non-renewable sources: renewable energy contributes positively, while fossil-fuel dependence exerts a negative effect, leaving the overall association slightly negative. Carbon intensity of energy use and per capita CO_2 emissions also display weak negative relationships with CESI. Sustainability performance depends on the combined interaction of cleaner energy structure, efficient energy use, and lower carbon dependence rather than on improvement in any single indicator.

The findings have some policy implications. Improvement in only one factor may not improve overall sustainability. A high renewable energy share or higher savings does not always lead to a high CESI when emissions, energy use, or climate conditions remain unfavorable. Therefore, energy efficiency, renewable energy, emission reduction, and resource management should be improved together. Policy priorities should also be adjusted according to country and regional conditions, rather than using a common transition path.

Despite its analytical usefulness, CESI remains subject to several limitations. The index depends on selected thresholds and functional forms that involve normative choices. However, these choices are based on widely used sustainability benchmarks. CESI measures observed sustainability outcomes rather than policy effort or transition readiness. Future research may extend the framework through sensitivity analysis and alternative weighting structures. It may also be applied at the subnational or sector-specific level.

Acknowledgments

The author sincerely acknowledges the valuable comments and suggestions provided by the Editors and Reviewers, which helped improve the clarity, consistency, and overall quality of the manuscript. The author also acknowledges the publicly available data sources used in this study. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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