frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 02 February 2026
DOI 10.3389/fenvs.2026.1759794

OPEN ACCESS

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RECEIVED 03 December 2025
REVISED 29 December 2025
ACCEPTED 05 January 2026
PUBLISHED 02 February 2026

CITATION
Lobonţ OR, Brândaş C, Doraş Lisnic A, Criste C and Cristescu M-P (2026) From green promises to measurable results? Who wins and who lags in the green transition race.
Front. Environ. Sci. 14:1759794.
doi: 10.3389/fenvs.2026.1759794

From green promises to measurable results? Who wins and who lags in the green transition race

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This study starts from the understanding that green finance is a central pillar of the green transition in the European Union, in which green finance is not just a financial instrument, but the mechanism through which both public capital (government or European funds) and private capital (banks, investors, companies) are directed towards projects that support environmental and sustainability objectives. The proposed research assesses which EU Member States perform best in the field of green finance and identifies the structural factors underlying these differences, using a composite index based on the entropy method. The index integrates eight indicators that capture financial effort and environmental outcomes, specifically green investments as a share of GDP, renewable energy share, environmental taxes, greenhouse gas intensity of the economy, Environmental Performance Index, green transport, protected areas, and waste generated *per capita*. Official international data sources, including Eurostat, the European Environment Agency, the World Bank, and Yale University, were utilized for all variables in 2023. All indicators were normalized, and weights were assigned objectively using the entropy method to ensure comparability and reduce subjective bias. The results show wide disparities across the European Union. Sweden, Denmark, Finland, and Lithuania form the leading group due to high levels of green investment, strong renewable energy profiles, and low greenhouse gas intensity. Large industrial economies such as Germany and Italy score lower because their high emission levels outweigh the effect of existing environmental measures. Smaller and service-oriented economies, such as Luxembourg and Malta, perform relatively well due to their moderate emissions and balanced environmental outcomes. At the opposite end, Bulgaria, Cyprus, and Czechia record the weakest results, shaped by carbon-intensive economic structures and limited green investment. These findings suggest that the interaction between financial commitment and structural characteristics, such as the energy mix and emission intensity, strongly influences performance in green finance. Strengthening green investment flows and accelerating emission reduction efforts remain essential for convergence across the EU. Tailoring national

green finance strategies to each country's structural profile can increase the effectiveness of financial instruments and support progress towards the objectives of the European Green Deal.

KEYWORDS

entropic method, European Union, green finance, green investments, greenhouse gas emissions

1 Introduction

The European Union's efforts to create a resource-efficient and low-carbon economy now rely heavily on green finance. Green finance provides financial mechanisms that channel both public and private capital towards projects supporting decarbonization, energy transition, and environmental innovation. Previous studies (Flaherty et al., 2017; Khan et al., 2022; Wang et al., 2022) have consistently demonstrated that green finance can enhance environmental performance and economic growth, reinforcing the financial system's role as a catalyst for sustainability. However, existing research remains fragmented, focusing mainly on individual countries or specific financial instruments rather than on broader cross-country dynamics within the EU.

Green finance represents a fundamental change in traditional financial systems (Zhang, 2023). The concept is understood as a mechanism for correcting market failures through fiscal policies, green credits, and market instruments that reduce negative externalities, while simultaneously generating social benefits and ensuring adequate financial returns (Flaherty et al., 2017; Bhattacharyya, 2022). Other studies emphasize the role of green financial instruments, such as green bonds, green loans, or ESG funds, in accelerating innovation and decarbonization of economies (Kumar et al., 2024). In this study, green finance performance is operationalized as a multidimensional construct integrating both financial inputs (e.g., green investments and environmental taxes) and environmental outcomes (e.g., GHG emissions, renewable energy share, and waste generation *per capita*). This distinction enables an assessment of Member States' ability to translate financial resources directed towards the green transition into concrete outcomes that promote economic sustainability and reduce environmental pressure.

Green finance has become a central pillar of European Union policies (Figure 1) in response to the global climate emergency and the commitments made under the United Nations Climate Change (2015), which aim to limit the increase in global average temperature to below 1.5 °C compared to pre-industrial levels. In this context, the European Union has strengthened its role as a global leader in the transition to a climate-neutral economy, establishing, through the European Commission (2019b), a new economic growth strategy based on energy efficiency, technological innovation, and reduced greenhouse gas emissions. Green finance is the financial mechanism through which these objectives are put into practice, ensuring that public and private capital are directed towards green investments and sustainable projects.

The importance of green finance has grown significantly with the adoption of the EU Sustainable Finance Strategy (Climate Adapt, 2021) and the EU Taxonomy Regulation (EU 2020/852), which

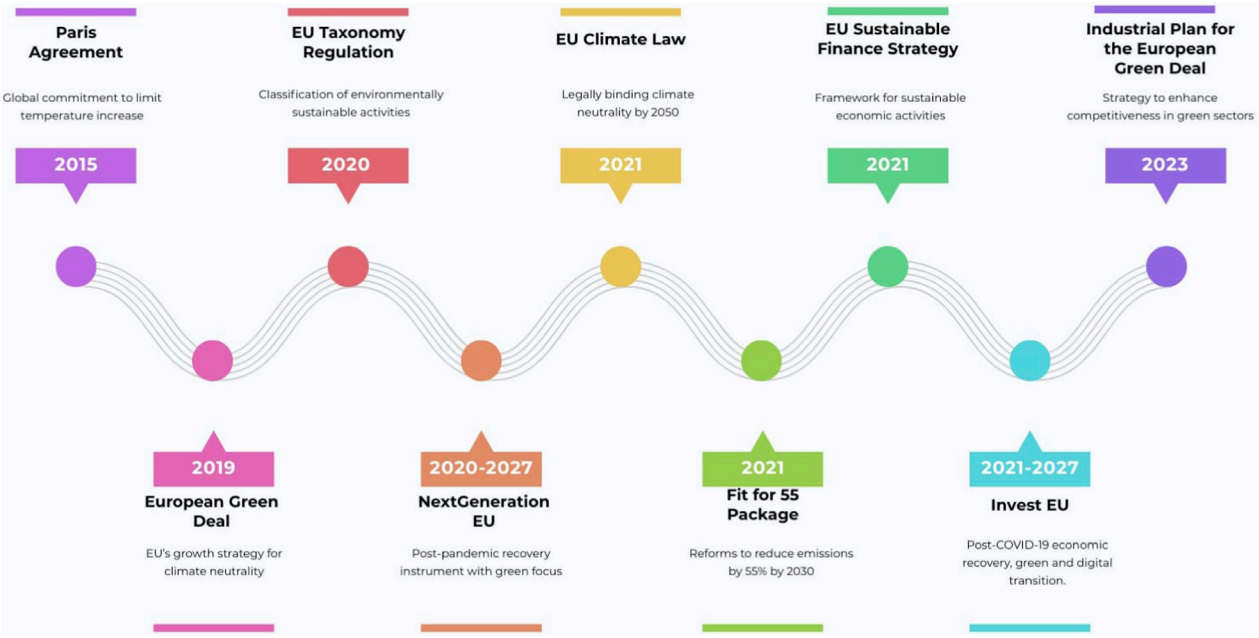

FIGURE 1
Timeline of key EU regulations and policy milestones supporting the green transition. Source: Own elaboration in Canva.

provide a common framework for classifying economic activities considered environmentally sustainable. These instruments aim to align financial markets with the Union's climate and environmental objectives, reducing information asymmetry and creating transparency in the assessment of green investments. At the same time, through the EU European Commission (2021), climate neutrality by 2050 has become a legally binding objective, reinforcing the need for a financial system capable of supporting the green transition on a European scale.

Concurrently, green finance plays an essential role in implementing the Digital and Green Transition, a strategic direction integrated into NextGenerationEU (2020–2027) — the Union's post-pandemic recovery instrument, which allocates at least 30% of funds to environmental and energy transition projects. In addition, the Fit for 55 package (European Council Council of the European Union, 2021) proposes a set of fiscal, energy, and industrial reforms that require a massive mobilization of capital to reduce emissions by 55% by 2030, strengthening the role of green finance as the financial infrastructure for these transformations.

Beyond its ecological dimension, green finance also has strategic economic value, as it is integrated into the Industrial Plan for the European Commission (2023), which aims to strengthen Europe's competitiveness in emerging sectors such as clean technologies, renewable energy, and the circular economy. Additionally, the InvestEU and Just Transition Mechanism initiatives support regions and industries that are more dependent on fossil fuels, ensuring a fair transition and reducing territorial disparities.

Thus, green finance is no longer just a complementary component of climate policies, but represents the integrating core of the European Union's economic and sustainability strategy. By redirecting financial flows towards sustainable investments, strengthening the stability of the financial system in the face of climate risks, and creating a common framework for assessing environmental performance, the European Union is transforming green finance into a key instrument for achieving the objectives of climate neutrality, sustainable growth, and economic cohesion among Member States.

Given this context, the study formulates a set of research hypotheses that guide empirical analysis. These hypotheses reflect expected differences in green finance performance across EU Member States and the role played by financial effort and environmental outcomes in shaping these variations.

H1. There are significant differences among EU Member States in their green finance performance, reflecting heterogeneous policy implementation and economic structures.

H2. Fiscal and financial indicators—particularly green investment and greenhouse gas emissions—exert the most decisive influence on the composite green finance index.

H3. Countries with higher levels of green investment and lower greenhouse gas emissions achieve stronger green finance performance.

H4. Less industrialized economies tend to perform better in the index due to lower emissions and increased green investments.

Despite growing scholarly attention, comparative assessments of green finance performance across EU Member States remain limited and conceptually fragmented. Existing studies (Larsen, 2023; Sun and Rasool, 2024; Bouchmel et al., 2024) generally focus on isolated financial instruments, such as green bonds or loans, and often rely on narrow temporal or sectoral scopes, thereby constraining understanding of the multidimensional and systemic nature of green finance. Only a few recent analyses (Kwilinski et al., 2025; Habib et al., 2025) have attempted to bridge the financial and environmental dimensions by integrating variables such as green investment flows, fiscal subsidies, greenhouse gas emissions, and renewable energy shares within a unified analytical framework.

However, the absence of a comprehensive, data-driven evaluation model continues to hinder our ability to identify which EU countries are most effective in converting financial commitments into tangible environmental and sustainability outcomes. Addressing this limitation, the present study proposes a cross-country, multidimensional assessment of green finance performance across the European Union, employing the entropy method to ensure objectivity and comparability in indicator weighting and national rankings.

A set of established theoretical perspectives supports the expected links between financial effort and environmental outcomes in the European Union. The Environmental Kuznets Curve suggests that developed economies tend to reduce environmental pressure once they reach higher income levels, which explains why several high-income Member States achieve stronger green finance performance. The Sustainable Finance Theory clarifies how financial markets and policy instruments can channel capital towards activities aligned with environmental objectives and the Sustainable Development Goals, reinforcing the role of green investments in the transition process. The Endogenous Growth Theory highlights the role of green investments in technological progress, suggesting that financial support for clean technologies can stimulate long-term innovation and strengthen the green transition. Together, these theoretical foundations justify the structure of the hypotheses and the composite index's multidimensional design.

The novelty of this study lies in four main aspects. First, it offers a multidimensional integration of green finance performance by combining both financial and environmental indicators into a single composite index, enabling a holistic evaluation of the "efficiency" of the green transition. Second, it applies the entropy method to ensure objective, transparent weighting, thereby representing a methodological improvement over previous studies that rely on subjective expert judgment or principal component analysis. Third, it uses the most recent 2023 data, to capture the post-pandemic evolution of EU economies in the context of the European Green Deal and the Sustainable Finance Taxonomy. Finally, it identifies the structural disparities among the 27 EU Member States, distinguishing leaders from laggards and revealing the factors shaping the uneven progress of green finance across Europe.

The main objective of this research is to evaluate and compare the performance of green finance across EU Member States by constructing a composite index using the entropy method. This approach allows for objective weighting of indicators, thereby avoiding subjective biases often present in expert-based or arbitrary weighting techniques. The index integrates financial and

environmental dimensions, providing a coherent framework for ranking countries by their capacity to align financial mechanisms with sustainable development outcomes.

The paper's contributions span both theoretical and practical dimensions. From a theoretical standpoint, the study develops an integrated conceptual and methodological framework for assessing national green finance performance. It demonstrates that financial indicators (such as green investment and fossil fuel subsidies) and environmental indicators (such as GHG emissions, renewable energy share, or environmental protection effort) can be combined coherently into a single analytical construct with high replicability. This contributes to the broader literature on sustainable finance measurement by providing a transparent, data-driven model applicable to other regional contexts.

From a practical perspective, the analysis produces an updated ranking of EU Member States, identifying which countries lead or lag in green finance performance. It further reveals key structural determinants, including the energy mix, economic size, and fiscal support mechanisms, and formulates policy recommendations to reduce fossil fuel dependence and enhance the effectiveness of green investment. By aligning its findings with the European Green Deal objectives, the study supports evidence-based policymaking and the design of more efficient financial instruments for sustainability. The results can guide both EU and national authorities in developing targeted fiscal incentives, improving access to sustainable finance, and strengthening monitoring frameworks for green spending efficiency. Moreover, by highlighting best-performing countries, the study provides a benchmark for convergence, encouraging policy learning and the replication of successful green finance practices across the Union.

To operationalize the study's objectives and provide a coherent analytical framework, a set of guiding research questions has been formulated. These questions aim to structure the empirical investigation, ensuring that the analysis systematically explores both the level and the determinants of green finance performance across EU Member States. They also serve to link the methodological approach, based on entropy weighting and cross-country comparison, with the study's broader theoretical perspective on the interaction between financial mechanisms and sustainability outcomes.

RQ1: How do EU Member States differ in their green finance performance according to entropy-based measurement?
RQ2: Which indicators contribute most to the observed variation in performance across countries?
RQ3: How do fiscal and financial policies, such as green investment and environmental taxes, influence countries' positions in the green finance ranking?
RQ4: What structural characteristics (e.g., energy profile, economic size) explain the divide between leading and lagging economies in the EU's green transition?

Together, these questions provide the foundation for a systematic empirical exploration of green finance performance in the European Union. By addressing them sequentially, the study not only quantifies disparities among Member States but also identifies fiscal, financial, and structural levers to enhance the effectiveness of green finance. The answers to these questions will ultimately help shape evidence-based recommendations to accelerate the EU's transition toward a more sustainable, financially resilient green economy.

The remainder of the paper is structured as follows: Section 2 reviews the theoretical background and previous literature; Section 3 presents the data and methodology; Section 4 discusses the empirical results and policy implications; and Section 5 presents the conclusions.

2 Literature review

In the context of the transition to a green economy and climate commitments, a central question emerges: how does the performance of EU Member States vary in their use of green finance instruments, and what are the main differences between them? This question guides recent research, such as Brühl (2021), Fu et al. (2023), and Tijanić and Kersan-Škabić (2025), on how countries are adopting green finance. The research spans investments in clean technologies to emission-reduction policies, highlighting the need for objective cross-country assessment frameworks. These comparative analyses underline that the success of green finance depends not only on the volume of funds mobilized but also on the efficiency with which financial mechanisms translate into measurable sustainability outcomes.

The implementation of green finance offers multiple opportunities and benefits. First, green finance contributes to reducing carbon emissions and pollution by facilitating investments in renewable energy, energy efficiency, clean transportation, and other environmentally friendly projects (Wang et al., 2022). Numerous studies confirm the positive impact of green finance on environmental performance. Flaherty et al. (2017) find that expanding green lending and issuing green bonds has led to significant decreases in polluting emissions and strengthened corporate environmental responsibility. This suggests that green project finance can accelerate the achievement of sustainable development targets, complementing government regulatory efforts (Shauna, 2022).

Second, implementing green finance brings long-term economic and social benefits. Redirecting capital to green sectors stimulates innovation and job creation in future industries (renewable energy, clean technology, sustainable transportation, etc.), contributing to sustainable economic growth. Recent studies of international samples have shown that green finance has significant positive effects on GDP growth, suggesting that green finance policies can be a driver of economic development, rather than a hindrance. For example, an econometric analysis by Khan et al. (2022) across 30 countries found that a 1% expansion of green finance is associated with a statistically significant increase in economic growth, supporting the economic and environmental co-benefit thesis. Together with this green finance mitigates the long-term economic risks from climate change (so-called transition and physical risks) by encouraging climate-resilient investments. In doing so, it improves long-term financial stability by reducing financial institutions' exposure to assets that may lose value amid decarbonization (e.g., fossil assets) (Hu and Gan, 2025). Xu et al. (2025) demonstrate that green finance policies foster

inclusive green growth at the regional and urban levels by stimulating technological innovation and energy efficiency.

Lastly, the development of green finance enhances transparency and accountability in the financial sector. The issuance of green financial instruments (such as green bonds) requires allocation and impact reporting, forcing borrowers and issuers to demonstrate the green use of funds and the environmental performance of financed projects (Kumar et al., 2024). This transparency brings reputational benefits to financial institutions and corporations that engage in green finance practices, enhancing investor and public confidence. Moreover, investors' growing appetite for green assets (green bonds, ESG funds) reflects a shift from short-term profit maximization to a long-term vision that incorporates environmental and social objectives. Numerous global and European initiatives support this trend. For example, the European Union launched the European Green Deal in 2020, which includes an Investment Plan for a Sustainable Europe. It has also implemented Sustainable Finance Taxonomy, a classification system for green economic activities, and ESG reporting obligations for investors, designed to increase capital flows to green projects and avoid greenwashing. These measures support the development of green finance on a large scale, thereby strengthening opportunities to finance the green transition across all Member States.

The literature confirms the positive correlation between green finance and sustainable performance. Moslehpour et al. (2023) demonstrate, in a study of the Vietnamese economy, that the expansion of green finance, including eco-friendly loans and investments, significantly improves sustainability indices, particularly when accompanied by technological advancements and increased energy efficiency. By analogy, in the European context, instruments such as green bonds, sustainable investment funds, and green budgeting have a favorable impact on the ecological transition, helping economies to decouple growth from carbon emissions. Ahmad et al. (2025) analyze the net-zero energy transition in the EU and demonstrate that green finance instruments promote the deployment of renewable energy. However, financial inputs alone do not secure fast decarbonization without parallel structural and technological reforms. Novák et al. (2025) develop comprehensive green finance indicators for emerging economies and demonstrate that inclusive, multidimensional metrics better capture combined environmental and economic effects.

Comparative studies confirm that EU Member States exhibit heterogeneous green finance performance. Several authors highlight a clear "leaders and laggards" structure across Europe. Lyeonov et al. (2019) show that Nordic and Western economies achieve higher sustainability scores due to consistent policy implementation and a larger share of renewables in their energy mix, while fossil-dependent or transition economies perform modestly. Mikča and Huttmanová (2025) reveal a dual pattern: one group of countries excels across the economic, environmental, and social pillars, while another shows uneven progress. Such findings point to persistent structural asymmetries driven by differences in institutional quality, fiscal support mechanisms, and policy commitment. They also emphasize the importance of policy coordination and the dissemination of best practices within the EU to promote convergence in green finance performance.

Building on these findings regarding cross-country green finance performance, a second strand of literature focuses on methodological approaches for constructing composite indicators of sustainability, among which the entropy method stands out for its objectivity and replicability. The technique derives from information theory (Shannon, 1948) and has been increasingly applied in multi-criteria assessments of sustainable development. Its main advantage lies in the ability to generate indicator weights objectively, based solely on the variability of the data, thereby eliminating subjective influence from expert judgment. Numerous studies have adopted entropy-based approaches to evaluate multidimensional sustainability domains. Jiang et al. (2020) employed an improved entropy method to measure the green finance development index in China and assess its impact on poverty reduction. Liu et al. (2021) analyzed the link between environmental regulation and green productivity using entropy-weighted indicators. Huang et al. (2023) and Shang et al. (2023) employed similar frameworks to analyze the spatial variations in carbon intensity and green financial development. In contrast, Huang and Gao (2024) investigated temporal patterns in the evolution of China's green finance sector. Ullah et al. (2025) employ entropy weighting to construct a sustainability governance index, demonstrating the method's suitability for complex, multidimensional systems. Li et al. (2025) further confirm the validity of entropy weighting for multidimensional sustainability indicators. These applications demonstrate the method's flexibility across environmental, financial, and policy domains.

The entropy method offers several advantages that explain its widespread adoption. It is an objective and reproducible weighting technique that relies entirely on empirical data, thereby increasing methodological transparency and stakeholder trust (Wang et al., 2020). Unlike subjective weighting methods such as Analytic Hierarchy Process or expert-based evaluation, entropy reduces human bias and ensures that more informative indicators receive proportionally higher weights. The technique is computationally straightforward and accommodates large, heterogeneous datasets, making it suitable for cross-country assessments of sustainability and green finance. Additionally, it captures the dynamic relevance of indicators, as indicators with greater variability across countries gain greater importance in the composite index, thereby reflecting real disparities in performance.

However, the entropy method also faces recognized limitations. Chen et al. (2023) argue that although the weighting process is objective, the initial selection of indicators remains a subjective step, as researchers determine which dimensions to include. Moreover, entropy assigns weights based on statistical variation rather than policy relevance, leading to the underestimation of stable yet crucial indicators. The method is also sensitive to extreme values, where countries with outlier data can distort the distribution of weights. Another methodological challenge is the lack of control for variable correlations, which can lead to double-counting of related dimensions, such as renewable energy share and GHG emissions. Despite these limitations, the entropy approach remains one of the most transparent and widely accepted methods for constructing composite sustainability indices, due to its clarity, adaptability, and empirical robustness.

Despite the growing body of literature on both green finance and composite sustainability indices, few studies have combined financial and environmental dimensions into a single analytical

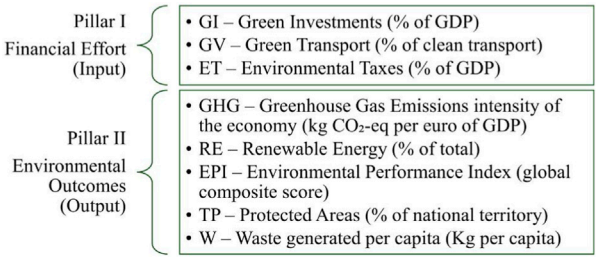

FIGURE 2
Structure of the composite green performance score. Source: Own elaboration.

framework for EU Member States. While entropy has been widely applied to evaluate urban sustainability, regional development, and energy efficiency (Adetama et al., 2021; Wang et al., 2020), its use in green finance assessment within the European Union remains limited. This gap limits understanding of how financial mechanisms translate into real sustainability outcomes across countries and of which structural or policy factors explain performance differences. The present study fills this gap by integrating these two strands of literature—green finance evaluation and entropy-based composite measurement—to provide an objective, data-driven assessment of EU Member States' performance in financing the green transition.

In summary, the literature consistently demonstrates that green finance contributes to environmental and economic sustainability, yet EU countries exhibit heterogeneous performance, shaped by structural and policy disparities. The entropy method, widely recognized for its objectivity and transparency, has proven effective in developing composite sustainability indices but has not yet been systematically employed to assess green finance performance at the EU level. By bridging these two domains, this study presents an innovative analytical framework for evaluating and comparing Member States' capacity to mobilize and allocate financial resources for sustainable development. This integration not only advances methodological rigor but also provides policymakers with valuable insights to enhance the effectiveness of green finance as a driver of the European Green Deal objectives.

3 Methodology and data

3.1 Methodology

The methodological objective of this study is to objectively measure and compare the performance of EU Member States in green finance and environmental outcomes, using a composite index as an analytical tool rather than an end in itself.

Eight indicators have been chosen to capture two complementary dimensions (Figure 2). Pillar I reflects the green financial effort. It includes Green Investments as a share of GDP (GI), Green Vehicles as a share of total vehicles (GV), and Environmental Taxes as a share of GDP (ET). Pillar II reflects environmental outcomes. It includes GHG Intensity of the Economy measured in kilograms of CO_2 equivalent per euro of GDP (GHG), the share of Renewable Energy in total energy (RE), the composite score of the Environmental Performance Index (EPI), the share of Protected Land (TP), and Waste generated *per capita* (W). This two-pillar approach is frequently used in the construction of sustainability indices, such as the OECD Green Growth Indicators (2023) or the Global Green Economy Index (2022), whereby the resulting composite index reflects both the green policies and financing implemented and their visible impact on the economy and the environment.

The selection of these eight indicators was guided by both theoretical relevance and policy significance, aiming to capture the dual aspects of green finance: financial effort and tangible environmental outcomes. While it was possible to start with a broader set of potential indicators and reduce them using statistical criteria, we chose to retain all theoretically meaningful dimensions to ensure no key policy-relevant factor was excluded. The entropy weighting method subsequently assigns higher weights to the most informative indicators and lower weights to those with limited variability, effectively highlighting the indicators that differentiate countries' performance without discarding theoretically essential metrics. This approach combines theoretical comprehensiveness with data-driven objectivity.

To combine these indicators into a single score, the entropic weighting method was used. This is an objective method for determining indicator weights based on data information (variability and value distribution), avoiding the subjectivity of manually assigning coefficients. The method's intuition is that an indicator with low informational entropy (i.e., high variability of values and apparent differences between countries) contributes more to differentiating performance and, therefore, receives a higher weight in the final index. Conversely, an indicator for which all countries have similar values (high entropy, low discrimination information) will receive a lower weight.

The entropy method has been widely used in the literature to construct composite indices of sustainable development, the environment, or finance, due to its objectivity and its elimination of subjective decision bias. For example, Shen et al. (2015) applied entropy weighting in a hybrid index to assess sustainable urbanization in China. Ding et al. (2016) employed a TOPSIS-entropy approach to evaluating urban sustainability in China. In the field of finance, Chen and Zhang (2024) constructed an index of green finance development for member countries of the Regional Comprehensive Economic Partnership using the entropy method to weight sub-indicators (green loans, green bonds, green investments). Additionally, Ma et al. (2023) evaluated the level of green finance and regional sustainable development in China using a similar method, calculating scores based on entropic weights and analyzing the coordination between green finance and a sustainable regional economy. These studies confirm the validity and usefulness of the entropy method in multi-criteria assessments of financial and environmental sustainability.

The entropy weighting method was selected because it ensures objectivity in determining indicator weights, eliminates subjective biases, and reflects each indicator's discriminating power based on data variability. It objectively assigns weights based on statistical dispersion, ensuring transparency and reproducibility. Compared with alternative methods such as Analytic Hierarchy Process (AHP),

Principal Component Analysis (PCA), or equal weighting, the entropy approach avoids expert bias and provides a fully data-driven framework.

The composite index calculation procedure included the following main steps, following the standard entropy weighting methodology (Wang et al., 2020).

1. Normalization of indicators - To make the different indicators (expressed in different units of measurement and having different scales of variability) comparable, the values of each indicator were normalized to a dimensionless scale. We used 0–1 normalization based on the indicator's extreme values, accounting for the indicator's nature (benefit or cost). Specifically, for a benefit type indicator (where a higher value is desirable, e.g., % renewable energy, EPI score, % protected areas), the normalization for country j was done with the standard formula (Equation 1):

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \quad (1)$$

where: x_{ij} = the value of indicator j for country i; r_{ij} = normalized value; n = the total number of countries, so that the country with the minimum value of the indicator has a normalized score of 0 and the country with the maximum value has a score of 1.

For a cost-type indicator (where a higher value is undesirable, e.g., GHG emissions, fossil subsidies), the inverse formula was applied (Equation 2):

$$r_{ij} = \frac{1/x_{ij}}{\sum_{i=1}^{n} 1/x_{ij}} \quad (2)$$

So the country with the highest gross value gets 0 (worst situation), and the country with the lowest value gets 1 (best situation).

2. Calculation of entropy weights - After normalization, the objective weights of each indicator were determined based on information entropy. First, the proportion of country j for indicator i was calculated as the normalized value of country j divided by the sum of the normalized values of indicator i across all countries. Then the entropy of each indicator was calculated using the (Equation 3) (Shannon, 1948):

$$E_j = -k\sum_{i=1}^{n} r_{ij}\, x \ln\left(r_{ij}\right) \quad (3)$$

where

E_j = entropy of indicator j; k = $\frac{1}{\ln(n)}$ is a normalization constant.

A large Ej (close to 1) indicates an almost uniform distribution of indicator values across countries (so not very informative as a differentiator). In contrast, a small Ej indicates significant differences across countries (very informative).

3. The degree of diversity (dj) was then calculated for each indicator according to Equation 4.

$$d_j = 1 - E_j \quad (4)$$

4. The weight (wj) of each indicator in the composite index was determined with Equation 5:

$$w_j = \frac{d_j}{\sum d_j} \quad (5)$$

The weight is practically proportional to the information provided by the indicator. This approach was preferred over assigning equal weights or relying on expert judgment to obtain an index that is as objective and data-driven as possible. The method is recognized in the literature for its robustness and avoidance of subjective influences. For example, Wang et al. (2020) argue that the entropic weighting method eliminates potential biases in decision-making and is easy to apply, with confirmed applications in assessing sustainable regional development.

5. Calculation of final scores and ranking - Ultimately, for each country, the green finance composite score was calculated using Equation 6:

$$Score_i = \sum_{j=1}^{m} r_{ij}\, x\, w_j \quad (6)$$

where wj is the entropic weight of indicator i.

Higher scores indicate stronger green finance performance, integrating both financial inputs and environmental outcomes.

We acknowledge, however, the limitations of the method. It assigns importance solely based on statistical variation rather than policy relevance, potentially undervaluing indicators with low variance but high environmental significance. Despite this, the approach remains robust for several reasons. First, the entropy method ensures objectivity and transparency, eliminating expert bias. Second, indicators were carefully selected based on theoretical and empirical relevance, aligning with frameworks such as the OECD Green Growth Indicators and the Global Green Economy Index. Third, the dataset covers all 27 EU Member States and uses harmonized, verified sources (Eurostat, OECD, World Bank), thereby enhancing comparability. Finally, robustness was tested by recalculating the composite index after excluding the SFF indicator (fossil fuel subsidies). The Pearson correlation between the original and revised scores was 0.62, indicating moderate consistency in absolute values. When comparing country rankings, the correlation increased to 0.81, suggesting that the relative positions of Member States remained broadly stable. These findings confirm that excluding the SFF variable influences the magnitude of scores but does not affect the overall ranking structure. All calculations were performed using Microsoft Excel.

We acknowledge that an alternative approach could have been to start with a broader set of potential indicators and then perform a reduction procedure using PCA or a correlation-based selection method. However, our objective was to ensure that all theoretically relevant dimensions of green finance and environmental performance were represented. The entropy weighting method naturally differentiates the contributions of each indicator, giving greater importance to indicators with stronger variability and less to more homogeneous ones, without discarding theoretically relevant factors.

TABLE 1 List of indicators included in the multi-criteria analysis (entropy weighting method).

Abbreviation	Indicator	UM	Description	Source
RE	Renewable energy	% of total	Share of energy from renewable sources	Eurostat (2025)
GI	Green investments	% of GDP	Climate change mitigation investments	Eurostat (2024)
EPI	Environmental performance index	Score	The EPI combines 58 indicators across 11 issue categories, from climate change mitigation and air pollution to waste management, fisheries and agricultural sustainability, deforestation and biodiversity protection	Yale University (2024)
GV	Green vehicles	% of total	This indicator measures the share of buses, including coaches and trolleybuses, and trains in domestic passenger transport	Eurostat (2025)
TP	Protected land	%	Terrestrial protected areas are wholly or partially protected areas of at least 1,000 ha designated by national authorities as scientific reserves with limited public access, national parks, natural monuments, nature reserves, wildlife sanctuaries, protected landscapes, and areas managed primarily for sustainable use	World Bank (2024)
GHG	GHG intensity of the economy	kg CO_2-eq per euro of GDP	The total amount of greenhouse gas emissions relative to the value produced by the economy, the indicator uses total emissions expressed in CO_2 equivalent and GDP expressed in euros	European Environment Agency (2025)
ET	Environmental taxes	% of GDP	Tax revenues collected by the state from activities that have an impact on the environment (taxes on energy, transport, pollution, and resource use)	Eurostat (2025)
W	Waste generated *per capita*	Kg *per capita*	The total amount of municipal waste produced by a country relative to its population. It includes waste collected by local authorities, household waste, and similar waste from small commercial activities	Eurostat (2025)

Source: Own analysis based on collected information.

3.2 Data

The analysis uses data from 27 EU Member States for 2023. This period was chosen because it provides the most recent, complete, and comparable dataset on green finance and environmental indicators. It also marks a mature phase in the EU's green transition—three years after the launch of key policy frameworks, such as the European Green Deal and the Sustainable Finance Taxonomy—allowing for the evaluation of early, measurable results.

The database comprises seven indicators that capture both input (financial effort) and output (environmental performance) dimensions of the green transition for all 27 EU Member States in 2023 (Table 1). These indicators were selected based on the following criteria: (i) relevance to EU green finance objectives, (ii) availability and comparability of data across all 27 Member States, and (iii) alignment with established frameworks such as the OECD Green Growth Indicators (2023) and the Global Green Economy Index (2022). This ensures that the measures are both theoretically grounded and policy relevant. The combination of these eight indicators balances input measures (financial effort) with output measures (environmental results), enabling a comprehensive assessment of each country's performance.

Most indicators in the analysis are expressed as percentages. The indicators combine relative measures with a single intensity-based variable, thereby increasing variation and improving the entropy-based information content captured. Using GHG intensity, measured in kilograms of CO_2 equivalent per euro of GDP, and waste generated *per capita*, expressed in kilograms per person, provides a complementary view, showing both relative performance and the scale of environmental pressure. The selected indicators provide clear variation, high informational value for the entropy method, and a direct link to environmental impact. The dataset covers all EU countries, with only a few missing values (two observations for the waste indicator, specifically for Ireland and Latvia). These cases were marked as missing and were not treated as zero. Sensitivity checks revealed that the absence of these values did not alter the overall country ranking, confirming the stability of the entropy-based results.

To apply the entropic weighting method, a dataset was collected for the eight indicators corresponding to the two thematic pillars (financial effort and environmental outcomes), as outlined above. The European Union was selected as the study area because it is one of the world's most advanced regions in implementing green finance regulation. The EU's coherent institutional framework—through instruments such as the European Green Deal, Sustainable Finance Taxonomy, and ESG disclosure regulations—ensures consistent policy environments across Member States, making cross-country comparisons both meaningful and reliable. Table 2 presents the raw values for the 27 EU Member States.

Once the raw values were collected, the 0–1 normalization procedure was applied, considering the nature of each indicator (benefit or cost type), as outlined in the formulas presented in the previous section. The normalization results are presented in Table 3.

To understand the distribution and contribution of each indicator in the construction of the composite score, a descriptive analysis of the normalized values was performed and presented in Table 4.

Analysis of the mean values indicates a relatively balanced distribution of data across the indicators. The average values for RE, GI, EPI, GV, TP, GHG, and ET are almost identical (0.037). This shows that the entropic method generated a relatively uniform distribution of importance among the indicators. W has a slightly

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TABLE 2 Values of selected indicators (raw data).

Country/Indicator	RE	GI	EPI	GV	TP	GHG	ET	W
Austria	41	0.66	68.9	23.1	29.5	200	2.01	782
Belgium	15	0.71	66.8	19.6	15.6	206	2.32	688
Bulgaria	23	0.28	56.2	11.2	41	644	3.35	490
Croatia	28	0.56	62.3	16.1	38.5	337	3.3	475
Cyprus	20	0.06	53.9	16.5	38.7	303	2.11	653
Czech Republic	19	0.42	65.5	19.5	22.2	499	1.56	538
Denmark	44	1.46	67.7	18.2	17	118	2.05	759
Estonia	41	0.6	75.7	16.4	21.4	523	2.61	373
Finland	51	0.73	73.8	17	13.4	231	2.26	468
France	22	0.85	67	16.3	28.4	141	1.77	527
Germany	22	0.52	74.5	16.5	37.6	223	1.71	613
Greece	25	0.17	67.3	15.2	35.2	342	4.11	523
Hungaria	17	0.94	59.8	24.5	22.6	343	2.16	429
Ireland	15	0.09	65.8	20.5	14.4	134	0.96	
Italy	20	0.26	60.3	16.7	21.6	183	2.55	489
Latvia	43	1.17	60.2	15.8	18.2	517	2.43	
Lithuania	32	1.47	64.1	7.9	17.1	261	1.61	446
Luxembourg	14	0.2	75.1	17.3	55.8	111	1.28	718
Malta	15	0.36	66.9	17.9	30.6	137	1.54	603
Netherlands	17	0.27	66.9	14.7	22.5	177	2.81	468
Poland	17	0.49	64.2	18	39.6	549	2.56	367
Portugal	35	0.25	61.9	11.8	22.9	241	2.01	505
Romania	26	0.52	57.3	18.7	24.5	270	2.25	305
Slovakia	17	0.41	65.1	21.7	37.6	301	2	472
Slovenia	25	0.37	62.4	14.5	40.4	214	2.8	517
Spain	25	0.22	64	16.1	28.1	176	1.64	465
Sweden	66	1.16	70.3	18.2	15.4	25	2.01	392

Source: Data collected by the author.

higher average (0.41), suggesting a more pronounced variation in the initial data. The median values are very close to the averages for each indicator. This indicates a symmetrical distribution of weights and a lack of dominant extreme values, except for GHG. For GHG, the median is significantly lower than the average, unlike the other indicators, which show that a few states have much higher values that raise the overall average.

The maximum values show where the most significant variations occur. GHG stands out with a maximum of 0.257. This represents a significant difference compared to the other indicators and confirms the high heterogeneity of emissions among countries. TP and GI also have high maximums, but these are significantly lower than those of GHG. On the other hand, the minimum values are similar across most indicators, but GI and GV have the lowest. This indicates that some countries begin at very low levels for these two dimensions.

The standard deviation confirms the degree of dispersion within the dataset. GHG has the highest value (0.009), indicating marked variability across countries and a greater influence on the resulting weights. The group of economic and policy indicators represented by GI, GV, and ET displays a combined deviation of 0.008. The group of environmental indicators, defined by RE, EPI, TP, W, and GHG, displays a combined deviation of 0.018. This pattern shows that environmental pressure indicators, particularly GHG emissions, drive most of the cross-country variation. Economic and policy indicators exhibit more limited dispersion, resulting in more uniform weights.

Through this rigorous methodology, based on objective data and a robust theoretical framework (informational entropy), we have

TABLE 3 Normalized indicator values.

Country/Indicator	RE	GI	EPI	GV	TP	GHG	ET	W
Austria	0,0556	0,0434	0,0391	0,0502	0,0393	0,0321	0,0336	0,0254
Belgium	0,0201	0,0467	0,0379	0,0426	0,0208	0,0312	0,0388	0,0288
Bulgaria	0,0307	0,0184	0,0319	0,0244	0,0547	0,0100	0,0560	0,0405
Croatia	0,0382	0,0368	0,0353	0,0350	0,0513	0,0190	0,0552	0,0418
Cyprus	0,0275	0,0039	0,0306	0,0359	0,0516	0,0212	0,0353	0,0304
Czechia	0,0253	0,0276	0,0371	0,0424	0,0296	0,0129	0,0261	0,0369
Denmark	0,0604	0,0961	0,0384	0,0396	0,0227	0,0544	0,0343	0,0261
Estonia	0,0557	0,0395	0,0429	0,0357	0,0285	0,0123	0,0437	0,0532
Finland	0,0691	0,0480	0,0418	0,0370	0,0179	0,0278	0,0378	0,0424
France	0,0303	0,0559	0,0380	0,0354	0,0379	0,0455	0,0296	0,0377
Germany	0,0293	0,0342	0,0422	0,0359	0,0501	0,0288	0,0286	0,0324
Greece	0,0344	0,0112	0,0382	0,0331	0,0469	0,0188	0,0688	0,0379
Hungary	0,0233	0,0618	0,0339	0,0533	0,0301	0,0187	0,0361	0,0463
Ireland	0,0208	0,0059	0,0373	0,0446	0,0192	0,0479	0,0161	
Italy	0,0267	0,0171	0,0342	0,0363	0,0288	0,0351	0,0427	0,0406
Latvia	0,0588	0,0770	0,0341	0,0344	0,0243	0,0124	0,0407	
Lithuania	0,0434	0,0967	0,0363	0,0172	0,0228	0,0246	0,0269	0,0445
Luxembourg	0,0195	0,0132	0,0426	0,0376	0,0744	0,0578	0,0214	0,0276
Malta	0,0205	0,0237	0,0379	0,0389	0,0408	0,0468	0,0258	0,0329
Netherlands	0,0237	0,0178	0,0379	0,0320	0,0300	0,0363	0,0470	0,0424
Poland	0,0225	0,0322	0,0364	0,0391	0,0528	0,0117	0,0428	0,0541
Portugal	0,0478	0,0164	0,0351	0,0257	0,0305	0,0266	0,0336	0,0393
Romania	0,0351	0,0342	0,0325	0,0407	0,0327	0,0238	0,0376	0,0651
Slovakia	0,0231	0,0270	0,0369	0,0472	0,0501	0,0213	0,0335	0,0420
Slovenia	0,0341	0,0243	0,0354	0,0315	0,0539	0,0300	0,0468	0,0384
Spain	0,0338	0,0145	0,0363	0,0350	0,0375	0,0365	0,0274	0,0427
Sweden	0,0903	0,0763	0,0399	0,0396	0,0205	0,2567	0,0336	0,0506

Source: Data processed by author.

TABLE 4 Descriptive statistics for normalized indicators.

Indicator	RE	GI	EPI	GV	TP	GHG	ET	W
Mean	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.040
Median	0.031	0.032	0.037	0.036	0.033	0.028	0.035	0.041
Maxim	0.090	0.097	0.043	0.053	0.074	0.257	0.069	0.065
Minim	0.020	0.004	0.031	0.017	0.018	0.010	0.016	0.025
Standard deviation	0.003	0.005	0.001	0.001	0.003	0.009	0.002	0.002

Source: Own analysis based on information collected.

developed a tool for benchmarking the performance of EU countries in green finance. In the following section, we present the analysis results, including the indicator weights, the ranking of final scores, and their interpretation in the context of the identified opportunities and benefits. We also provide references to other studies for validation.

TABLE 5 Entropy weights of indicators in the green finance index, year 2023.

Indicators	Weights
RE	0.11279
GI	0.257
EPI	0.00406
GV	0.02408
TP	0.07979
GHG	0.44149
ET	0.05034
W	0.03045

Source: own calculation based on collected data.

4 Results and discussions

Applying the described calculation procedure, entropic weights were derived for the seven selected indicators, capturing their relative contribution to distinguishing the performance of EU Member States in green finance. These weights reflect the degree to which each indicator explains cross-country variation, providing an objective basis for constructing a composite index. Table 5 presents the resulting weights, offering insight into which financial and environmental aspects are most influential in differentiating national performance across the Union.

The distribution of weights provides some fascinating insights. Two components dominate the index: GHG and GI. Together, they account for more than 70% of the total weight. This shows that emission levels and environmental investments primarily define the differences between Member States. Other indicators contribute to a lesser extent, as their values are more homogeneous across Europe.

GHG has the highest weight, ~44.15%. This confirms that total emissions vary significantly between Member States. The differences are striking. Sweden has 25 kg CO_2 equivalent per euro of GDP, while Poland has 549, Germany has 223, and Bulgaria has 644. These high contrasts explain the index's dominant weighting of the GHG indicator. A high share (25.7%) also went to Green Investments (GI), indicating that differences in climate mitigation investments across countries are significant. Indeed, according to Eurostat data, in 2023, only two countries (Lithuania and Denmark) reached ~1.5% of GDP in private investment for climate change mitigation, while most countries had less than 1% (Ireland and Cyprus even had less than 0.1%). The relatively high variability of this indicator gave it substantial weight in the index. Renewable energy (RE) accounts for a modest share (~11.28%), with significant differences (ranging from ~66% in Sweden to ~11–15% in Luxembourg, Belgium, and Malta). The lower share probably indicates that the distribution of countries according to this indicator, although wide, is not very pronounced. Many countries fall within the 20%–40% range, with a few extremes, which means that entropy is still relatively high. In contrast, the EPI (overall environmental performance) score received almost no weight (~0.41%). This is because all EU countries have relatively high and close EPI scores (ranging from ~62 to ~78 out of 100), with internal differences being smaller than for the previous indicators. In practice, the EPI does not sufficiently "discriminate" against EU countries (they all do relatively well globally, with the EU having many countries in the EPI world top 20). Thus, the EPI does not add much additional information for intra-EU differentiation, which explains the low entropic weight. Green vehicles (GVs) also have a low share (~2.41%), indicating that although there are variations between countries (e.g., Hungary, with passenger transport by trains and buses at approximately 24.5% vs. Lithuania, with approximately 8%), they are not as determinant as emissions or green investment. Protected land area (TP) also has a small share (~7.98%), reflecting that although there are countries with over 30% protected territory (e.g. Slovenia, Croatia, Bulgaria) and some with barely ~10–15% (e.g. Ireland, Denmark, Romania), about half of the countries are clustered between 20% and 30%, reducing the differentiation—ranking of EU countries. Environmental taxes (ET) and waste (W) have low weights, at 5.03% and 3.05%, respectively. ET is in a relatively compact range, between 0.96 (Ireland) and 4.11 (Greece), which limits differentiation. W varies from 305 in Romania to 782 in Austria, but the distribution of values suggests that many countries fall within the range of 450–600.

To provide a clearer picture of the indicator's relevance, a visual summary was added. Figure 3 shows the proportional contribution of each indicator to the composite index, highlighting the dominance of GHG and SFF in the overall weighting structure. This graphical illustration enhances the transparency of the entropy-derived weights and visually confirms the substantial impact of emission and fiscal variables on the index composition.

Calculating the composite scores based on these weights yields the ranking of green finance performance in the EU by 2023 (Table 6).

The composite scores highlight apparent differences between Member States and provide a direct answer to RQ1. The results show that green finance performance is not uniform across the EU. Sweden ranks first with 0.14913, and the gap to the following country is large (~0.08). This difference confirms hypothesis H1, which supports the existence of significant variations between countries, generated by different economic and energy structures.

The Nordic countries are at the top of the ranking. Sweden and Denmark score highly due to low emissions and high investment levels. This responds to RQ4 and supports H4. Economies with a clean energy profile and a smaller economy tend to perform better. Lithuania confirms the same pattern: moderate emissions and high investments in the green transition, placing it in the top three. France and Luxembourg achieve solid scores. Both combine substantial investments with moderate emissions. Austria, Finland, Latvia, and Malta demonstrate a balanced performance across several indicators, placing them in the top half of the ranking. Hungary, Belgium, and Germany are in the middle segment, with values around 0.033. These countries exhibit a mixed combination of emissions, investments, and green policies. The Czech Republic, Bulgaria, and Cyprus occupy the bottom positions, with scores around 0.021. These results show high emissions and low environmental investment. The fossil fuel-based energy structure, particularly in Bulgaria and the Czech Republic, explains their positions. This reinforces the answer to RQ4. Economies with a carbon-based industrial profile face difficulties in the green transition.

Romania, Spain, the Netherlands, Italy, and Estonia are at the bottom of the median group. Their scores are influenced by high

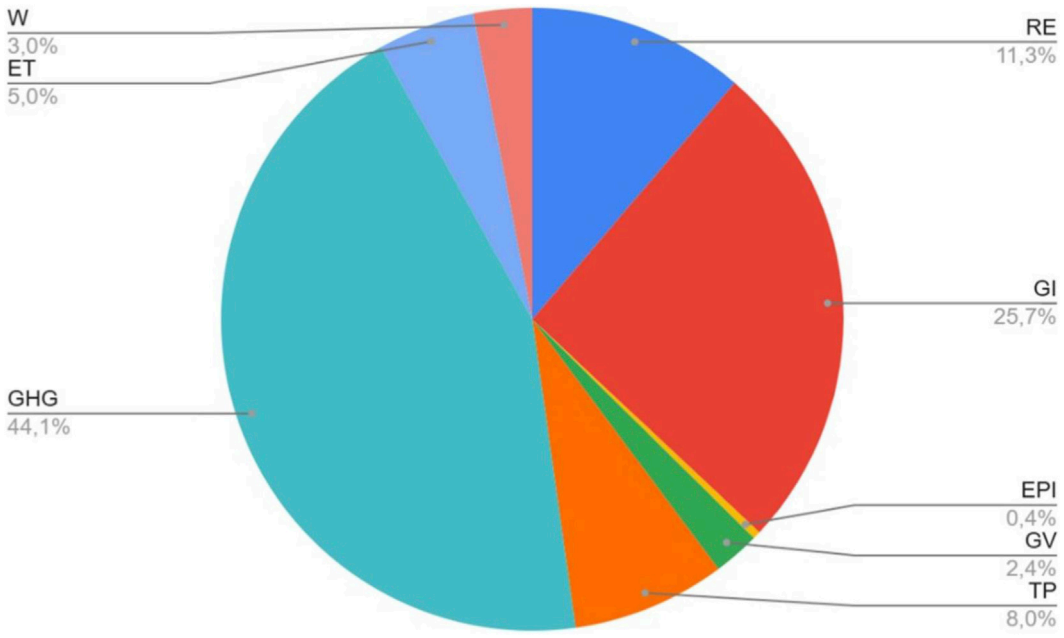

FIGURE 3
Distribution of entropy weights across indicators. Source: Own elaboration.

TABLE 6 Composite scores and ranking of EU member countries, year 2023.

Country	Score	Ranking	Country	Score	Ranking
Sweden	0.14913	1	Romania	0.03084	15
Denmark	0.06095	2	Spain	0.03029	16
Lithuania	0.04570	3	Netherlands	0.03022	17
France	0.04455	4	Italy	0.02958	18
Luxembourg	0.04005	5	Estonia	0.02898	19
Austria	0.03857	6	Ireland	0.02857	20
Finland	0.03808	7	Portugal	0.02747	21
Latvia	0.03684	8	Slovakia	0.02721	22
Malta	0.03573	9	Poland	0.02509	23
Hungary	0.03383	10	Greece	0.02435	24
Belgium	0.03369	11	Bulgaria	0.02173	25
Germany	0.03227	12	Czechia	0.02160	26
Slovenia	0.03207	13	Cyprus	0.02128	27
Croatia	0.03132	14			

Source: own calculation based on collected data.

emissions levels or lower investment levels, which answers RQ3. The results show that investment levels and the tax structure influence the final position, thereby validating H3. Countries with low green investment scores tend to fare even worse despite good overall environmental performance.

The analysis of the score distribution also answers RQ2. The indicators that contributed most to the variation in positions are GHG and GI. Their high weight in the model is reflected in the ranking's structure. Countries with low emissions and high investments are at the top, while those with high emissions and limited investments are at the bottom. This confirms hypothesis H2 regarding the decisive role of fiscal and financial indicators. The entropy weighting results (Table 5) indicate that GHG emissions and green investments (GI) collectively dominate the composite index, accounting for nearly 70% of the total. This also confirms the second hypothesis (H2), supporting the assumption that fiscal and financial indicators exert the most decisive influence on Member States' differentiation.

The composite scores validate all the hypotheses formulated. They reveal apparent differences between states, confirm the dominant influence of investments and emissions, and explain how the economic and energy structure shapes performance in green finance.

To illustrate these differences more clearly, Figure 4 presents a horizontal bar chart comparing the top 5 and bottom 5 EU Member States in the green finance ranking. This visual comparison highlights the magnitude of disparities across the Union and the concentration of high performers among smaller or policy-active economies.

To provide a spatial overview, Figure 5 maps the composite index across the EU-27. Countries in darker shades indicate stronger green finance performance, while those in lighter shades indicate weaker outcomes. This visual reinforces the north–south and west–east divide, with Nordic and Central European countries generally outperforming others.

The highest composite score (0.14913) represents only 15% of the theoretical maximum (1.0), suggesting that even the best-performing Member States still have substantial room for improvement in aligning financial mechanisms with sustainability goals.

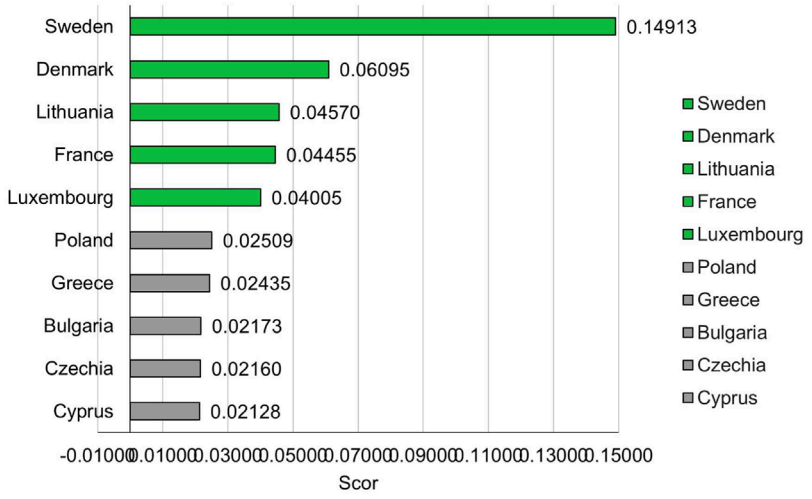

FIGURE 4
Green finance performance ranking: top 5 vs. bottom 5 EU countries. Source: Own elaboration.

The results show a concentration of high performance in northern Europe. Sweden is highlighted in the most intense shade of green, confirming its dominant score in the index. This position is explained by low emissions, a high share of renewable energy, and a consistent level of environmental investment. Denmark and Finland share similar characteristics, indicating a strong profile in both financial investment and environmental outcomes.

Central and Western European countries, such as Austria, Luxembourg, France, and Germany, are located in the middle of the distribution. They combine relatively sound fiscal policies with moderate environmental performance, as reflected in the map's medium color intensity. Southern and Southeastern Europe: Romania, Bulgaria, Greece, Cyprus, and, to some extent, Italy and Spain are at the bottom of the ranking. Low green investment values, high emission levels, and a lower share of renewable energy explain the paler shades. These countries are characterized by low financial effort in the green transition and uneven environmental performance, both of which affect the final score.

The map confirms a high degree of heterogeneity among states. The green transition is progressing at varying speeds, and the entropic results indicate that each state's position depends simultaneously on both financial effort and environmental performance. Countries with ambitious fiscal policies and a favorable energy mix stand out most in the composite analysis.

To better understand structural differences, countries were grouped into six economic types. The classification takes into account economic size, industrial structure, energy profile, and institutional capacity. Each type includes a policy recommendation based on the composite score and the indicators that most influence performance. Table 7 presents the economic types, representative countries, structural profile, and directions for intervention.

To identify the average profile for each group, the indicators' averages were calculated by economic type. These values were summarized in a comparative radar chart (Figure 6).

The radar chart shows that northern and small innovative economies perform similarly across all variables, with advanced preparedness for European environmental objectives. These economies have the highest percentage of renewable energy; EPI is the best of all groups; emissions are the lowest; and green vehicles and transition investments are high. Large industrial economies are characterized by high emissions, a lower share of renewable energy, and limited financial effort for the transition (a small share of green vehicles, and green investments remain low). Emerging economies depend on European funds and have low levels of green investment, high emissions, and the lowest EPI. Despite the significant size of environmental taxes, these economies do not make sufficient use of renewable resources. Island and peripheral economies are more vulnerable to environmental indicators and more dependent on energy imports. This profile confirms the differences identified in the individual scores.

Correlation analysis (Table 8) provides a clear picture of the relationships among indicators and confirms the database's internal consistency. Pearson coefficients show a moderate positive correlation between GI and RE, with r = 0.585. This relationship indicates that countries with high levels of green investment also tend to have a higher share of renewable energy. EPI is positively correlated with RE and W, with low-to-moderate effect sizes (r = 0.270, r = 0.218). This indicates that aggregate environmental performance is partly associated with both energy structure and resource use, but remains relatively independent of variations in fiscal and transport policies.

GHG shows several negative correlations. The relationship between EPI and emissions is negative (r = −0.323), suggesting that states with higher EPI scores tend to have lower emissions. Negative correlations with GV (r = −0.158) and W (r = −0.361) indicate that countries with higher emissions tend to have lower environmental performance, lower public transport use, and lower *per capita* waste generation. The positive correlation between environmental taxes and emissions (r = 0.458) indicates that economies with higher emissions tend to apply higher environmental taxes. This reflects the fiscal dimension of their

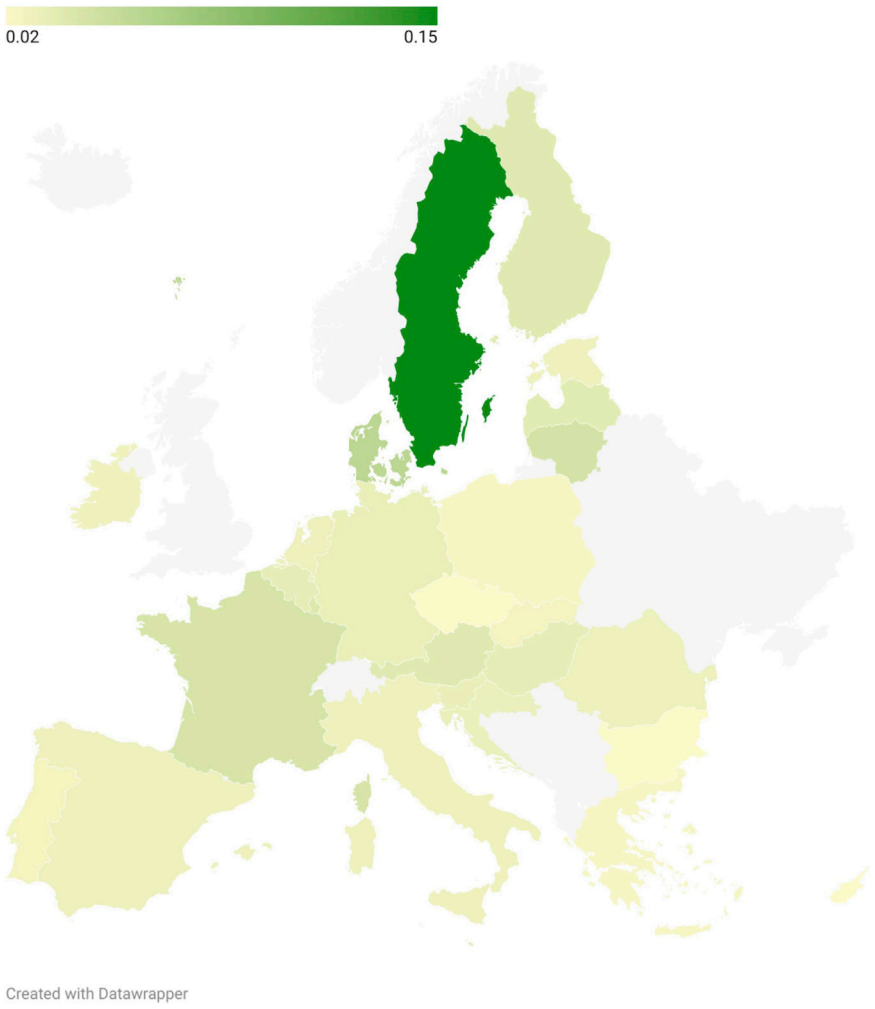

FIGURE 5
Spatial distribution of green finance performance in the EU-27. Source: Own elaboration in Datawrapper.

TABLE 7 Economic typologies in the EU and policy recommendations for the green transition.

Economy type	Countries	General profile	Policy recommendation
Large industrial and exporting economies (1)	Germany, Italy, France, Spain, Portugal	Economies with an extensive industrial sector and high emissions, the energy mix is still dependent on fossil fuels	Increase investment in renewable energy for industry, introduce clean technologies in production, and expand energy efficiency programs in factories
Diversified average economies (2)	Netherlands, Belgium, Austria, Czech republic, Slovenia	Mixed economies, a high technological level, and pressures from transportation and urbanization	Expand green financing for SMEs, modernize urban infrastructure, and improve sustainable mobility
Small, innovative, and Nordic economies (3)	Denmark, Sweden, Finland, Ireland	Economies with strong innovation and robust climate policies	Strengthening green leadership; exporting know-how and transition technologies to other member states
Emerging and transition economies (4)	Romania, Croatia, Hungary Estonia, Lithuania Latvia	Economies are undergoing structural recovery, with limited green financial infrastructure	Strengthen public financial institutions, create green financial products, and use European funds for local investments
Peripheral economies with high energy dependence (5)	Greece, Poland, Bulgaria Slovakia	Countries with slow energy transition and high energy imports	Investments in climate resilience, energy efficiency in services and buildings, modernization of tourism infrastructure
Island economies oriented towards services (6)	Cyprus, Malta, Luxembourg	Small economies, dependent on services, vulnerable to climate and economic shocks	Strengthening national financial institutions for the green transition; using European funds to create domestic green markets

Source: Own elaboration.

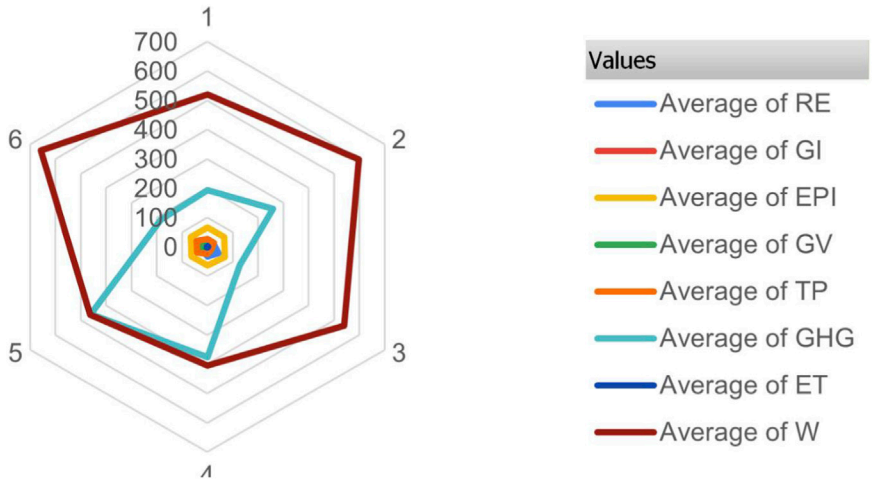

FIGURE 6
Radar chart of financial effort and environmental outcomes profile of EU member states. Source: Own elaboration.

TABLE 8 Pearson correlation matrix among the seven indicators.

Indicator	*RE*	*GI*	*EPI*	*GV*	*TP*	*GHG*	*ET*	*W*
RE	1							
GI	0.585	1						
EPI	0.270	0.146	1					
GV	−0.117	−0.028	0.141	1				
TP	−0.457	−0.502	−0.054	−0.079	1			
GHG	−0.117	−0.074	−0.323	−0.158	0.173	1		
ET	0.087	−0.112	−0.246	−0.264	0.190	0.458	1	
W	−0.105	−0.003	0.218	0.196	0.206	−0.361	−0.267	1

Source: own calculation based on collected data.

TABLE 9 VIF results.

Indicator	R2	VIF
RE	0.10	1.11
GI	0.09	1.10
EPI	0.05	1.05
GV	0.02	1.03
TP	0.08	1.09
GHG	0.07	1.08
ET	0.07	1.07
W	0.05	1.05

Source: own calculation based on collected data.

industrial structure. TP shows moderate negative correlations with GI and RE (r = −0.502 and r = −0.457, respectively). Countries with large protected areas are not always those that invest heavily in a sustainable future or achieve high shares of renewable energy. Simultaneously, TP is weakly positively correlated with GHG and W, with r values of 0.173 and 0.206, respectively. These values suggest that some countries with large protected areas may have higher emissions or higher *per capita* waste levels, depending on their economic profile.

ET shows negative correlations with GV and W, with r = −0.264 and r = −0.267, respectively. Countries with high environmental taxes tend to have more efficient transport systems and lower *per capita* waste levels. The correlation with GI is weakly negative (r = −0.112), indicating that the tax structure does not necessarily align with the volume of green investments.

Overall, the correlation model shows a coherent system. Green investments are closely tied to the energy transition, while emissions are linked to environmental performance and the structural profile of the economy. Additionally, environmental taxes influence resource consumption and production behavior. These relationships confirm the logic of the indicators used and how they contribute differentially to the final score of Member States.

To verify collinearity between indicators, we calculated the Variance Inflation Factor. The results are shown in the following table (Table 9).

The VIF values are below the threshold of 5, indicating that the indicators are not collinear and can be combined into a composite index without statistical overlap.

Our ranking can be compared with a similar index constructed by Chen and Zhang (2024); they found that regions with the most intense development of green finance (measured by green loans, green bonds, and investments) also achieved the sharpest reduction in fossil energy consumption. Analogously, in the EU, we observe that Sweden has channeled resources into green finance (loans and investments, including those made through EU funds) and reduced its dependence on fossil energy, thereby reaching the top. Another study (Ma et al., 2023) demonstrates a strong correlation between the development of green finance and regional sustainable economic growth: regions with high green finance scores also tend to have high economic sustainability indices. In the EU context, the Nordic

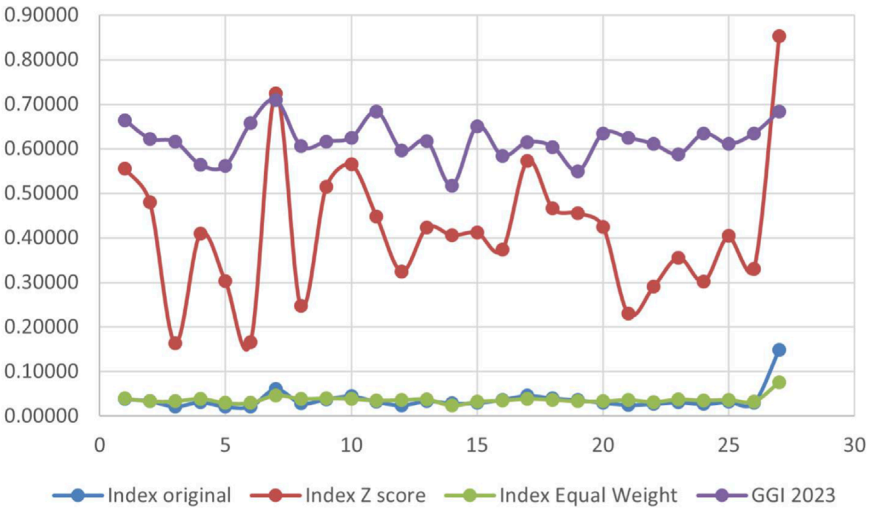

FIGURE 7
Comparison of the original index with Z score, equal weights, and OECD GGI 2023. Source: Own elaboration.

countries (Denmark, Sweden, Finland), which rank high in our index, are also economies with a recognized sustainable profile, indicating a positive correlation. Moreover, our results confirm the findings of Taghizadeh-Hesary and Yoshino (2019), who argued that the right financial incentives can attract private capital into green projects and thus reduce the public burden of the transition. Leading countries (e.g., Sweden, Denmark) have built strong market-based financial mechanisms (e.g., municipal green bond issues, guarantee schemes) to mobilize private green investments, resulting in high green investment (GI) as a percentage of GDP and, consequently, high composite scores. Additionally, the substantial gap in green investment (~15 times between Denmark/Lithuania and Cyprus/Ireland) underscores a significant opportunity: mobilizing private capital and accessing EU environmental funds can transform slower economies into future green leaders. In the EU, there are already instruments such as the Modernization Fund (for Eastern countries) or InvestEU that can be utilized to increase green investments, which currently rank at the bottom of the league table.

To verify the stability and consistency of the constructed index, three robustness tests were conducted: alternative scaling, alternative weighting, and external validation (Figure 7). The analysis aims to determine whether the order of countries changes significantly when the normalization methods or weight structure are changed and whether the index converges with established international indicators.

Three methods were used to verify robustness: recalculating the index using Z-score normalization, recalculating the index with equal weights, and external validation by comparing it with the international Green Growth Indicator (GGI) 2023. The Pearson correlation coefficients between the original index and the z-score and equal weights indices are ~0.79 and 0.94, respectively, indicating that changing the normalization method does not alter the relative order of countries and that the results primarily depend on the indicator values rather than the weighting scheme. The correlation with the GGI is 0.4; the index captures common trends with international indicators but retains a distinct structure due to its focus on green finance and specific investment and emissions indicators. This difference is to be expected, as the GGI measures overall progress in green growth, while the index developed in this study is geared towards performance in green finance and environmental outcomes.

The results indicate significant differences among Member States in their combined green performance. The Nordic countries and a few Central European countries lead the ranking, benefiting from proactive policies (high green investment, abundant renewable energy, and environmental taxes that support the transition) and lower-emitting economic profiles. In contrast, large Western and some Eastern economies are lagging, mainly due to very high absolute emissions, intensive resource use, and an energy structure that is more dependent on fossil fuels, which are holding back the green transition. In these cases, green investments and environmental taxes fail to offset the environmental pressure generated by the economic and energy profile. This suggests that while the EU is aggressively promoting sustainable finance, implementation and impact differ substantially from country to country, some are already reaping visible benefits (less pollution, protected natural capital, stimulated green investments), while others still have opportunities not yet fully exploited.

Overall, the analysis provides consistent answers to all four research questions (RQ1–RQ4) and confirms the corresponding hypotheses (H1–H4). EU Member States differ substantially in their green finance performance (RQ1/H1), fiscal and financial indicators dominate the explanatory structure of the index (RQ2/H2), countries with stronger green investment and lower fossil subsidies achieve higher scores (RQ3/H3), and smaller, less industrialized economies outperform larger emitters due to structural and policy asymmetries (RQ4/H4). These findings offer a coherent empirical explanation for the observed disparities and underline the need for targeted, differentiated policy interventions to strengthen green finance mechanisms across the European Union.

5 Conclusion

The composite index, constructed using the entropy method, revealed significant differences in green finance performance among EU Member States. The results confirm a clear divide between countries with strong financial commitment to the green transition and those where structural characteristics continue to constrain progress. The Nordic countries, particularly Sweden and Denmark, achieve the highest scores. Their performance reflects high levels of green investment, strong shares of renewable energy, and low greenhouse gas intensity, creating favorable conditions for aligning financial and environmental objectives. Lithuania and France also appear in the upper part of the ranking, supported by balanced investment levels and moderate environmental pressure.

In contrast, several Member States obtain significantly lower scores. Cyprus, Bulgaria, and Czechia are placed at the bottom of the ranking due to their limited green investment efforts and high greenhouse gas intensity. Several mid-ranking countries, such as Romania, Spain, the Netherlands, and Italy, exhibit mixed profiles, where weaker environmental outcomes offset advances in financial indicators. These differences confirm that a country's capacity to mobilize and direct financial resources towards the green transition depends strongly on its structural energy profile and economic characteristics.

The results provide direct empirical answers to the four research questions. First, Member States differ markedly in their green finance performance, confirming substantial heterogeneity (RQ1) in the implementation of sustainability policies, also validating the first hypothesis (H1) that economic structure generates significant disparities across countries. Second, the entropy weights indicate that fiscal and financial indicators, especially green investments and greenhouse gas intensity, are the primary determinants of countries' relative positions (RQ2), suggesting that fiscal effort and emission patterns account for most of the observed variation, confirming hypothesis H2. Third, countries with higher green investment levels and lower greenhouse gas intensity achieve higher composite scores (RQ3), supporting the hypothesis that financial mechanisms directly influence transition performance. Finally, smaller or less industrialized economies perform better in relative terms (H4), as their lower emission intensity and more flexible economic structures enable financial measures to translate more effectively into environmental results (RQ4).

The ranking pattern also highlights the structural challenges faced by large industrial economies. Germany, Italy, and Spain score in the lower half of the distribution, not because of insufficient environmental regulation, but due to their emission-intensive economic structures and relatively modest green investment ratios. This result suggests that performance differences should always be interpreted in the context of economic size, energy mix, and production structure.

The robustness tests confirm the stability of the entropy-based results and strengthen the validity of the composite index. The alternative normalization using Z scores and the recalculation with equal weights produce rankings that remain highly consistent with the original index, with Pearson correlations of approximately 0.79 and 0.94, respectively. This shows that country positioning depends primarily on the underlying data rather than on the weighting scheme. The lower correlation with the OECD Green Growth Indicator reflects the distinct conceptual focus of the index developed in this study, which targets financial effort and environmental outcomes rather than broad green growth dimensions.

The relationship between the entropy results and the radar chart is also clear. The radar profiles by economic type mirror the dominant influence of green investments and greenhouse gas intensity observed in the entropy weights. Small Nordic and innovative economies display balanced and favorable positions across most variables, while large industrial and transition economies show pronounced weaknesses in emissions and investment levels. This convergence between statistical weighting, spatial patterns, and structural profiles provides additional confidence in the interpretability of the composite index.

The Pearson correlations and the Variance Inflation Factor analysis confirm the database's internal coherence. The correlation matrix shows meaningful but not excessive relationships among the indicators, reflecting a balanced structure of financial and environmental dimensions. Green investments are positively associated with renewable energy, while greenhouse gas intensity is negatively linked to environmental performance and waste generation, supporting the theoretical logic of the selected variables. At the same time, VIF values remain close to one for all indicators, indicating the absence of multicollinearity and confirming that each indicator contributes distinct information to the composite index. These results validate the dataset's statistical integrity and support the reliability of the entropy-based weighting and the resulting national rankings.

Based on these findings, tailored policy approaches are needed. High-emission and industrialized countries (e.g. Germany, Poland, Italy) would benefit from expanding green investment programs, modernizing energy systems, and strengthening incentives for low-carbon technologies.

For economies under-investing in green projects (e.g., Ireland, Cyprus, Romania), mobilizing transition capital is essential. Their governments should make better use of available EU funds, such as the Modernization Fund and the InvestEU program, to finance the expansion of renewable energy, sustainable transport, and other priority green initiatives. Meanwhile, creating domestic incentives (such as public guarantees, tax breaks, and public-private partnerships) can attract substantial private capital into the green economy, following the model of leading countries. Denmark, for example, has issued green municipal bonds and implemented public guarantee schemes to steer private investment towards sustainable projects, resulting in a very high level of green finance as a share of GDP. The up to 15-fold difference in green investment levels between leaders (Denmark, Lithuania) and laggards (Cyprus, Ireland) highlights the considerable potential for catching up. With appropriate financial measures, lagging economies can accelerate their transition and rapidly improve their performance in the coming years. For smaller economies, maintaining balanced green finance frameworks and consolidating progress in renewable energy and waste management can support long-term sustainability.

This research makes a twofold contribution. Methodologically, it develops an objective, entropy-based composite index that integrates financial and environmental indicators into a unified framework for measuring green finance performance across EU countries. This approach enhances transparency, comparability, and

replicability in sustainability measurement, offering a data-driven alternative to subjective weighting methods. Empirically, the study provides a comprehensive ranking of EU Member States based on both financial inputs and environmental outcomes, revealing the structural and policy factors that explain performance gaps. The results provide policymakers with concrete insights into how fiscal incentives, subsidy reforms, and targeted green investments can accelerate convergence within the European Union's green transition.

The study also has limitations. The entropy method assigns indicator weights solely on the basis of statistical variability, which may underestimate the policy importance of indicators with lower dispersion, such as the Environmental Performance Index. The dataset includes one indicator with partial missing values (waste *per capita*), which reduces coverage for two Member States. Although robustness checks confirm the ranking's stability, the composite index does not capture correlations among indicators, and overlapping thematic areas may affect the results' sensitivity. Despite these limitations, the analysis provides a reliable and coherent picture of Member States' progress in green finance. It highlights the critical role of financial mechanisms in achieving the objectives of the European Green Deal and the EU's climate objectives.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

OL: Supervision, Writing – review and editing. CB: Writing – review and editing, Validation, Supervision. AD: Writing – original draft, Data curation, Methodology, Conceptualization. CC: Writing – original draft, Visualization. M-PC: Writing – review and editing, Supervision.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This work was supported by a grant from the Romanian Ministry of Research, Innovation and Digitalization, the project with the title "Economics and Policy Options for Climate Change Risk and Global Environmental Governance" (CF 193/28.11.2022, Funding Contract no. 760078/23.05.2023), within Romania's National Recovery and Resilience Plan (PNRR) - Pillar III, Component C9, Investment I8 (PNRR/2022/C9/MCID/I8) – Development of a program to attract highly specialized human resources from abroad in research, development and innovation activities, and by the LBUS internal research grant no. 2129/03.06.2022.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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