



Unequal transitions: Social progress and decarbonization contradictions across 160 countries

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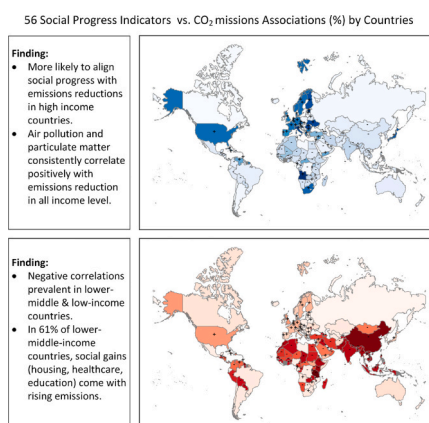
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HIGHLIGHTS

- Analyzes CO₂–SPI links via correlation, trend, and clustering
- Wealthier nations align CO₂ cuts closely with SPI gains.
- Poorer nations trade emissions for basic social progress.
- Decarbonization may threaten housing and employment in rich nations.
- Equity-focused climate policy is crucial to avoid inequalities.

GRAPHICAL ABSTRACT



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ABSTRACT

Efforts to mitigate climate change through CO₂ emissions reduction must be balanced with achieving social progress sustainably and equitably. Yet, their interlinkages remain insufficiently understood across global contexts. This study uses a multi-method diagnostic to find structural inconsistencies between emissions and social progress across income levels, extending beyond correlation analyses. This study examines the associations between total CO₂ emissions and 55 Social Progress Indicators (SPIs) across 160 countries from 2011 to 2023. Unlike traditional Environmental Kuznets Curve interpretations, this study disaggregates SPI categories to reveal uneven relationships often concealed in aggregate models. Using Spearman correlation, Theil-Sen bootstrapping, and hierarchical clustering, this study identifies trajectory patterns where high-income countries show a larger share of positive correlations (29 %), reflecting alignment between decarbonization and social improvements, particularly in health, education, and environmental quality. Nevertheless, contradictions persist in areas such as equal access to quality healthcare, intimate partner violence, freedom of peaceful assembly, equality before the law and individual liberty, world press freedom, equal access to quality education, academic freedom, political

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rights, equal protection, housing affordability, and vulnerable employment. Lower-middle and low-income countries exhibit a larger share of negative correlations (46 % and 38 %, respectively), suggesting that SPIs' improvement frequently coincides with rising emissions, with many emitting more annually for each unit of social improvement. Moreover, the prevalence of weak correlations in high-income (53 %) and upper-middle-income (61 %) nations suggests that additional policy-driven mechanisms and economic transitions mediate SPI-emission relationships. Correlation results do not imply causation; rather, they reflect statistical associations based on temporal co-movement, appropriate for a diagnostic study to identify patterns of alignment and contradiction. These findings highlight the need for differentiated, justice-oriented climate policies that reduce emissions without deepening inequality, particularly in lower-income contexts, and support the joint pursuit of environmental and social objectives at national and global levels.

1. Introduction

Transitioning to low-carbon energy systems is essential to achieving global Sustainable Development Goals (SDGs) and mitigating climate change (Chapman et al., 2018). However, the paper focuses not on the energy mix itself but on how national CO₂ trajectories correlate with broad social progress outcomes, addressing an underexplored empirical gap in existing literature. While reducing fossil fuel consumption and greenhouse gas emissions is critical, sustainability also demands a balanced approach that considers both environmental integrity and social stability (Wang and Lo, 2021). The failure to account for the social dimensions of decarbonization risks may worsen issues such as energy poverty, social exclusion, and inequality (Fragkos et al., 2021). Therefore, climate policies must prioritize both environmental sustainability and social equity to ensure a just transition for all nations.

Social sustainability is an evolving concept shaped by the diverse needs and values of communities, offering a dynamic framework for promoting the wellbeing and quality of life for all individuals (Rahimpour et al., 2024). As such, energy transitions must be carefully designed to consider all stakeholders and minimize potential harm. This concern has been framed as 'just transition', which recognizes that low-carbon shifts can generate or intensify social and environmental tensions (Lèbre et al., 2020), as evidenced by varied outcomes in each country. Germany, for instance, has broadly shared the benefits of clean energy. Fossil fuel-exporting nations such as Saudi Arabia have resisted complete transitions, fearing economic disruption. Although Australia possesses large fossil fuel reserves, it has significantly accelerated its deployment of solar and wind technologies in recent years, yet continues to face internal conflicts over coal exports and environmental justice concerns. Elsewhere, policies aimed at reducing emissions in the UK, South Africa, and Chile have coincided with widening inequalities and social unrest (Chapman et al., 2018; Fakhri et al., 2024; Gaete-Morales et al., 2018; Hochstetler, 2020). In India, renewable energy adoption is disproportionately concentrated in empowered communities, leaving historically marginalized groups behind (Mondal et al., 2023). These divergent social outcomes could potentially undermine public support for low-carbon energy transitions and raise critical policy questions about the relationship between emission trends and social sustainability, about whether and how decarbonization supports broader social progress globally (Fraser et al., 2023).

In recent years, a growing body of research has examined the intersection of environmental goals and social outcomes in sustainability transitions (Caglar et al., 2025). Studies have highlighted how inequality in race, income, and gender can shape emissions outcomes across diverse contexts, including the United States, Latin America, and Europe (Goldstein et al., 2022; Koengkan and Fuinhas, 2021; Valls Martínez et al., 2022). At a broader level, frameworks such as the "safe and just space" have assessed national progress in meeting social thresholds within ecological limits (Fanning et al., 2022; O'Neill et al., 2018), while Others have employed interlinkage analysis to assess SDG interactions at global or regional levels (Laumann et al., 2022; Wu et al., 2022). Recent contributions also focus specifically on the relationship between income inequality and CO₂ emissions, showing how inequality has historically shaped emission trajectories (Andersson, 2023), how non-linear dependencies

complicate cross-national patterns (Dorn et al., 2024), and how network dynamics reveal multiple options linking inequality and emissions (Fernández Fernández et al., 2024). Moreover, the just transition literature has explored the distributional effects of decarbonization in specific sectors or regions, such as coal communities and renewable energy labor markets (Fernández Intriago et al., 2025; Heffron and McCauley, 2018).

Despite these contributions, important gaps remain. Existing research on just transitions and the interactions between sustainability indicators often focuses on aggregate levels or through limited social metrics or sectoral case studies, leaving critical gaps in understanding the structural tensions between emissions trends and multidimensional social progress over time (Liu et al., 2019; Moreno et al., 2024; Nakaishi et al., 2022; Okushima, 2021; Rodríguez-Rosa et al., 2017; Sharmin et al., 2022; Xiao et al., 2024). Most studies have focused on technological innovation, economic incentives, or institutional change, while underexploring the structural tensions between decarbonization and social development (Brisbois and Cantoni, 2025; Köhler et al., 2019; Markard et al., 2012). Given that Sustainable development indicators are interdependent. Progress in one area can support or hinder another, including climate mitigation, making understanding their mutual interactions vital (Xing et al., 2024). While individual studies offer insight into parts of this puzzle, what remains lacking is a comprehensive country-level assessment that captures the interaction and dynamics of development between a broad range of social indicators and emissions trends (Huan et al., 2023), crucial for context-specific sustainability strategies. This study uniquely captures multidimensional alignment and tension patterns by disaggregating 55 SPIs across income groups and countries.

This study addresses the gap by exploring the relationship between CO₂ emissions and 55 SPIs in 160 countries. SPIs include key indicators related to basic needs, wellbeing, and opportunity, ranging from nutrition, sanitation, and education to environmental quality, freedom, and inclusiveness (De Sisto et al., 2024; Htütich et al., 2024). This study also incorporates gross domestic product per capita (GDPPC) and the CO₂ per capita relative to the Social Progress (SP) Index to contextualize the findings and assess how countries' emissions and social outcomes differ. Using Theil–Sen trend estimation with bootstrapping, Spearman correlation, and hierarchical clustering, patterns of alignment or conflict between emissions and social indicators that reflect broader structural dynamics are identified. While causal identification approaches (e.g., natural experiments or instrumental variables) are valuable for isolating specific drivers of change, they are less suited to discovering structural interdependencies across various social indicators and countries. Recent literature underscores that diagnostic, correlation-based mappings can reveal systemic misalignments and transitions that would otherwise remain obscured in narrowly defined causal studies, especially when causal clarity is vague (Schandl et al., 2025; Yang et al., 2024). The inclusion of non-parametric trend estimation enables validation beyond static correlation, adding temporal robustness to the detected emission–SPI correlation, and, unlike scenario-based projections, this approach provides a diagnostic map of real-world misalignments. Specifically, this study answers the following questions: (1) What correlation patterns exist between national decarbonization trends and social progress in each country and income level? and (2) What do these patterns reveal about the equity of global sustainability transitions?

By examining a broad set of SPIs, this study moves beyond the overshoot or shortfall framing (Fanning et al., 2022) to better understand the complexities of emissions reduction and its social implications on income. This study identifies national trajectories that expose structural tensions between emissions reduction and social development and introduces a typology of aligned and conflicted pathways as a new framework for understanding transition dynamics. The findings challenge the assumption that decarbonization inherently supports social wellbeing. This study addresses the evolving discourse on just transitions by offering empirical evidence to guide future research and equity-focused climate policy.

2. Method

This study analyzed the temporal association between total fossil fuel-related CO₂ emissions and 55 SPIs for 160 countries from 2011 to 2023. SPIs are collected from the Social Progress Imperative (Harmacek et al., 2024), offering consistent time series and broad coverage across countries. The inclusion of 55 SPIs aimed to capture multidimensional development beyond traditional economic metrics. The selection of SPIs prioritized indicators with consistent temporal coverage, empirical relevance to social sustainability, and conceptual linkages to CO₂ emissions, and global comparability. Compared to other indices like the Human Development Index used in the Sustainable Development Index, the SPI offers a broader scope in capturing the societal wellbeing of countries, such as access to freedom, food, sanitation, and housing, which are often overlooked (Harmacek et al., 2025). It is closely aligned with the SDGs. Moreover, SPIs include housing, education, energy access, health infrastructure, pollution, and mobility, which have links to fossil fuel-based development, making them theoretically and empirically suitable for investigating trade-offs and synergies with CO₂ emissions. This combination of conceptual breadth, SDG alignment, and empirical accessibility makes the SPI system a suitable framework for evaluating socially inclusive sustainability transitions. While environmental indices like the Environmental Performance Index address ecosystem vitality and climate change, they are not designed to measure the sustainability and multidimensional nature of societal wellbeing as SPI. GDPPC is also included to examine whether it aligns with or contradicts decarbonization efforts in each country, serving as an economic indicator closely linked to development and living standards. Moreover, total annual CO₂ emissions from fossil fuels from different usage sections and industry are considered a sustainable development determinant, as collected by Our World Data ('Global Carbon Project', 2024). It reflects the utilization of countries' energy resources needed for driving economic activities and sustainable development. Further, the CO₂ per capita to SP Index is considered to understand the relationship between countries' emissions and social outcomes (see Supplementary Data 1 for country-level data and income-level statistics). Together, they allow for a multidimensional assessment of how social conditions evolve alongside decarbonization.

The data were normalized to a 0–1 range for each country separately over the years to ensure comparability. The normalized data were used for interaction analysis using Spearman's correlation coefficients between SPI and CO₂ emission for each country. Equal weighting across SPIs was applied to avoid normative bias in interpreting results, which is appropriate for exploratory, correlation-based diagnostics. Hierarchical clustering was subsequently applied to countries to determine similar correlation patterns between emissions and social indicators to compare sustainability efforts across different economic contexts. Finally, the Theil–Sen trend estimation with bootstrapping was employed to detect statistically significant trends in emissions and SPIs. The results were used based on income group classifications to explore how the correlations between CO₂ emissions and social indices change between low-income, middle-income, and high-income nations. This step enables a thorough investigation of whether particular income groups show various trends and correlations. This clarifies whether the degree of economic growth influences the balance between social sustainability

and emission reductions.

2.1. Normalization

In a multi-index evaluation system, the evaluation indices usually have different dimensions and orders of magnitude owing to their various natures. When there is a significant difference in the levels of each index, using the original index values for analysis may emphasize the impact of indices with higher values while diminishing the influence of those with lower values. Therefore, to ensure reliability, the original data needs to be normalized (Wei et al., 2023). Min-max normalization is applied to all data (Eqs. (1) and (2)) to make the indicators comparable later (Huan et al., 2023). It requires first considering the attributes of the indicator changes, including positive (the bigger the data are, the better performance for sustainable development) and negative (the smaller the data are, the better performance for sustainable development) (Supplementary information Table 1) (Harmacek et al., 2025).

$$x = \frac{y_i - y_i^{\min}}{y_i^{\max} - y_i^{\min}} \quad (\text{positive indicator}) \quad (1)$$

$$x = \frac{y_i^{\max} - y_i}{y_i^{\max} - y_i^{\min}} \quad (\text{negative indicator}) \quad (2)$$

y_i is the original data of the evaluation indicator, $y_i^{\max}$ and $y_i^{\min}$ are the maximum and minimum values of the indicator in each country, and x is the normalized data of each indicator that is between 0 (worst performance) and 1 (best performance). A score of 1 reflects the maximum observed performance in the country's time series rather than an absolute achievement of the indicator. This approach preserves within-country temporal variance and avoids compressing temporal variation in large emitters like China and the US, preventing unrealistic uniform results and improving within-country association identification.

2.2. Interactions among CO₂ emissions and SPIs

Spearman's correlation coefficient is used to quantify the association between CO₂ and SPI for every country. It is widely used to determine general symmetric relationships beyond the linear correlation between two variables (Kühnel et al., 2023; Pradhan et al., 2017). Moreover, it can discern non-linear relationships while exhibiting reduced susceptibility to outlier effects, and it does not require the data to be normally distributed (Hauke and Kossowski, 2011). This method supports our focus on statistical association, not causal inference.

To highlight statistically robust relationships, Spearman correlation coefficients (r) with $|r| > 0.6$ and p -value < 0.05 were considered positive or negative associations based on established sustainability correlation studies (Xing et al., 2024). A positive association indicates that improved performance (reduction) in CO₂ corresponds with enhanced performance in SPIs, or conversely, diminished performance (increase) in CO₂ aligns with poorer performance in SPIs (progress in one indicator aligns with progress in the other). Negative correlations imply that improved performance in CO₂ corresponds with poorer performance in SPIs or that deteriorating performance in CO₂ aligns with enhanced performance in SPIs (where progress in one indicator contradicts progress in the other). Correlations with $-0.6 < r < 0.6$ or $p > 0.05$ were treated as weak or non-significant and not classified further, as it has been advised against overinterpreting the Spearman correlation coefficient as an indicator of the degree of association between two variables (Pradhan et al., 2017).

The p -value is tested against the null hypothesis of X being independent of Y to calculate the p -value. To achieve this, a permutation test was applied, in which the values of X were randomly permuted 10,000 times within each country's time series while keeping Y unchanged. The null hypothesis is rejected if the corresponding p -value is lower than or equal to a predetermined significance level of 0.05. When the correlation between X and Y is significant at this threshold, there is an inter-linkage between the two variables (Laumann et al., 2022).

Based on the interaction between indicators, positive, negative, and weak correlation ratios were calculated for each country and income group of countries (Eq. (3)). According to the World Bank Atlas method, income groups are based on gross national income (GNI) per capita in 2022–2023. This fixed-year grouping aligns with standard practices in global comparative analyses (Peng et al., 2023; Sarkodie, 2022; Xiao et al., 2024) and reflects the current development status of countries for greater policy relevance. It is acknowledged that some countries, such as Bangladesh, Cambodia, Laos, Nepal, Haiti, Zimbabwe, and Moldova, shifted between income categories from 2011 to 2023. However, short-term transitions around thresholds generally do not drastically alter a country's structural development characteristics. They are unlikely to bias the correlation patterns assessed in this study significantly. These classifications include High-Income countries (GNI of \$14,005 or more), Upper-Middle Income countries (GNI between \$4516 and \$14,005), Lower-Middle Income countries (GNI between \$1146 and \$4515), and Low-Income countries (GNI of \$1045 or less).

$$Ratio_{type} = \frac{SN_{type}}{TN} \quad (3)$$

where $Ratio_{type}$ is the ratio of the selected indicator pairs out of the total number of all possible combinations; type refers to positive or negative interaction. SN_{type} is the number of positive or negative correlations of indicator pairs, and TN is the total number of indicator pairs.

This ratio-based approach enables scale-independent comparisons across income groups by focusing on the proportion of statistically significant SPI-emissions correlations within each country. These proportions reflect a normalized summary measure of the degree of alignment or conflict between social progress and decarbonization. Income groups aggregate them to reveal systematic patterns. The method avoids distortions from country size, emission volume, or indicator scale differences. It aligns with standard practice in multi-country sustainability assessments (Xing et al., 2024).

Further, agglomerative hierarchical clustering was applied to identify countries with similar correlation patterns between CO₂ emissions and SPIs (Z. Liu et al., 2023). This method provides a structural perspective that extends beyond raw emissions or development levels, revealing sustainability dynamics that may reflect similar institutional or economic contexts. Ward's linkage and Euclidean distance were chosen as clustering metrics. Starting with each nation as an independent cluster, this approach gradually combines the most similar clusters. Euclidean distance is used to gauge the distance between clusters. Ward's minimum variance method determines optimal merges by minimizing increases in the total within-cluster variance, or error sum of squares (Jalal et al., 2024; Ward Jr., 1963). This method keeps monotonicity and efficiently lowers space distortion (Strauss and Von Maltitz, 2017). Using a dendrogram-heatmap, the final cluster structure is visualized, where countries with similar correlation patterns are aggregated, enabling practical interpretation of world social and environmental trends.

2.3. Trend estimation method

Following Spearman's correlation to find an interrelationship between CO₂ emissions from fossil fuels and SPIs, it is assessed whether these relationships are reflected in trends. Thus, Theil-Sen with bootstrapping is used to investigate whether statistically significant growing or declining trends over time exist in both CO₂ emissions and SPI indicators, ensuring that the found correlations are backed by consistent temporal trends rather than static ones (Dong et al., 2024; Vazquez Santiago et al., 2024). Moreover, this allows nations to be categorized into decarbonization pathways. This method is a strong non-parametric regression approach that can be applied to non-normally distributed datasets (Guo and Rasmussen, 2023). Slopes are estimated for all pairs of points (Eq. (4)) as:

$$m_k = \frac{x_j - x_i}{t_j - t_i} \text{ for all } 1 \leq i \leq j \leq n \quad (4)$$

where t represents time (years), x is the indicator value, i and j are indices over time series, and m_k 's are the slopes between each pair of observations. The final Theil-Sen slope estimate ($\hat{m}$) is the median of all computed slopes (Eq. (5)):

$$\hat{m} = \text{median}(m_k) \quad (5)$$

There are several advantages to this method. This method is insensitive to outliers and considers the autocorrelation issue in the data, unlike the Mann-Kendall test. This method provides a more stable alternative to linear regression and ordinary least squares methods. The Theil-Sen method can be significantly more accurate and robust in estimating the parameters through bootstrap resampling, even with nonnormal and heteroskedastic data (Li et al., 2022). A bootstrap resampling technique with 5000 iterations is applied to ensure statistical robustness. Confidence intervals (90 %) were derived from the bootstrapped slopes, and trends were considered significant if zero was outside this interval. A positive or negative trend is assigned based on the slope sign; otherwise, the trend is considered non-significant. The Theil-Sen regression with bootstrapping is used to investigate the association in emissions groups across national conditions from 2011 to 2023.

Overall, correlation-based diagnostics are justified for mapping structural tensions and synergies across nations. This approach is consistent with recent calls for holistic, cross-sector solutions in sustainability research (Schandl et al., 2025) and critiques of narrowly defined causal explanations (Yang et al., 2024). The objective is not to establish causality but to detect systemic patterns and diagnose structural associations where tensions or synergies emerge. Correlation analysis is particularly suitable in this context because it (1) shows how variables move together without assuming linearity, (2) enables cross-country comparability, and (3) provides, in combination with trend estimation and clustering, a mapping of sustainability pathways. In this sense, correlation is used as a diagnostic device to identify systematic patterns in global transitions rather than as evidence of causal mechanisms.

3. Results

The selected indicators capture key aspects of sustainable development, offering a comprehensive view of national quality of life across three dimensions: basic human needs, foundations of wellbeing, and opportunity (Supplementary information Table 1). To ensure reliability, indicators with the most complete and authoritative national-level data were used (Harmáček et al., 2025). Over 95 % of indicators span the whole 13-year period (2011–2023). Country indicators with fewer than seven continuous years were excluded, leading to ~5 % data omission due to reporting gaps. This study excluded approximately 5 % of country-indicator pairs due to missing data or lack of temporal variation (e.g., constant values in some high-income indicators). Although limited, these exclusions reflect a technical constraint of correlation-based analysis. The results, however, are based on valid indicator pairs, as detailed in Supplementary Data 2. Thus, this issue does not affect the robustness of our findings. The study used the total emissions of fossil fuels, which shows whether absolute emission reduction (decarbonization) occurred in each country from 2011 to 2023. While intensity-based measures, such as CO₂ per GDP improvements, are important, the ultimate goal is to achieve absolute reductions in total emissions (Fanning et al., 2022), which is a core principle of global climate targets (e.g., IPCC goals).

3.1. Overall correlation between SPIs and decarbonization

Among the 8389 indicator pairs analyzed, 2590 have negative correlations between SPIs and decarbonization progress, exceeding the 1457 pairs with positive correlations (Supplementary Data 2,

Table 1

Distribution of positive, negative, and weak correlations between SPIs and decarbonization across income groups.

Income group	Number of countries	Positive ($r > 0.6$ & $0.05 > p$ -value), in percentage	Negative ($-0.6 > r$ & $0.05 > p$ -value), in percentage	Weak ($0.6 > r > -0.6$ & $0.05 > p$ -value), in percentage
High-Income	51	29	17	54
Upper-Middle-Income	44	11	28	61
Lower-Middle-Income	41	12	46	42
Low-Income	24	15	38	47

spreadsheet “Correlation-pairs”). Table 1 presents the ratio, which is the proportion of positive, negative, and weak correlations to the total possible associations in each income group. High-income countries exhibit the highest share of positive correlations, 29 %, indicating greater alignment between social progress and decarbonization. In contrast, while considerable variation exists within each group, low-income and lower-middle-income countries show the highest ratio of negative correlation ($-0.6 > r$ and $0.05 > p$ -value), 38 % and 46 %, respectively, indicating that efforts to decarbonize in these two groups of countries are more likely to conflict with social progress goals. This may reflect structural challenges in balancing emission reduction with economic development, poverty alleviation, and climate goals, where fossil fuels might drive growth. While broadly consistent with the Environmental Kuznets Curve hypothesis, this trend is refined by our indicator-level disaggregation. Weak correlations ($|r| < 0.6$ and p -value > 0.05) are higher in high-income (54 %) and upper-middle-income (61 %) countries, suggesting that more complex relations and the effects of other policies and factors behind emissions have an impact on social indicators or may indicate policy mediation, saturation effects, or decoupling phenomena, where emissions trends do not strongly impact SPI performance.

3.2. Patterns by countries in the income group and SPI category

Agglomerative hierarchical clustering (Fig. 1) identified SPIs that are frequently involved in significant correlations (positively or negatively) with CO₂ emissions in more than 60 % of countries. These indicators are concentrated in the domains of basic human needs and wellbeing, including household air pollution, women with advanced education, recycling, basic sanitation service, population with no schooling, child stunting, internet users, early marriage, unsafe water, sanitation and hygiene, citable documents, child mortality, lead exposure, and access to essential health services.

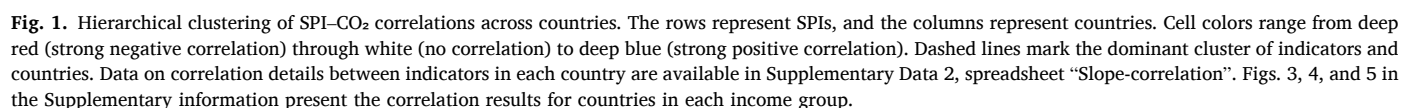
To interpret these associations, Theil–Sen was applied to classify each country’s decarbonization trend as positive (+), negative (−), or statistically non-significant (*). The results indicate that a strong correlation does not necessarily correspond to significant trends. However, the trend shows that when the correlation is positive, the median slopes of indicators have the same directional trend. Conversely, when correlations are negative, SPI indicators and decarbonization trends have opposite trends (Supplementary Data 2, spreadsheet “Slope-correlation”). Given that, in the meta-cluster dominated by negative correlation, countries with negative decarbonization trends show improvements in social indicators alongside rising emissions. Moreover, these SPI improvements coincide with emission reductions in the cluster that includes the EU and other early-transition countries. Developing SPIs and GDPPC aligned with decarbonization in these countries potentially reflects the role of structural mechanisms such as renewable energy investments and carbon pricing policies (e.g., the EU Emissions Trading System). Despite significant emission reductions, nations like Sweden have sustained economic, life expectancy, and social welfare progress. This demonstrates that emissions alone do not predict social outcomes, as technological advancements and policy interventions are

crucial (Bianco et al., 2024). Meanwhile, countries like Venezuela, Angola, and Yemen have higher negative correlations with SPIs alongside deteriorating GDPPC, suggesting that emission reductions in these cases may reflect economic or political crises rather than intentional climate policies.

Some indicators show a mix of different correlation patterns across countries with different income levels (Fig. 1 and Supplementary information Fig. 1), particularly indicators in rights and voice, freedom and choice, and education components. Despite improved life expectancy and nutrition, many countries experience declining institutional quality (e.g., corruption, rule of law), equality, democratic quality, freedom, and life satisfaction, even in well-developed democracies. These trends underscore the need for context-specific strategies that ensure emissions reductions do not come at the cost of social progress.

The alignment between SPIs and decarbonization is most frequent in high-income countries. The highest rates of positive correlation between SPIs and decarbonization improvement are seen in pollution (61 %) and species protection (51 %) for high-income countries; political rights, legal equality, and education (each 23 %) for upper-middle-income; press freedom (46 %), air pollution (44 %), and intimate partner violence (34 %) for lower-middle-income; and air pollution (46 %), young people not in education, employment or training (42 %), and particulate matter (42 %) for low-income countries. The persistence of air quality alignment in lower-income countries means that these countries, which mostly had historically worse emissions performance, had worse environmental quality indicators (based on the Theil–Sen trend). Air pollution remains high in lower-middle-income countries due to limited environmental regulations (Stern, 2017), while in many low-income nations, lower fossil fuel use keeps pollution levels modest. However, this is changing in parts of South Asia and Africa (Sanyal and Wuebbles, 2022). Many higher income levels led to improvement in environmental quality indicators, regardless of worsening emissions. Improvements in income allow for investments in cleaner technologies or adaptive measures that counteract pollution’s impact.

The percentage of countries with strong correlations ($r > 0.6$ or $r < -0.6$, $p < 0.05$) in various SPI component categories reveals that housing, nutrition, and water/sanitation dominate in lower-income nations, e.g., 70 % of lower-middle-income countries show a strong SPI-emission association in housing. These shares are lower in high-income and upper-middle-income countries. Environmental quality indicators consistently correlate across all income levels (49 %–66 %). In contrast, rights and voice, and inclusive society components show fewer strong correlations, especially in wealthier countries, suggesting these aspects are more directly influenced by governance structures than by emissions. Decarbonization policies that do not integrate institutional reforms could create unequal societal impacts, disproportionately affecting marginalized communities. These patterns emphasize that, in lower-income nations, emissions remain more closely tied to the development of basic infrastructure and essential services, whereas in wealthier countries, the association is less, reflecting more regulated practices and decoupling (complete category breakdown is in Supplementary information Table 2).



3.3. High-income countries: conflicts within progress

To explore the results further, this study focuses on high-income countries, where emissions trajectories and social progress exhibit distinct patterns. Clustering countries revealed that most countries with similar emissions are grouped in the same cluster. Therefore, countries were classified according to emission trend, using Theil-Sen bootstrapping analysis, which identified positive (+), negative (−), or statistically non-significant (*) trend in emissions performance or decarbonization (Fig. 2) (see Supplementary Data 3 for more details on the different income and trend classification).

Among countries with a statistically significant reduction in emissions (i.e., a positive trend of decarbonization or better performance), 21 % to 63 % of SPI show negative correlations. These include equal access to quality healthcare, intimate partner violence, freedom of peaceful assembly, equality before the law, and individual liberty index, basic sanitation service, world press freedom index, equal access to quality education, academic freedom, political rights, equal protection index, dissatisfaction with housing affordability, primary school enrollment, and satisfaction with availability of quality healthcare. These negative correlations do not imply causality but highlight structural

contradictions, where improved emissions performance (emissions reduction) does not necessarily coincide with improvements in well-being. These tensions highlight the need to understand better underexplored socio-political vulnerabilities in implementing climate policies.

Specific cases, such as those of the UK, Luxembourg, France, Germany, Switzerland, Belgium, and Spain, demonstrate that improvement in emissions performance (i.e., statistically significant emissions reduction and a positive trend) is negatively correlated with quality-of-life indicators, including freedom of choice, dissatisfaction with housing affordability, and healthcare satisfaction. Moreover, 21 % of countries have a negative correlation ($-0.6 > r$ and $0.05 > p$ -value) between emissions performance improvement and vulnerable employment (UK, Netherlands, France, Israel, and Trinidad and Tobago). However, 46.4 % of countries in this cluster experienced simultaneous improvements in emissions performance and vulnerable employment, illustrating variation in outcomes depending on institutional and policy contexts.

The variation within income groups, especially among high-income countries, is particularly notable. These divergences reflect complex interactions between factors and potential mechanisms, such as differences in climate governance, investment in social sectors, and policy instruments such as carbon pricing, social compensation, and the timing of policy implementation. In some cases, tensions may stem from

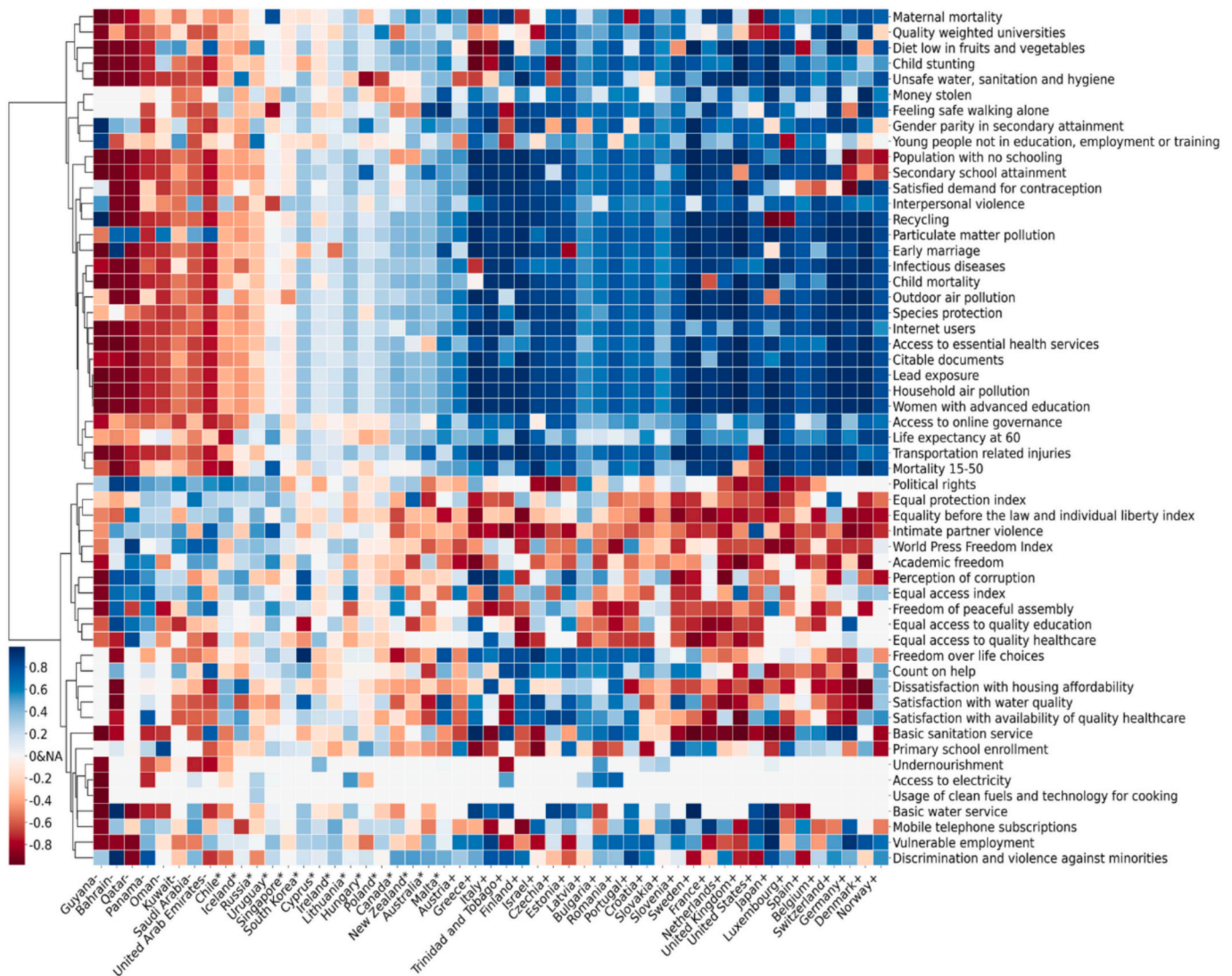


Fig. 2. Clustering different types of correlations (Positive, negative, and weak) for various indicators within high-income countries. The rows represent countries, and the columns represent SPIs.

austerity-era spending cuts or regressive energy costs during the low-carbon transition (Bouzarovski and Simcock, 2017; Markkanen and Anger-Kraavi, 2019; Sovacool and Dworkin, 2015). This contextualization is further examined in the Discussion.

Spearman correlations identify statistical associations, while Theil–Sen estimates clarify the trend’s direction and magnitude, such as the steep decline in Sweden’s Equal access to quality healthcare (slope = −9.6), Satisfaction with healthcare (slope = −6.4) and Access to essential health services (slope = 8.8) while falling CO₂ emissions (Supplementary Data 2, spreadsheet “Slope-correlation”). These examples highlight how social outcomes can diverge even under similar emissions pathways, depending on how transition policies are financed and governed, especially when parallel policy choices shape outcomes differently.

In countries with increasing emissions trends, including several fossil fuel exporters, higher emissions are often linked to better performance in SPIs, such as reduced vulnerable employment in 37.5 % of cases. This likely reflects the role of fossil fuel revenues in funding social programs and infrastructure, even as emissions increase. However, half of these oil-exporting nations (e.g., Qatar, Bahrain, and Oman) exhibited a strong statistical association between rising emissions and increased particulate matter pollution.

Undernourishment, usage of clean fuel and technology for cooking, and access to electricity are not associated with emissions change in most of the high-income countries due to the saturated effect, except in Romania, Latin America (Panama, Chile, Guyana, Trinidad and Tobago), Russia, Saudi Arabia, and the United Arab Emirates.

Finally, in countries with non-significant emissions trends ($p > 0.05$), including Canada, Australia, Hungary, South Korea, and Iceland, 93.2 % of SPI-emission relationships are weak. For example, Canada’s emissions reduction remained stable and non-significant, supported by hydro-power and nuclear energy, and reinforced by strong climate policies (ECCC, 2022), resulting in weak correlations despite changes in social factors (Supplementary Data 2). In such cases, social progress appears largely decoupled from emissions trajectories, reinforcing that correlation does not imply causation and that many social indicators evolve independently of emissions trends.

3.4. Association in the group of emission trends across income

Around 27 % of 160 countries show a statistically non-significant emission trend, indicating diverse circumstances; some may maintain

stable emissions while pursuing other priorities. Some others are transitioning toward either growth or reduction of CO₂ emissions with broader socio-economic goals. In these countries, the correlation between emissions and SPI is weak in more than 92 % of cases. In this section, the study emphasizes the 25 % of countries experiencing a decrease in emissions and 48 % of countries where emissions increase, as these subsets provide clearer insights into the interplay. Supplementary Data 2 provides further information on the median slope and trend of SPI and emissions. Table 2 compares emission trend groups across income levels, highlighting strongly associated SPIs and their alignment direction with emissions performance over time.

In countries where emissions were increasing (worse) by year, a negative correlation indicates that social progress and rising emissions have historically been linked, meaning that better SPI performance has often coincided with worsening decarbonization performance. In comparison, a positive correlation means worse performance for SPIs was aligned with increased emissions. The results of these countries with different incomes showed that 61 % of SPIs performed better in lower-middle-income countries. This number in high-income, upper-middle-income, and low-income countries is 46 %, 53 %, and 45 % which shows fewer indicators that improve with rising emissions than lower-middle-income countries. This reflects that in lower-middle-income countries, active industries create more social improvement, leaving limited flexibility to balance emissions growth and social progress, considering 29 countries that had higher emissions over time, while social indicators, such as housing, nutrition and medical care, information and communications, education, environmental quality, and water and sanitation, improved. Moreover, 15 % of SPIs in low-income nations in this group worsened alongside higher emissions, compared to 12 %, 10 %, and 9 % in lower-middle, upper-middle, and high-income countries, respectively. This suggests that low-income countries, alongside more emitting and being industrialized, face structural challenges that impact social indicators, making it difficult to separate the effects of emissions from other economic factors.

In countries where emissions decreased, 49 % of SPIs improved in high-income countries, which is higher than in other income groups. However, 23 % and 20 % of SPI indicators got worse in low-income and lower-middle-income countries, compared to just 9 % in upper-middle and 16 % in high-income countries. This relatively higher percentage of SPIs with a negative trend by year could suggest that broader socio-economic challenges, such as economic contraction, resource scarcity, and political instability, are likely the reason for these emission

Table 2
Ratio of positive and negative correlation and trend of indicators in each income and all countries.

Income group	Decarbonization trend	Theil-Sen median slope (progress in decarbonization/year)	Number of countries	% indicators positively correlated with decarbonization	% indicators negatively correlated with decarbonization	% indicators weakly correlated with decarbonization
High income	Positive (emission decrease)	3.6–9.3	28	49	16	35
	Negative (emission increase)	−4.1 to −9.7	8	9	46	45
	Non-significant	-	15	4	3	93
Low income	Positive (emission decrease)	2.7–5.6	2	35	23	42
	Negative (emission increase)	−9.8 to −3.4	19	15	45	40
	Non-significant	-	3	0.6	1.9	97
Lower middle income	Positive (emission decrease)	4.9–8.6	3	35	20	45
	Negative (emission increase)	−10.1 to −5.2	29	12	61	27
	Non-significant	-	9	3	5	92
Upper middle income	Positive (emission decrease)	4.9–9.5	6	38	10	52
	Negative (emission increase)	−8.6 to −4.8	21	10	53	37
	Non-significant	-	17	3	3	94

reductions rather than their planned or strategic management.

Additionally, SPI performances can be compared under different emissions trends across income groups. For example, in high-income countries, 49 % of indicators had better performance (positive correlation) with better CO₂ emissions performance, compared with 46 % in countries with worse emissions performance. This indicates that high-income countries with decreasing emission trends had slightly more improvement in their SPIs, reflecting their institutional capacity and policy, which enabled simultaneous decarbonization and social progress. However, in high-income countries with an emissions decreasing trend (better performance), 16 % of SPIs had worse performance, while in high-income countries with an emissions increasing trend (worse performance), 9 %. It shows fewer SPIs with worse performance in high-income countries where their CO₂ emissions are increasing. Moreover, in high-income countries with decarbonization improvement, 49 % of SPIs show better performance (i.e., positive correlation with emissions). Meanwhile, in upper-middle-income countries with a rising emission trend, 53 % of SPIs show better performance. These suggest that while high-income countries with decreasing emissions tend to see improvements in social progress, upper-middle-income countries with rising emissions still experience a slightly higher share of SPI improvements.

3.5. Spatial distribution of SPI-emission relationships

Fig. 3a illustrates that European countries, known for robust institutional frameworks and strong climate policies, have the highest percentages of SPIs positively correlated with decarbonization. Notably, Romania (63 %) and Switzerland (60 %) display high shares of positive SPI-emission correlations and low negative correlations (<15 %), indicating effective and socially inclusive sustainability progress. In countries like the United States, Japan, and Germany, over 50 % of SPIs align positively with decarbonization, showing that climate action and social progress coexist despite high historical emissions. However, in wealthy countries with ecological overshoot (in countries exceeding 1.9 t CO₂ per capita (Chancel, 2022)), resource use must be dramatically reduced to get within fair shares of biophysical boundaries, highlighting the importance of recognizing country-level differences in sustainable consumption and transition capacity (Ivanova and Middlemiss, 2021). In Uganda and Turkey, while 24–30 % of SPIs deteriorate with emissions increases, nearly half still improve, highlighting the dual effects of carbon-intensive growth on social progress. While some social progress benefits from carbon-intensive growth, others suffer. Green growth strategies may help sustain SPI improvements while reducing environmental risks.

Fig. 3b highlights that SPI challenges during decarbonization are most prevalent in developing regions such as Central and North Africa, South and Southeast Asia, and the Middle East. In these regions, structural economic dependencies on fossil fuels or limited resources to invest in sustainable transitions likely drive the observed tensions. All countries with over 30 % negative correlations experienced an increase in emissions over the years (except Venezuela), indicating challenges in balancing decarbonization with social progress. Among countries with over 50 % negative correlation and high average CO₂ emissions per capita relative to the SP index (Fig. 3b) are China, Malaysia, Qatar, Bahrain, the UAE, and Iran. These significant emitters of the world require carefully designed decarbonization strategies to ensure that social indicators are not compromised. Nations such as Saudi Arabia, Oman, Kuwait, and Mongolia have under 50 % ratios of negative correlation with decarbonization despite high average CO₂ emissions per capita to the SP index. This pattern may reflect fossil-funded welfare continuity. However, the resilience of these systems should be tested under conditions of deep decarbonization. Many low and lower-middle-income countries, such as Tanzania, Gambia, Kenya, Bangladesh, Myanmar, Pakistan, and Nepal, show negative correlation ratios exceeding 67 %. These nations tend to see more significant SPI improvements alongside rising fossil fuel-based energy use. However,

achieving higher SPI needed higher annual emissions per capita, indicating their reliance on fossil-based development pathways for social improvements. To avoid replicating high-emission pathways, these nations require support for low-carbon development models that still deliver SPI gains. Interestingly, the United Kingdom (29 %), United States (29 %), Netherlands (26 %), and Luxembourg (25 %) show negative SPI correlations despite overall emission reductions, reflecting that even in wealthy nations, some aspects of social wellbeing may decline during decarbonization. Furthermore, Kazakhstan, Australia, Canada, Turkmenistan, Russia, Libya, and South Korea are some of the countries that maintained high emissions with non-significant trends (p -value > 0.05) while having social improvement (Fig. 3). However, they are among the biggest emitters in the world. They face increasing pressure to align welfare gains with meaningful decarbonization.

3.6. Comparison of production- vs. consumption-based CO₂ emissions

A comparison of consumption- and production-based CO₂ emissions reveals that across 120 countries with available consumption-based emissions data (Supplementary Data 2, spreadsheet “Consumption-based”), in 17 countries, the direction of emissions trends diverges between the two accounting methods. Among these, only six countries exhibit a statistically significant change. Examples include Kyrgyzstan, Latvia, Jamaica, and Malta, which show increasing consumption-based emissions. In contrast, their production-based emissions remain statistically insignificant. By contrast, Benin and Botswana exhibit declining consumption-based emissions despite increases in production-based emissions.

Consumption-based emissions reveal additional dynamics when considering the correlation between emissions and SPIs. In high-income countries, numerous indicators shift from weak to strong correlation, or vice versa, when switching from production- to consumption-based accounting. In countries such as Australia, Latvia, Canada, Slovakia, Malta, and Austria, over 21 indicators shift from weak to strong correlation. In several of these cases, such as Latvia, Canada, Australia, and Malta, consumption-based emissions also follow a statistically robust trend, reinforcing the robustness of these correlations.

Conversely, a decline in correlation strength (from strong to weak) occurs across 30 or more indicators in countries such as Romania, Slovenia, Israel, United Arab Emirates, Trinidad and Tobago, Croatia, Switzerland, Czechia, Portugal, Bulgaria, and Norway. All these countries experienced reduced production-based emissions between 2011 and 2023, except the United Arab Emirates, which saw an increase. However, in most cases, consumption-based emissions trends are not statistically significant, potentially explaining the weaker correlations.

In some countries, the direction of strong correlations also flips. In Malta, for instance, SPI indicators such as child stunting, maternal mortality, money stolen, feeling safe walking alone, access to online governance, satisfaction with healthcare, access to essential health services, equality before the law, and early marriage shift to negative correlations with consumption-based CO₂ emissions, suggesting that increased consumption emissions coincide with improvements in these indicators. In Trinidad and Tobago, both production- and consumption-based emissions correlate with worsening gender parity in secondary education, while in Slovenia, both forms of emissions correlate with improvements in vulnerable employment.

Country-level clustering changes substantially when shifting to consumption-based emissions, while SPI indicator clustering remains relatively stable. These findings underscore the importance of incorporating consumption-based accounting, particularly in high-income countries, to better capture social and environmental implications of emissions and to address concerns related to the Netherlands fallacy and unequal exchange (Steininger et al., 2014; Givens et al., 2019).

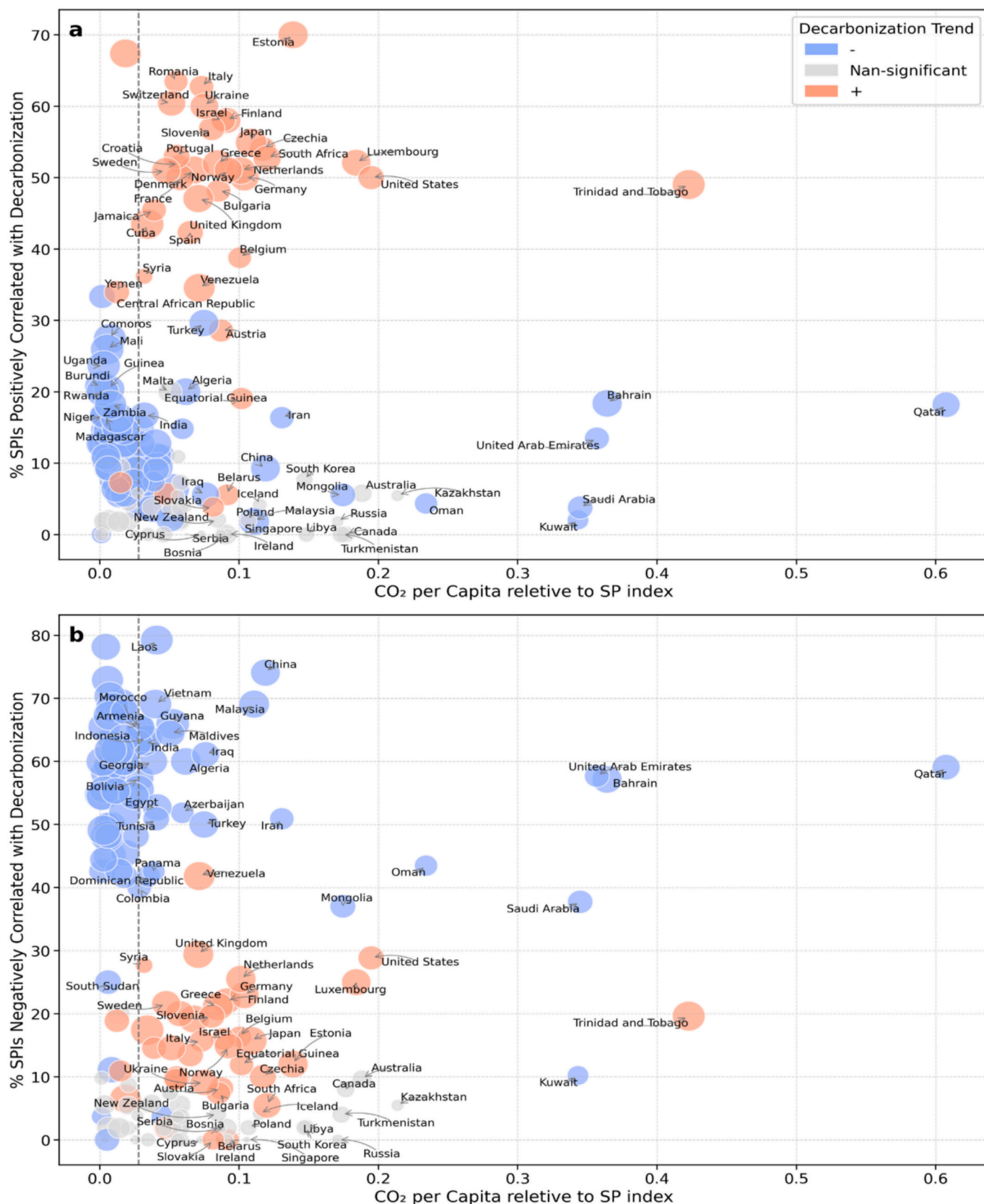


Fig. 3. Proportion of SPI-emission correlation and CO₂ per capita relative to SP index by countries. (a) Proportion of positive correlation (%) among 55 SPIs in each country, and (b) Proportion of negative correlation (%). Larger bubble sizes show a larger trend in emission increase or decrease. The vertical line at $x = 0.028$ represents the ratio of 1.9 tCO₂ per capita (a benchmark for sustainable emissions) to an SP index of 65 (a moderate level of social development) (Htitch et al., 2024). Countries to the left of this line have low emissions but also low social progress scores, typically low- or lower-middle-income countries whose emissions are often increasing in parallel with rising SPI levels.

4. Discussion

Previous studies (Huan et al., 2023; Wei et al., 2023; Xing et al., 2024) have shown that trade-offs often outweigh synergies in climate-related indicators. This study deepens those insights by mapping how decarbonization interacts with various SPIs across income groups and countries. Although emissions fell in over half of high-income countries, driven by strong policies and innovation, these reductions were often matched by education, healthcare, and environmental quality gains. However, emissions reductions were not consistently accompanied by improvements in equity and political rights indicators such as housing affordability, freedom of choice, and vulnerable employment. These conflicts can stem from a range of social problems, for instance, inclusiveness, where communities are excluded from planning due to missing participation mechanisms, while inclusive decision-making processes that engage affected communities and strengthen accountability can reduce perceptions of unfairness and increase public support; voice and rights, where affected people report having little or no say in decision-making and grievance systems remain ineffective; education, where insufficient training limits communities' ability to adapt and; employment, where low-carbon projects replace traditional jobs without adequate alternatives (Siciliano et al., 2021). Politically, stringent and rapid transitions can amplify perceptions of corruption and unfairness, fueling social backlash, weakening cohesion, and eroding democratic quality, and straining public services (Fraser et al., 2023; Ivanova and Middlemiss, 2021; Sasse and Trutnevyte, 2023). This reflects a just transition that warns that, in the absence of justice-oriented policy design, decarbonization may coincide with increased social vulnerabilities (Kent, 2018), e.g., the Yellow Vest movement in France against the rising fuel taxes (Martiskainen et al., 2021). Tools such as Renewable Portfolio Standards, Auctions, retraining funds for workers displaced by low-carbon transitions, energy rebates for low-income households, and progressive carbon pricing schemes that recycle revenue into social programs have been identified to sustain social stability (Fragkos et al., 2021). However, their distribution and design heavily affect the social impact of decarbonization. Even well-intentioned mechanisms like Feed-in Tariffs can disproportionately burden vulnerable groups through higher energy costs and unequal access to subsidies, which may also explain the negative SPI-emissions associations observed in many high-income countries (Bianco et al., 2024; Fraser et al., 2023). Without redistributive measures and targeted welfare, climate policies risk undermining public support and deepening inequality (Okushima, 2021).

In upper-middle countries, fossil fuel-based development remains the dominant pathway. State-subsidized industrial sectors often resist decarbonization, requiring carbon taxation and subsidy reforms supported by transparent governance to manage resistance (Black et al., 2023). Lower-middle-income countries show SPI gains (e.g., housing, nutrition and medical care, information and communications, and water and sanitation) alongside rising emissions in 71 % of countries, underscoring the urgent need for international support to adopt cleaner growth pathways (Ameli et al., 2021). Although middle-income countries expanded renewables, growth was typically below 10 % (Nakaishi et al., 2022). High capital costs and limited affordable finance restricted a faster transition from fossil energy (Ameli et al., 2021). Continued fossil dependency risks future plateau and lock-in effects, as observed in many wealthier nations (Foster et al., 2024). These countries need to apply different policies and measures, as many high-income countries are adopting comprehensively implemented and planned climate policies, such as supporting renewable energy deployment, energy efficiency, sustainable transport, and emissions reductions in industry and waste, such as feed-in tariffs, biofuel adoption, eco-design and energy labeling, energy audits, and green building certifications.

Many low-income countries have raised emissions to expand energy access and development, but often at the cost of environmental indicators. However, unlike wealthier countries with entrenched fossil

systems, their less entrenched infrastructure offers a unique opportunity to leapfrog to low-carbon systems. Cost-competitive solutions such as off-grid solar offer scalable, inclusive energy access without the environmental and social costs of fossil fuels (Chapman et al., 2018; REN21, 2021; Sasse and Trutnevyte, 2023). However, these transitions depend on critical materials like cobalt and tellurium, where supply constraints may hinder affordability and equity (Bandpey et al., 2024).

Across all countries, patterns show that adopting a low-carbon transition does not consistently align with social improvements. Many indicators, especially those tied to rights, freedom, equity, and employment, often show weak or negative association with emissions reductions. This suggests that decarbonization policies have limited influence in domains shaped more directly by governance and institutional inequality. Given that there is a broad scope to improve them by transforming provisioning systems into a fairer distribution of income and universalizing access. However, these reforms often face resistance from entrenched interests and industries that benefit from the current fossil-based status quo (Fanning et al., 2022). Moreover, a substantial share of associations, particularly in high- and upper-middle-income countries, are classified as weak. Prior studies warn against over-interpreting weak Spearman correlations (Pradhan et al., 2017), yet their prevalence points to several important dynamics. First, policy mediation may buffer SPIs from direct dependence on fossil fuel emissions, as in welfare provision, environmental regulation, or renewable energy support (as seen in Canada). Second, saturation effects in higher-income nations reduce variability in some SPIs such as education, limiting opportunities for strong correlations with emissions. Third, decoupling phenomena are evident where emissions decline. At the same time, social progress continues independently, consistent with broader evidence that development and environmental trajectories can separate. Finally, weak associations may also reflect temporal lags and confounding factors, since the effects of decarbonization on equity, governance, or institutional indicators may progress over longer time-scales. These weak correlations highlight complex interactions and multivariate dependencies, such as policy, institutions, or long-term processes beyond immediate emissions trajectories, that can shape sustainability. These suggest the need for further research using techniques to understand dynamic interdependencies.

Between 2011 and 2023, SPI gains in many nations, especially fossil fuel exporters, were funded by emissions-intensive revenues, often at the cost of long-term sustainability. Such gains reflect the economic reliance on resource extraction or the short-term benefits, such as previously limited access to energy and job creation. Without structural diversification and low-carbon alternatives, their SPI improvements continue without emission reduction. Ironically, negative SPI-emission correlations in countries like the US, the UK, and the Netherlands could incentivize a return to carbon-intensive models if low-carbon strategies are perceived as socially regressive. Even in sustainability leaders like Sweden, strong SPI-emission correlations persist, highlighting the difficulty of fully decoupling social outcomes from carbon emissions. However, environmental quality indicators such as air pollution and particulate matter remain highly sensitive to emissions, offering high-leverage policy entry points with visible co-benefits.

Policy design must reflect this complexity. Rather than a single policy approach, strategies tailored to national contexts appear most effective due to countries' variability in social outcomes. The initial level of social progress and income in nations is crucial for future improvement; in some nations, addressing internal issues, such as the level of development, may take priority over the low-carbon energy transition. Therefore, there is a need to reconsider the previous rationality that stipulates the possibility of promoting SPI through carbon-intensive growth. High-income nations should refine policies to prevent economic marginalization while scaling low-carbon energy and addressing emerging inequalities. Middle- and low-income economies should prioritize clean energy expansion without prematurely restricting fossil fuels, ensuring equitable access to energy services and sustainable

growth. International frameworks like the Paris Agreement must reflect differentiated responsibilities, not only in emissions but in social development capacity.

These insights position climate action as a societal transformation, not merely an environmental or technological shift. Our empirical assessment of SPI-emissions within the Just Transition framework exposes that such shifts do not inherently deliver equitable outcomes, and conflicts persist alongside declining emissions. Environmental improvements should be coupled with social protection to avoid unintended consequences, especially for vulnerable communities. Without such integration, transitions risk entrenching inequality rather than alleviating it.

While some of the outcomes of this study align with the Environmental Kuznets Curve hypothesis, this study extends its utility by disaggregating across 55 SPIs and analyzing temporal and structural dynamics. Furthermore, trade-offs between decarbonization and SPI outcomes in many countries reveal tensions that GDP-based models cannot capture alone. These findings highlight a structural contradiction that impedes just and inclusive sustainability transitions, particularly where environmental gains coincide with social stagnation. The results support a shift from passive monitoring to proactive governance diagnostics.

Instead of simply tracking outcome-level performance, this method enables early detection of structural misalignments between environmental and social progress. It offers a flexible approach that is applicable even in data-scarce settings and may inform SDG planning, climate finance eligibility, or mining legislation reviews. The approach complements existing sustainability indices by mapping directional tensions and trend alignments. It creates space for more context-specific, justice-aware policy design.

Moreover, the limitation of the network established in this study is that it does not prove causality and directionality as an undirected weighted network, while it identifies trends and associations. Granger causality was tested on a representative indicator pair to check whether it can be used in this study to derive the direction of the association (Supplementary information Table 3). This exploratory step found limited inference due to limitations in short time series. Causal analyses require additional data, longer timeframes, and the control of external variables and methodological improvements to move from correlation to causality (Xing et al., 2024).

5. Conclusion

This study analyzed the relationship between CO₂ emissions and Social Progress in 160 countries from 2011 to 2023, revealing significant variations in SPI-emission correlations across nations with different income groups. High-income countries have advanced in decarbonization largely without economic setbacks, yet contradictions remain in housing affordability, employment stability, and political rights, indicating that climate gains do not automatically translate into equitable social outcomes. In contrast, more nations with lower-middle and low-income countries exhibit negative correlations between decarbonization and essential social indicators, such as housing, nutrition, and education, reflecting dependence on carbon-intensive infrastructure for development. Climate goals must be considered alongside broader development priorities. Middle-income countries face the risk of long-term fossil fuel lock-in, as social improvements are still occurring in parallel with rising emissions.

Environmental quality indicators (e.g., air pollution) are consistently linked to emissions across all income levels and offer promising entry points with visible co-benefits. Clustering and trend analyses further indicate that emissions reductions alone do not guarantee social progress. Even in high-income nations, social contradictions persist, underscoring the need for just transition strategies that embed equity at the core of climate action. This highlights the importance of inclusive governance, redistribution, and targeted investment.

Although sustainability is achievable, the transition remains highly unequal. High-income countries can implement clean energy policies and technological innovations. However, middle and low-income nations require significant financial and technological support to avoid emissions-heavy development pathways. Development trajectories, political institutions, and historical responsibilities shape outcomes, underscoring the inadequacy of a one-size-fits-all approach.

Analyzing 55 SPIs, this study finds that the idea that wealthier countries decouple emissions from social progress does not hold uniformly. The results vary across indicators and countries, showing that aggregate metrics are insufficient to explain transitions. Correlation and trend analysis allow earlier detection of policy misalignment and distributional tension. Our findings underscore the importance of distinguishing production-based and consumption-based emissions in future analyses. Excluding the latter remains a limitation in capturing the full global environmental burden, particularly in trade-intensive, high-income economies.

Based on these insights, we propose using Structural Trade-off Diagnostics (STD) as a complementary tool to SDG dashboards, ESG indices, and correlation matrices. Unlike conventional instruments, STD explicitly reveals uneven and directional patterns between environmental and social indicators. This enables policymakers to identify “passive responders” and “structural drivers” of harm, guiding more targeted interventions. Applying the STD in SDG planning, climate finance eligibility, and sustainable investment protocols can provide an operational pathway to advance just and balanced transitions.

This study establishes a global, empirical baseline that identifies real-world patterns of alignment and contradiction between emissions and social development. These findings provide directions for transition planning and highlight the need for interdisciplinary solutions integrating environmental modeling, social policy, and governance studies. Equity and justice must be embedded at every stage of the transition process to ensure that sustainability is not merely a cleaner version of inequality. Future research could use causal methods to identify the drivers behind the observed patterns and confirm underlying mechanisms, while our correlation- and trend-based analysis detects systemic alignments and conflicts across multiple countries and indicators. Moreover, there is a need to pursue sector-specific studies and complementary metrics, such as carbon damage as a share of national income, to track whether sustainability transitions are truly equitable.

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CRedit authorship contribution statement

Atieh Fahimi Bandpey: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Saeed Rahimpour:** Writing – review & editing, Supervision, Visualization, Investigation, Formal analysis, Conceptualization. **Marcelo Fuentes:** Writing – review & editing, Visualization, Formal analysis. **Andrzej Kraslawski:** Writing – review & editing, Investigation, Formal analysis, Validation, Supervision, Conceptualization, Ideation.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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