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Optimizing Green GDP Accounting: An Entropy-Based Model and G20 Evidence

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Abstract: Green GDP accounting has re-emerged as a practical instrument for aligning economic evaluation with environmental sustainability, yet cross-country measures often suffer from indicator arbitrariness and insufficient empirical validation. This study develops an entropy-based Green GDP accounting framework and applies it to the G20 over 2016–2020, using country-level economic and environment-related indicators retrieved from the Trading Economics database. First, an entropy-weighting scheme is implemented to generate a transparent composite Green GDP metric that integrates economic output with ecological constraints in a comparable manner across countries. Second, the robustness of the accounting results is assessed through three complementary validation strategies. Grey relational analysis (GRA) is used to examine consistency between the proposed Green GDP outcomes and benchmark sustainability-relevant indicators, yielding a high relational degree (0.850). Kendall's coefficient of concordance further confirms strong agreement in country rankings ($W = 0.925$), indicating stable ordering and reduced sensitivity to single-indicator perturbations. Finally, partial least squares regression (PLSR) is employed as a predictive validation tool to evaluate how key environmental and development factors are associated with Green GDP performance, achieving satisfactory explanatory capacity ($R^2 = 0.666$) and identifying influential drivers with VIP > 1. Overall, the findings suggest that entropy-based Green GDP accounting provides a replicable and empirically validated alternative to conventional GDP-centric evaluation, supporting evidence-based policy design for sustainable growth. This research contributes to monitoring and policy implementation of SDG 8, SDG 12, and SDG 13.

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1.Introduction

In recent decades, rapid economic expansion has frequently been accompanied by escalating environmental pressures, including resource depletion, climate related risks, and ecosystem degradation. These tensions have intensified international calls, consistent with the United Nations 2030 Agenda for Sustainable Development, for performance metrics that go beyond conventional GDP by incorporating environmental externalities and ecological constraints[1]. Against this backdrop, Green Gross Domestic Product, or Green GDP, has been proposed as a corrective accounting concept that adjusts economic output to better reflect the environmental costs and benefits associated with development.

Despite its conceptual appeal, Green GDP accounting remains far from standardized and is rarely institutionalized in national accounting practice. Prior approaches differ substantially in indicator selection, weighting rules, and data availability, resulting in limited comparability across countries and low reproducibility across studies[2]. A persistent methodological bottleneck is the reliance on expert judgment or ad hoc weighting schemes, which can embed subjectivity and undermine the credibility of composite results[3]. In particular, many composite Green GDP measures lack an explicit data driven weighting logic that remains stable under cross country heterogeneity, which weakens interpretability and limits policy uptake.

To address these limitations, this paper proposes a refined and replicable Green GDP accounting framework grounded in an objective weighting strategy. We construct a multi dimensional indicator system covering three pillars, resource utilization, environmental governance costs, and ecological benefits. To minimize subjectivity in aggregation, the entropy weight method is employed to generate data driven indicator weights and to produce a transparent Green GDP index. This approach is appropriate for Green GDP accounting because it assigns weights based on the information content and dispersion of each indicator across observations, reducing dependence on subjective judgment. This feature is particularly valuable for cross national applications where indicators vary widely in scale, variability, and measurement conventions across countries. The empirical analysis uses G20 country level data for 2016 to 2020 collected from the Trading Economics database, which compiles officially released statistics into harmonized indicator series. The final analytical panel includes country year observations defined by a consistent missing data rule applied to all indicators, as specified in the methodology section.

Beyond index construction, we examine the robustness and ecological relevance of the proposed Green GDP accounting results through a triangulated validation design. Grey relational analysis is used to evaluate the similarity between the Green GDP index and environmental indicator patterns under limited sample size and potential non linearity, while Kendall's coefficient of concordance assesses whether country rankings are consistently ordered and stable across indicators. In addition, partial least squares regression is applied as a predictive validation tool because it can handle correlated predictors and provides interpretable diagnostics such as VIP scores, which help identify the most influential indicators associated with Green GDP performance. These analyses are used to assess predictive coherence and practical interpretability rather than to imply causal identification.

Accordingly, this study pursues two objectives, to develop a transparent and scalable framework for Green GDP accounting suitable for cross national comparison, and to empirically validate its environmental significance across diverse national contexts. The contributions are threefold, a reproducible entropy based accounting pipeline, a cross country application to G20 economies from 2016 to 2020, and a multi method validation strategy that strengthens robustness and policy relevance. Compared with prior Green GDP studies that rely on subjective weighting or single method validation, this paper combines entropy based aggregation with triangulated validation to enhance reproducibility and cross country interpretability. By bridging methodological rigor and cross national applicability, the study supports evidence based monitoring and policy design related to SDG 8, SDG 12, and SDG 13.

2.Literature Review

Green GDP has gradually evolved into a key concept in the broader discourse on sustainable development, serving as a bridge between environmental preservation and economic growth. Traditional GDP metrics focus solely on the output value of goods and services without accounting for the depletion of natural resources or degradation of ecosystems[4]. In response, scholars and institutions have introduced various Green GDP models to integrate ecological and environmental costs into national income accounting.

Early efforts in Green GDP estimation primarily focused on deducting environmental costs, such as pollution control and resource depletion, from gross output[5]. These approaches provided a basic adjustment mechanism to reflect environmental damage but often suffered from limited scope and inconsistent data standards. Later models expanded this framework by incorporating the valuation of ecosystem services, such as clean air, biodiversity, and water purification. These developments enriched the conceptual foundation of Green GDP but also introduced new complexities in valuation methods and data reliability.

Most existing models face several methodological limitations. One major challenge is the subjectivity involved in selecting indicators and determining their relative importance[6]. Manual weighting or expert scoring methods are frequently used, leading to potential bias and reduced comparability across countries or regions[7]. In addition, many models emphasize the cost side of environmental impact while underrepresenting the benefits generated from ecological restoration, green investment, and sustainable practices. This creates a one-sided view of environmental-economic interactions.

Recent approaches have attempted to address these gaps by proposing multi- dimensional index systems. These systems often evaluate resource utilization efficiency, environmental management expenditures, and ecological benefits as separate but interrelated components[8]. The growing application of quantitative weighting techniques, such as the entropy method, has further enhanced the objectivity of indicator systems by assigning weights based on data variation rather than subjective judgment.

Recent advances in environmental–economic accounting have converged around two major reference frameworks. The first is the United Nations System of Environmental-Economic Accounting (SEEA), particularly the 2021 Ecosystem Accounting standard, which provides an integrated statistical architecture for recording ecosystem extent, condition and services alongside the System of National Accounts (SNA). SEEA Ecosystem Accounting is explicitly designed to link biophysical indicators to economic activities and to track changes in ecosystem assets over time.

The second is the natural-capital perspective articulated in The Economics of Biodiversity: The Dasgupta Review, which argues that economic success should be evaluated in terms of inclusive wealth, with produced, human and natural capital treated as a unified portfolio of assets. In this view, conventional flow-based indicators such as GDP are inadequate because they do not record depreciation of natural capital or the services provided by ecosystems. The Review therefore calls for macroeconomic metrics that explicitly internalize environmental degradation and ecosystem services into assessments of national prosperity and sustainability.

This paper builds on these frameworks but departs from them in three ways. First, rather than constructing a full set of satellite accounts, we develop a synthetic, entropy-weighted Green GDP index that can be implemented with widely available cross-country data. This responds to the implementation gap noted in SEEA and related initiatives, where many countries lack the statistical capacity to operationalize complex accounting tables at scale. Second, we explicitly integrate both environmental costs and ecological benefits into a single macro-indicator, while treating resource-use efficiency as a multiplicative adjustment. This design translates the natural-capital logic of depreciation and restoration into a tractable empirical formula for G20 economies. Third, we empirically validate the index against key climate-related variables (carbon emissions, precipitation, temperature) using grey correlation, Kendall's W and PLS regression, thereby providing an evidence-based bridge between accounting frameworks and observed ecological outcomes.

In this sense, the contribution of the paper is not to replace SEEA or the broader natural-capital literature, but to propose a policy-oriented Green GDP metric that is (i) methodologically transparent, (ii) reproducible with standard international datasets, and (iii) suitable for comparative assessment across large economies. The model can therefore complement existing accounting frameworks by offering a parsimonious indicator that highlights the environmental performance of economic activity under a common methodological umbrella.

3.Methodology

3.1 Green GDP definition and related definitions

Green GDP in this study refers to an adjusted measure of national economic performance that accounts for environmental governance costs and ecological benefits alongside conventional GDP. The purpose is to reflect economic output under environmental constraints and to support sustainability oriented evaluation across countries and time.

In conceptual terms, Green GDP can be expressed as follows. Green GDP equals GDP minus environmental governance costs plus the value of ecological benefits. Resource utilization is treated as a core pillar that reflects how efficiently economic activities use natural resources and how much environmental pressure is generated per unit of output. In this paper, the above expression is used to clarify the accounting logic, while the empirical analysis operationalises Green GDP as a composite index constructed from observable indicators.

Resource utilization describes the efficiency and conservation of natural resource use in economic activities. Higher resource efficiency implies lower resource pressure for a given level of output and is therefore consistent with greener growth.

Environmental governance costs refer to the expenditures and resource inputs devoted to pollution control, environmental treatment, restoration, and compliance. Under a Green GDP logic, these costs represent economic resources that are required to offset environmental damage and are therefore deducted when assessing net sustainable performance.

Ecological benefits refer to the measurable positive outcomes associated with improved environmental quality and ecosystem functioning, such as reduced pollution related risks, improved ecosystem stability, and enhanced ecological service capacity. Under a Green GDP logic, these benefits are added because they represent positive ecological value generated or preserved alongside economic activity.

To reduce subjectivity in indicator weighting and to improve cross country comparability, this study constructs a Green GDP index using the entropy weight method. The entropy approach assigns weights based on the information content of indicators across observations, which is suitable for multi indicator evaluation when indicators differ in dispersion and scale.

3.2 Data and sample

This study uses annual country level data for G20 economies from 2016 to 2020. All indicators are retrieved from the Trading Economics database, which compiles officially released statistics and reports the original sources for each series, including the World Bank World Development Indicators and national statistical agencies. The Green GDP index is constructed from the indicator system described above. For external validation, three environmental indicators are used, namely carbon dioxide emissions, precipitation, and temperature.

All variables are aligned to the same annual frequency and harmonised to consistent units before analysis. Missing observations are handled using a consistent rule across countries and years. Isolated one year gaps are filled using linear interpolation, and remaining missing country year observations are removed to avoid biased comparisons. The final dataset is then standardised and normalised to support entropy based aggregation and subsequent validation analysis using grey relational analysis, Kendall's coefficient of concordance, and partial least squares regression.

3.3 Selection of variables

To operationalise Green GDP as a reproducible composite index, this study selects measurable indicators that map onto three pillars, resource utilisation, environmental governance costs, and ecological benefits. The selection logic is to capture, respectively, the intensity of resource use in production, the economic burden of pollution control and restoration, and the positive outcomes associated with environmental improvement. All indicators are designed to be comparable across countries and years and are subsequently normalised before entropy based weighting.

(1) Resource utilisation

Resource utilisation reflects how intensively an economy consumes key natural resources to generate output. In cross country accounting, the most consistent operationalisation is intensity type indicators, where lower values indicate better resource efficiency and lower environmental pressure. The indicators include the following.

Energy intensity is defined as energy consumption divided by GDP. Lower energy intensity indicates higher energy efficiency.

Water intensity is defined as production related water use divided by GDP. Lower water intensity indicates higher water productivity.

Resource consumption elasticity is defined as the growth rate of primary energy consumption divided by the growth rate of GDP. A lower elasticity indicates that energy demand grows more slowly than output, which is consistent with decoupling.

Land utilisation is defined as utilised land area divided by total land area. This indicator is intended to capture land use efficiency in the sense of reducing idle land and improving spatial use, subject to cross country data comparability.

(2) Environmental governance costs

Environmental governance costs represent the economic resources required to control pollution, treat emissions, and restore damaged ecosystems. Under a Green GDP logic, these costs reduce net sustainable performance and are therefore treated as cost type indicators, where lower values are better. The cost indicators include water pollution treatment cost, air pollution treatment cost, and solid waste treatment cost.

Water pollution treatment cost is calculated as annual wastewater discharge multiplied by an average unit treatment cost.

Air pollution treatment cost is calculated as annual emissions of key air pollutants multiplied by an average unit treatment cost.

Solid waste treatment cost is calculated as annual treated waste volume multiplied by an average unit treatment cost.

For reproducibility, unit treatment costs are harmonised to a common currency basis and applied consistently across countries. When national unit costs are unavailable for isolated observations, a documented imputation rule is applied to avoid biased cross country comparisons.

(3) Ecological benefits

Ecological benefits represent the positive value associated with improvements in environmental quality and ecosystem functioning. Because direct monetary valuation is often unavailable at scale, ecological benefits are operationalised using composite benefit constructs that can be consistently measured across countries.

Health benefits capture improvements in population health conditions associated with cleaner environments.

Ecosystem benefits capture improvements in ecosystem service capacity and ecological stability.

Cultural benefits capture economic gains associated with ecological improvement through ecotourism and related cultural industries, using comparable macro indicators.

These benefit constructs are treated as benefit type indicators, where higher values indicate stronger ecological gains.

3.4 Indicator System Construction

The Green GDP index system in this study integrates economic performance with environmental costs and ecological returns through a structured multi indicator design. The framework contains three primary dimensions.

The first dimension, resource utilisation, captures the intensity of resource use in economic activity. It is measured by energy intensity, water intensity, resource consumption elasticity, and land utilisation.

The second dimension, environmental governance costs, reflects the economic burden associated with pollution treatment and ecological restoration. It is measured by water pollution treatment cost, air pollution treatment cost, and solid waste treatment cost.

The third dimension, ecological benefits, captures the positive outcomes associated with improved environmental conditions and ecosystem functioning. It is measured by health benefits, ecosystem benefits, and cultural benefits.

Before entropy weighting, each indicator is classified as either benefit type or cost type. Benefit type indicators are defined such that higher values indicate better performance. Cost type indicators are defined such that lower values indicate better performance. Cost type indicators are converted during normalisation to ensure consistent directional meaning across the index. The detailed indicator list and entropy derived weights are reported in Table 1.

Table 1. Green GDP index system and weight

Projects	Explanatory variables	Effect direction	Weights
Resource Utilization	Energy intensity (energy consumption per GDP)	Cost type (lower is better)	20.57%
	Water intensity (water use per GDP)	Cost type (lower is better)	27.41%
	Resource consumption elasticity factor	Cost type (lower is better)	33.96%
	Land use index	Benefit type (higher is better)	18.06%
Environmental Management Costs	Water pollution treatment costs	Cost type (lower is better)	33.85%
	Air pollution treatment costs	Cost type (lower is better)	19.94%
	Solid waste pollution treatment costs	Cost type (lower is better)	46.21%
Value of Ecological Benefits	Health benefits	Benefit type (higher is better)	22.68%
	Ecosystem benefits	Benefit type (higher is better)	61.50%
	Cultural benefits	Benefit type (higher is better)	15.82%

3.5 Weight Calculation: Entropy Method

Let xi_j denote the original value of indicator j for country i, where i= l, ...,n and j= 1, ..., m.To make indicators comparable across diferent units and scales, all indicators are first normalisedusing a min max transformation.

For benefit type indicators, where a higher value indicates better performance, normalisation is defined as:

$$z_{ij}=\frac{x_{ij}-min_i x_{ij}}{max_i x_{ij}-min_i x_{ij}}$$

For cost type indicators, where a lower value indicates better performance, normalisation is defined as:

$$z_{ij}=\frac{max_i x_{ij}-x_{ij}}{max_i x_{ij}-min_i x_{ij}}$$

After normalisation, z_{ij} lies in the interval [0, 1], and larger values consistently represent bettergreen performance.

Second, the proportion of country i in indicator j is computed as:

$$p_{ij}=\frac{z_{ij}}{\sum_{i=1}^{n} z_{ij}}$$

If $\sum_i z_{ij} = 0$ for a given indicator, we set $p_{ij} = 1/n$ to avoid division by zero.

Third, the entropy value of indicator j is calculated as:

$$e_j=-k\sum_{i=1}^{n} p_{ij}\ln p_{ij}\ , where\ k=\frac{1}{\ln n}$$

The scaling constant k ensures $0 \leqq e_j \leqq 1$. indicators with more dispersed values across countriescontain more information and therefore tend to have lower entropy values.

Fourth, the information divergence of each indicator is computed as $d_j=1-e_j$, and the entropyweight is then obtained as:

$$w_j=\frac{d_j}{\sum_{j=1}^{m} d_j}$$

Indicators with larger divergence d_j receive larger weights w_j .

Fifth, within each dimension, the normalised indicators are aggregated into a dimension specific sub index using entropy weights. Let J_R, J_C, and J_B denote the sets of indicators belonging to resourceutilisation, environmental governance costs, and ecological benefits, respectively. The sub indicesare computed as:

$$R_i=\sum_{J\in J_R} W_j Z_{ij}\ ,\quad C_i=\sum_{J\in J_C} W_j Z_{ij}\ ,\quad B_i=\sum_{J\in J_B} W_j Z_{ij}$$

Finally, to maintain unit consistency, conventional GDP is rescaled into a unit free index $GGDP_i$ using the same normalisation procedure. The Green GDP index for country i is then defined as:

$$GreenGDP_i = (GDP_i - C_i + B_i) \times R_i$$

Where C_i, B_i and R_i are dimension specific sub indices constructed from entropy weights computed within each dimension. This multiplicative specification ensures that inefficient resource use reduces the effective Green GDP index, thereby internalising resource pressure alongside environmental governance costs and ecological benefits in the overall sustainability adjusted performance measure.

3.6 Empirical Validation Framework

To assess the ecological relevance and empirical robustness of the constructed Green GDP index, we conduct a cross country validation analysis for G20 economies over 2016 to 2020. Three complementary techniques are used. First, grey relational analysis is applied to evaluate the similarity between the Green GDP index and key environmental indicator patterns, which is suitable for multi indicator comparison under limited sample size and potential non linear relationships. Second, Kendall's coefficient of concordance is used to test whether country rankings implied by the Green GDP index are consistent with rankings implied by each environmental indicator, providing a nonparametric assessment of ranking stability and agreement. Third, partial least squares regression is employed as a predictive validation tool because it can handle correlated predictors and yields interpretable diagnostics such as VIP scores. In the PLSR model, the environmental indicators are used as predictors and the Green GDP index is treated as the outcome, so that VIP scores identify which indicators are most informative for explaining cross country variation in Green GDP performance. Together, this validation design strengthens confidence that the index captures environmentally meaningful information and remains interpretable across heterogeneous ecological and economic contexts.

3.7 Addressing potential endogeneity

A potential concern in empirical validation is endogeneity and mechanical overlap. The Green GDP index is constructed from a set of indicators that may be influenced by environmental conditions and policy responses, and environmental pressure may in turn affect governance costs and ecological benefits. To reduce direct mechanical overlap, the three external validation variables used in grey relational analysis, Kendall's concordance testing, and PLSR, namely carbon dioxide emissions, precipitation, and temperature, are not included as components in the Green GDP indicator system. This separation ensures that the validation exercises do not simply reproduce the index construction inputs.

Nevertheless, the empirical relationships reported in this paper should be interpreted as associational and prediction oriented rather than causal. Reverse causality, omitted variables such as energy prices, industrial structure, and regulatory stringency, and policy feedback effects may jointly shape both Green GDP performance and environmental indicators. A causal identification strategy would require additional design elements such as instrumental variables, quasi experimental variation, or structural modelling, which are beyond the scope of this study. Future research can build on the proposed framework by combining the Green GDP index with dynamic panel methods or quasi experimental designs to evaluate the causal effects of green accounting reforms and environmental governance on ecological outcomes.

4.Results and Analysis

To evaluate the ecological relevance of the proposed Green GDP index, we conduct empirical validation tests using G20 data for 2016 to 2020. The analysis assesses the degree to which the Green GDP index is aligned with three external environmental indicators, namely carbon dioxide emissions, precipitation, and temperature. The results are interpreted as associational and validation oriented rather than causal.

4.1 Grey Correlation Analysis

Grey relational analysis evaluates the closeness between the Green GDP index and each environmental indicator by comparing their normalised patterns. In this study, the Green GDP index is treated as the reference sequence, and each environmental indicator is treated as a comparative sequence. Table 2 reports the grey relational grades. All grades exceed 0.5, indicating a meaningful level of alignment between the index and the selected ecological indicators.

Table 2. Grey correlation degree

Indicator	Correlation Degree	Ranking
Carbon dioxide emissions	0.850	1
Precipitation	0.737	2
Temperature	0.694	3

The highest grade is observed for carbon dioxide emissions, suggesting that the Green GDP index is most closely aligned with carbon related environmental pressure among the three validation indicators. This result supports the ecological relevance of the index, while also indicating that carbon emissions provide the most informative external benchmark for distinguishing cross country Green GDP performance in the sample.

4.2 Kendall's W Consistency Test

To assess the concordance between Green GDP scores and ecological conditions across countries, we employed Kendall's W test. The results demonstrate a significant agreement between the rankings ($W = 0.925$, $p < 0.01$), suggesting that the Green GDP index aligns well with broader ecological trends. This statistical consistency reinforces the model's interpretive robustness.

Table 3. Kendall consistency test

Item	Mean rank	Median	Test statistics
Green GDP	2.75	1413	
Precipitation	2.25	739	
Carbon dioxide emissions	4	426935.5	
Temperature	1	13.065	
Overall Kendall's W	$W = 0.925$; $\chi^2 = 33.300$; df = 3; $p < 0.001$		

Note: Mean rank is obtained from the rank-based procedure underlying Kendall's W. The chi-square test uses df = k − 1, where k is the number of ranked variables (k = 4).

4.3 Partial Least Squares Regression

The previous validation results indicate that the proposed Green GDP index is closely aligned with key environmental indicators. To provide additional predictive validation and to identify which ecological indicators are most informative for explaining cross country variation in Green GDP, we apply partial least squares regression. PLSR is appropriate in this context because the predictors may be correlated and the sample size is limited. In this model, precipitation, carbon dioxide emissions, and temperature are treated as explanatory variables, while Green GDP is treated as the outcome variable. The results are interpreted as associational and validation oriented rather than causal. The model is estimated on the subset of countries with complete observations for all variables.

Table 4. Explanation of variance of factors

Factors	X Var	Cum. X Var	Y Var	Cum. Y Var (R^2)	Adj. R^2
1	0.514	0.514	0.619	0.619	0.581
2	0.282	0.796	0.046	0.665	0.59
3	0.204	1	0.001	0.666	0.541

Table 4 reports the explained variance by PLSR components. The first component explains 51.4 percent of the variance in the predictor block and 61.9 percent of the variance in the outcome. Adding a second component increases the cumulative explained variance of the predictor block to 79.6 percent and the cumulative explanatory power for the outcome to R^2 = 0.665. The third component increases the cumulative explained variance of the predictors to 1.000 but contributes almost no additional explanatory power for the outcome, with cumulative R^2 increasing only marginally from 0.665 to 0.666. Therefore, a two component solution is sufficient for predictive validation in this study.

Table 5. Summary table of independent variable VIP

Variables	Factor 1	Factor 2	Factor 3
Precipitation	0.296	0.42	0.423
Carbon dioxide emissions	1.484	1.447	1.446
Temperature	0.843	0.854	0.855

Table 5 reports VIP values. Carbon dioxide emissions consistently shows VIP values greater than 1 across components, indicating that it is the most influential predictor in explaining variation in Green GDP within the PLSR framework. By contrast, precipitation and temperature have VIP values below 1, suggesting comparatively weaker explanatory importance in this specification. Figure 1 visualises the VIP results.

Figure 1: VIP values for predictors in the PLSR model

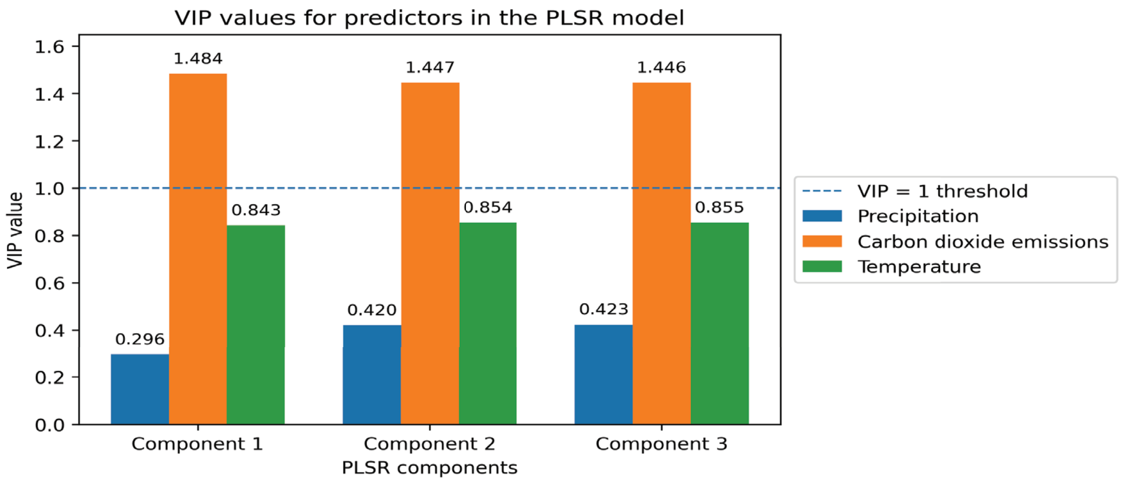

Table 6 reports the estimated model coefficients. Because the predictors are measured on different scales, the standardised coefficients provide a more interpretable comparison of relative contributions. The standardised results indicate a positive association between carbon dioxide emissions and Green GDP, a small positive association for precipitation, and a negative association for temperature. These coefficient patterns should be interpreted as predictive associations rather than evidence of causal effects. The positive association with carbon dioxide emissions should be interpreted cautiously because total emissions are scale dependent and may partly capture country size effects rather than purely environmental performance.

Table 6. Results of model coefficients

Variables	Green GDP	Green GDP (standardized)
Constants	4769.188	0
Precipitation	0.107	0.011
Carbon dioxide emissions	0.002	0.733
Temperature	-181.951	-0.181

5.Discussion

5.1 Indicator Validity and Environmental Relevance

The validation evidence suggests that the proposed Green GDP index is environmentally meaningful in the sense that it is systematically aligned with core ecological indicators. The grey relational grades indicate substantial pattern closeness between Green GDP and each external indicator, and Kendall's coefficient of concordance further shows strong agreement among the country rankings implied by Green GDP and the selected ecological indicators. Together, these results support the indicator validity of the index and its ecological relevance for cross country benchmarking.

Importantly, the validation does not imply that higher Green GDP necessarily corresponds to uniformly better ecological outcomes. Rather, it indicates that the index co varies with ecological conditions and pressures in a consistent and interpretable way. This is particularly relevant in cross country settings where environmental pressures are heterogeneous and may be linked to economic scale and industrial structure. In this regard, precipitation and temperature reflect broader climatic conditions, while carbon dioxide emissions capture energy and industrial pressure that is closely intertwined with macroeconomic activity in large economies. The alignment of Green GDP with these heterogeneous indicators supports the robustness of the index as a composite measure designed to integrate environmental governance costs and ecological benefits into national level performance assessment.

The PLSR results provide additional predictive validation and help identify which external indicators are most informative for explaining cross country variation in Green GDP. VIP statistics show that carbon dioxide emissions consistently exceed the conventional threshold of 1, while precipitation and temperature remain below it. This pattern indicates that, within the current specification and sample, the Green GDP index is most tightly associated with the carbon dimension of environmental pressure. At the same time, the carbon dioxide indicator used in validation may be scale dependent when measured in total emissions, which means that part of the association can reflect country size effects rather than purely environmental performance. Accordingly, the proposed index can be interpreted as a carbon anchored Green GDP measure in its current form. Future extensions could strengthen ecological coverage by incorporating additional indicators that capture water stress, biodiversity, waste, and local air pollutants more directly, and by testing alternative normalisations such as per capita or intensity based emissions to reduce scale effects.

5.2 Cross-National Applicability

Applying the proposed Green GDP index to the study sample demonstrates substantial cross country dispersion, indicating that the framework can differentiate national performance profiles when environmental governance costs, ecological benefits, and resource utilisation are considered jointly. Unlike conventional GDP, which primarily reflects economic output, the proposed index provides an alternative ordering that embeds environmental constraints and ecological returns into the assessment of national performance. This feature supports cross national benchmarking and enables comparisons that are more informative for sustainability oriented evaluation.

The decomposition of the index is particularly useful for policy interpretation. In some countries, relatively strong resource utilisation performance coexists with weaker ecological benefit values, suggesting that efficiency gains in production do not automatically translate into measurable ecological improvements within the observed period. In other cases, moderate overall index performance may coexist with high environmental governance cost scores, which can be interpreted as a burden associated with pollution control, compliance, and ecological restoration. These contrasting profiles imply that improving Green GDP is not only a question of increasing environmental expenditure, but also of adjusting the structure of growth through cleaner energy use, industrial upgrading, and more effective conversion of governance inputs into ecological outcomes.

The results also highlight practical considerations for cross national implementation. The usefulness of Green GDP accounting depends on consistent indicator definitions, harmonised units, and adequate statistical capacity to produce comparable environmental and ecological series. In this sense, alignment with internationally recognised accounting practices for environmental and natural capital information can facilitate broader adoption and improve policy usability. Embedding Green GDP metrics into routine planning and budgeting processes may further strengthen their role in long term sustainable economic planning and environmental governance.

5.3 Political economy and institutional context of Green GDP implementation

Implementing Green GDP is not only a technical exercise in measurement, but also a political economy process that can reshape incentives for governments, firms, and citizens. Incorporating environmental costs and ecological benefits into performance assessment can change how growth is evaluated and rewarded, which may generate resistance from actors that benefit from high growth and high emission trajectories. A widely discussed example is China's early Green GDP initiative in the mid 2000s, where preliminary estimates implied that environmental damage could offset a nontrivial share of reported economic output. However, the initiative encountered substantial contestation over methodology, data credibility, and political implications for growth oriented evaluation systems, and its institutionalisation was not sustained. This episode illustrates that Green GDP adoption is highly sensitive to governance incentives and administrative accountability structures. Add citations here.

These experiences suggest that the effectiveness of Green GDP reforms depends on whether accounting outputs are linked to decision rights and policy levers. When fiscal transfers, credit allocation, and official evaluation remain dominated by conventional GDP targets, Green GDP accounting is likely to be used mainly for signalling rather than for enforcement. By contrast, when Green GDP or related natural capital indicators are integrated into budgeting rules, public investment appraisal, procurement criteria, or intergovernmental transfer formulas, accounting information is more likely to translate into behavioural change. This mechanism is consistent with the broader policy logic advocated by international environmental economic accounting frameworks that emphasise institutional embedding rather than measurement alone. Add citations here.

For G20 members, this implies that adopting an entropy based Green GDP index is a necessary but not sufficient condition for greener development. The index can help reveal environmental costs that are not visible in conventional GDP, enable structured cross country comparison, and provide a consistent reference for prioritising environmental governance and ecological restoration. However, its practical impact ultimately depends on whether governments are willing and able to adjust fiscal frameworks, industrial policies, and performance evaluation systems so that ecological outcomes carry comparable weight to output growth in administrative and political decision making.

5.4 Policy Implications

The proposed Green GDP framework provides actionable guidance for governments seeking to reconcile economic growth with environmental sustainability. By incorporating environmental governance costs and ecological benefits into a single accounting structure, the index can be used to diagnose trade offs that conventional GDP does not capture. In practice, policymakers can use the index and its sub dimensions to support three types of decisions. First, it can inform priority setting by identifying whether weak overall Green GDP performance is driven primarily by resource utilisation pressure, governance cost burdens, or insufficient ecological benefits. Second, it can support monitoring by tracking changes over time and evaluating whether policy packages, such as industrial upgrading, energy transition, or pollution control investment, are associated with improved sustainability adjusted performance. Third, it can strengthen accountability by providing a transparent and replicable metric for reporting progress toward sustainability oriented development goals.

Beyond domestic planning, the index can also serve as a supplementary tool in financial and international contexts when used with appropriate caution. It can support screening and evaluation of green public investment portfolios, provide additional evidence for ESG related reporting, and facilitate cross country benchmarking for sustainability dialogues. However, Green GDP should be treated as a complementary indicator rather than a substitute for official national accounts or detailed environmental regulatory metrics. Its policy usefulness is maximised when the index is paired with clear indicator definitions, consistent units, transparent data provenance, and governance arrangements that translate accounting information into budgetary and regulatory action.

6.Conclusion

This study develops an optimized and empirically validated Green GDP accounting framework that integrates environmental costs and ecological benefits into the assessment of national economic performance. By constructing a multi dimensional indicator system and applying entropy weighting, the proposed approach reduces common limitations in existing Green GDP practices, particularly subjective indicator weighting and weak cross country comparability. The framework is designed to be transparent, reproducible, and scalable for macro level sustainability evaluation.

Using G20 annual data from 2016 to 2020, the empirical assessment indicates that the Green GDP index exhibits stable and interpretable associations with core ecological indicators, including carbon dioxide emissions, precipitation, and temperature. The combined evidence from grey relational analysis, Kendall's coefficient of concordance, and partial least squares regression supports the robustness and consistency of the accounting results. Importantly, these tests are employed to validate the practical relevance and predictive coherence of the index rather than to make causal claims.

From a sustainable development perspective, the findings contribute directly to specific Sustainable Development Goals. First, by offering a sustainability adjusted performance metric that complements conventional GDP, the model supports SDG 8 by enabling policymakers to monitor economic performance alongside environmental constraints. Second, the integrated treatment of environmental costs and ecological benefits provides an accounting basis that aligns with SDG 12 by encouraging resource efficiency and responsible production and consumption through measurable incentives and benchmarking. Third, the model supports SDG 13 by incorporating climate related pressures into economic evaluation and enabling cross national comparison of climate compatible development trajectories. In practical terms, the framework can assist governments in setting medium term and long term targets, evaluating policy trade offs, and improving the accountability of environmental governance by linking ecological outcomes to economic assessment.

Several limitations remain. The validity of Green GDP accounting depends on indicator availability and the quality of ecological valuation, and cross country data constraints may restrict the inclusion of broader ecological dimensions. Future research can extend the framework by incorporating biodiversity and social equity related indicators, exploring dynamic time series modelling to capture Green GDP evolution over longer horizons, and applying the approach to developing economies where environmental governance and data systems differ substantially. Overall, the proposed framework provides a feasible pathway for integrating ecological sustainability into macroeconomic assessment and for supporting long term sustainable economic planning and environmental governance.

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Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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