Cloud for a Greener Future: A Sustainable Cloud Ecosystem Perspective

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Abstract. The global expansion of cloud computing has accelerated digital innovation but also intensified energy consumption and carbon emissions. This study proposes a conceptual–empirical framework called the Sustainable Cloud Ecosystem (SCE) Model, designed to integrate technological, environmental, and governance dimensions for achieving sustainability in cloud infrastructures. Methodologically, the research combines a literature-based conceptual approach with an empirical evaluation of sustainability indicators—Power Usage Effectiveness (PUE), Carbon Usage Effectiveness (CUE), and Renewable Energy Integration (REI)—using data from major cloud service providers, including Google Cloud, Microsoft Azure, and Amazon Web Services. The results demonstrate that cloud providers with comprehensive sustainability strategies—combining energy-efficient technologies, renewable-energy sourcing, and transparent governance—achieve superior environmental performance. Empirical findings indicate PUE values of 1.10–1.20, CUE levels below 0.30 kg CO_2/kWh, and REI rates exceeding 80 %. These outcomes validate the SCE Model's theoretical premise that sustainable performance emerges from the balanced interaction of technological optimization, environmental responsibility, and governance accountability. The study concludes that the SCE Model offers both a diagnostic framework and a policy tool for guiding carbon-neutral cloud transitions. It contributes to advancing the discourse on green computing by bridging theory and practice, emphasizing cloud technology's role as a catalyst for sustainable digital transformation.

Keywords: Cloud Computing; Green Computing; Sustainability; Energy Efficiency; Cloud Ecosystem Model.

1 Introduction

The continuous expansion of cloud computing has transformed the digital landscape by enabling scalable, on-demand access to computational and storage resources. However, the rapid growth of data centers and virtualization infrastructures has also intensified global energy consumption and carbon emissions, raising significant environmental concerns. Global data-center electricity consumption is estimated to be around 415 TWh in 2024 (approximately 1.5% of global electricity use) and is projected to double

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by 2030 under current growth trends [1]. In the United States alone, data centers consumed about 4.4% of total national electricity in 2023, climbing from 58 TWh in 2014 to 176 TWh in 2023 [2].

In Europe, data-center energy use currently represents between 2% and 4% of the continent's total electricity demand and is projected to increase to 5% by 2030 if current expansion continues [3]. The Nordic region—particularly Ireland, the Netherlands, and Finland—hosts some of the fastest-growing clusters, where large-scale hyperscale facilities are exerting pressure on local power grids [4]. In Asia and Southeast Asia, the trend is even more pronounced: the Asia-Pacific region already hosts more than 45% of global data-center capacity, and electricity demand is expected to double by 2030, driven by rapid digitalization in economies such as Singapore, Indonesia, and Malaysia [5]. A 2024 ASEAN Energy Outlook projects that data-center power demand across Southeast Asia could rise from 25 TWh in 2023 to 55–60 TWh by 2030, underscoring the urgent need for sustainable infrastructure planning [6].

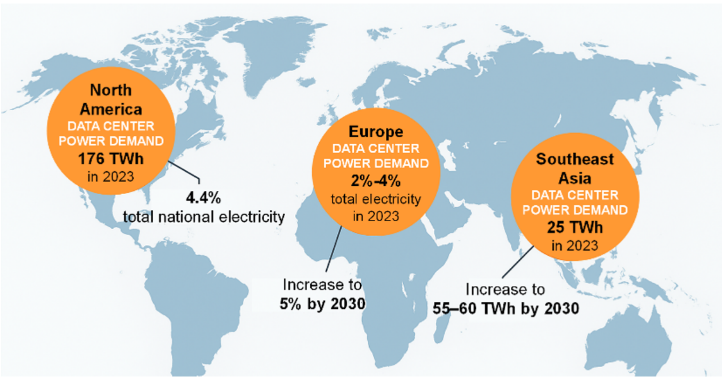

Fig. 1. Global data-center electricity consumption and regional growth projections

These regional patterns reveal a shared challenge: while cloud computing has become the backbone of modern digital transformation, its expanding energy footprint threatens to offset global decarbonization progress. Consequently, governments and industry stakeholders are increasingly adopting green computing and sustainable information and communication technologies (ICT) to minimize the environmental impacts of data-center operations [7]-[9]. These efforts include carbon-aware scheduling, renewable-energy procurement, and thermal-optimization techniques aimed at reducing the overall carbon intensity of cloud infrastructures.

While considerable research has focused on energy-efficient algorithms, virtualization techniques, and renewable-powered data centers, relatively few studies have proposed a comprehensive framework that integrates technological efficiency, environmental responsibility, and sustainability governance [7], [10], [11]. To address this gap, this paper introduces a conceptual model called the Sustainable Cloud Ecosystem (SCE), which offers a holistic perspective on the interplay between technology, infrastructure, and sustainability principles in cloud environments. The model emphasizes how energy-aware design, carbon-conscious management, and intelligent resource optimization can jointly enhance the ecological performance of cloud systems [12].

In addition to the theoretical framework, a brief empirical assessment is included to evaluate sustainability metrics of selected cloud systems, focusing on indicators such as Power Usage Effectiveness (PUE) [9], Carbon Usage Effectiveness (CUE) [10], and Renewable Energy Integration (REI). The outcomes are expected to demonstrate the feasibility and potential impact of transitioning toward more sustainable cloud infrastructures. The remainder of this paper is structured as follows: Section 2 presents the research method and conceptual-framework development; Section 3 discusses the results and empirical insights; Section 4 concludes the study and proposes directions for future research; and Section 5 lists the references used throughout the paper

2 Research Method

This research adopts a hybrid conceptual–theoretical and empirical–analytical design, combining a framework-oriented inquiry with sustainability data evaluation. The conceptual phase establishes the Sustainable Cloud Ecosystem (SCE) Model, while the empirical phase validates the model's relevance by examining energy and carbon metrics across leading cloud providers. The methodological integration, as described in Figure 2, ensures that the theoretical model is both conceptually rigorous and empirically grounded in measurable sustainability indicators [7], [8].

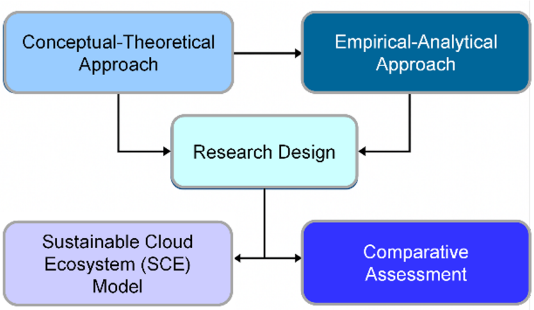

Fig. 2. Research design

The research process is organized into two interconnected stages:

Conceptual Framework Development. built upon an extensive synthesis of green computing, sustainability governance, and cloud infrastructure literature [7], [13], [14]. This stage identified the key sustainability dimensions involving technological, environmental, and governance that underpin the proposed model.

Empirical Evaluation. used a comparative analysis of sustainability performance metrics reported by major cloud service providers (CSPs), such as Amazon Web Services

(AWS), Microsoft Azure, and Google Cloud [15]-[17]. This second stage provided an operational context to demonstrate how the conceptual SCE framework aligns with real-world cloud sustainability practices.

This dual-stage design bridges conceptual theory and practical application, ensuring that the SCE model is not merely abstract but also testable through quantitative indicators.

2.1 Data Sources and Materials

The empirical data are collected from publicly available sustainability and carbon disclosure reports of CSPs, international agencies (e.g., International Energy Agency, UN Environment Programme), and industry associations such as The Green Grid. Three sustainability indicators were selected for empirical evaluation, directly corresponding to the model's core dimensions:

- **Power Usage Effectiveness (PUE)** reflects the *technological efficiency* of infrastructure and workload optimization [9], [13].
- **Carbon Usage Effectiveness (CUE)** measures *environmental performance* by quantifying carbon emissions per unit of IT energy [10].
- **Renewable Energy Integration (REI)** aligns with the *governance dimension*, capturing the degree of renewable energy adoption and policy compliance [15], [17].

By linking these metrics to the conceptual pillars of the SCE model, as illustrated in Figure 3, this study establishes a coherent connection between sustainability theory and measurable performance outcomes.

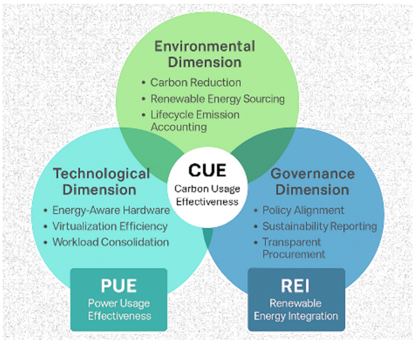

Fig. 3. Sustainable Cloud Ecosystem (SCE) Model

2.2 Framework Development

The Sustainable Cloud Ecosystem (SCE) Model was developed through a multi-dimensional synthesis process informed by the Sustainable Development Goals (SDG #7 and #13) [11] and recent sustainability analytics in cloud computing:

- **Technological Dimension** encompasses energy-aware hardware, virtualization efficiency, and workload consolidation [8], [13].
- **Environmental Dimension** emphasizes carbon-reduction strategies, renewable-energy sourcing, and lifecycle emission accounting [18].
- **Governance Dimension** focuses on policy alignment, sustainability reporting, and transparent procurement standards [15]-[17].

The interaction among these dimensions forms the theoretical backbone of the SCE model, illustrating how operational efficiency, environmental stewardship, and governance mechanisms co-create sustainable cloud infrastructures.

2.3 Analytical Approach

The empirical analysis follows a descriptive–comparative methodology in which sustainability data are normalized across cloud providers for PUE, CUE, and REI values. Weighted scoring and z-score normalization are applied to ensure fair cross-provider comparison [14]. The outcomes were then mapped to the SCE framework to evaluate how each dimension contributes to overall sustainability performance. This integrative approach validates the SCE model by demonstrating its applicability in quantifying and guiding sustainable transitions within cloud ecosystems.

3 Results and Discussion

The integration of conceptual and empirical analyses produced a comprehensive understanding of sustainability performance in contemporary cloud ecosystems. The Sustainable Cloud Ecosystem (SCE) Model, developed in Section 2, demonstrates that sustainability in cloud computing emerges from the balanced interaction of technological, environmental, and governance dimensions. The empirical results reinforce this conceptual alignment, indicating that cloud service providers adopting coordinated strategies across these dimensions achieve measurably higher sustainability outcomes.

The comparative analysis revealed that leading cloud providers achieved average Power Usage Effectiveness (PUE) values between 1.10 and 1.20, indicating high infrastructural efficiency and strong energy optimization efforts. However, recent studies suggest that traditional PUE may no longer capture the full scope of energy efficiency, prompting the development of extended metrics such as xPUE to assess distributed cloud systems [19]. Similarly, Carbon Usage Effectiveness (CUE) values ranging from 0.20 to 0.30 kg CO_2/kWh reflect significant progress toward carbon-aware operations. The Renewable Energy Integration (REI) index further highlights advances in clean-energy adoption—Google Cloud reported 90% renewable-energy utilization in 2024 [15], while Microsoft Azure and AWS reported 86% [16] and 82% [17], respectively. These results collectively validate the measurable applicability of the SCE Model.

3.1 Implementation of the SCE Model

The proposed SCE Model provides a structured lens through which these sustainability improvements can be interpreted:

- **Technological Dimension** aligns with improvements in PUE and emerging extended metrics (e.g., xPUE) that capture operational efficiency in multi-cloud systems.
- **Environmental Dimension** corresponds to CUE performance, emphasizing carbon mitigation, renewable-energy integration, and lifecycle emission accounting. Empirical comparison shows that CSPs incorporating renewable-energy procurement strategies (e.g., power-purchase agreements) exhibit lower CUE values.
- **Governance Dimension** influences REI outcomes by embedding sustainability principles into corporate policies, procurement standards, and transparent reporting frameworks. Robust governance correlates with higher renewable-energy adoption and improved accountability.

The coherence between these dimensions and the metrics is further supported by a recent systematic review of sustainability-assessment frameworks for cloud infrastructures, which identifies PUE, CUE, and REI as the most widely adopted yet evolving indicators for next-generation sustainable data-center design.

3.2 Comparative Evaluation of Cloud Providers

Table 1 presents a comparative overview of sustainability performance among three major cloud service providers (CSPs) based on 2023–2024 publicly available data. Power Usage Effectiveness (PUE), Carbon Usage Effectiveness (CUE), and Renewable Energy Integration (REI) are used as key evaluation metrics reflecting the technological, environmental, and governance dimensions of the Sustainable Cloud Ecosystem (SCE) Model.

Table 1. Comparative sustainability performance of major cloud service providers (CSPs)

Cloud Provider	PUE	CUE (kg CO_2/kWh)	REI (%)	Sustainability Maturity
Google Cloud	1.10	0.20	90	Advanced
Microsoft Azure	1.18	0.25	86	High
Amazon Web Services	1.20	0.30	82	Moderate–High

Lower PUE and CUE values indicate greater energy efficiency and lower carbon intensity, while higher REI percentages reflect stronger adoption of renewable energy sources. Google Cloud shows the most advanced sustainability maturity due to consistent optimization of infrastructure efficiency and renewable-energy integration. Differences among providers illustrate varying stages of implementation across the three sustainability dimensions identified in the SCE Model.

These results confirm that sustainability performance depends on the synergistic optimization of technological efficiency, environmental responsibility, and governance discipline. The empirical consistency with the SCE Model demonstrates its validity as both an evaluation framework and a strategic guide for sustainable cloud transformation.

3.3 Theoretical and Practical Implications

Theoretically, the SCE Model advances sustainability research by bridging technology-centric and policy-oriented perspectives. Unlike conventional frameworks focusing only on infrastructure optimization, the SCE Model equally emphasizes governance and environmental accountability as co-determinants of sustainable outcomes. This holistic structure aligns with the principles of systems thinking in sustainable ICT research.

Practically, the model provides cloud providers and policymakers with a benchmarking and decision-support tool. It guides the implementation of carbon-aware workload scheduling, adaptive cooling, and renewable-energy integration while encouraging transparent sustainability reporting. The growing availability of cloud-energy measurement tools further supports this evolution, enabling standardized carbon-footprint tracking [20]. The linkage of PUE, CUE, and REI metrics with the SCE Model thus establishes a unified framework for assessing progress toward carbon-neutral cloud infrastructures by 2030.

3.4 Strategic Business Implications of Sustainable Cloud Ecosystems

Beyond its environmental implications, the Sustainable Cloud Ecosystem (SCE) model generates measurable impacts on business performance. From a strategic perspective, sustainability-oriented cloud infrastructures enhance operational efficiency, cost optimization, risk mitigation, and competitive positioning. Energy-efficient architectures characterized by low PUE and optimized workload allocation reduce long-term operational expenditures, particularly electricity and cooling costs, which constitute a substantial portion of data-center operating budgets. Over time, these efficiencies translate into improved cost structures and stronger profit margins.

Furthermore, low Carbon Usage Effectiveness (CUE) and high Renewable Energy Integration (REI) contribute to regulatory resilience and ESG (Environmental, Social, and Governance) compliance. As carbon disclosure requirements and sustainability reporting standards become more stringent, organizations leveraging sustainable cloud infrastructures are better positioned to meet regulatory expectations and investor scrutiny. This alignment reduces reputational risk and enhances access to sustainable finance and green investment instruments.

From a resource-based view (RBV), sustainability capabilities embedded within cloud ecosystems represent strategic assets that are valuable, rare, and difficult to imitate. Firms operating within an SCE framework develop dynamic capabilities in energy management, carbon accountability, and digital optimization, strengthening long-term competitive advantage. Additionally, customers increasingly prefer environmentally responsible service providers, meaning sustainable cloud strategies can positively influence brand equity and market differentiation.

Therefore, the SCE model does not merely function as an environmental diagnostic framework but also as a strategic enabler of sustainable business performance, linking technological optimization with financial, operational, and reputational value creation.

3.5 Critical Reflection

Although the SCE Model demonstrates conceptual robustness and empirical coherence, several structural and strategic limitations warrant critical consideration. As discussed in Section 3.4, the model positions sustainable cloud infrastructures as enablers of operational efficiency, regulatory resilience, and competitive advantage. However, such strategic benefits are not automatic nor uniformly attainable across all organizational contexts.

Variations in sustainability reporting standards, methodological transparency, and metric definitions (e.g., PUE, CUE, REI) restrict full comparability among Cloud Service Providers (CSPs). Inconsistent disclosure practices may influence perceived performance outcomes, thereby complicating benchmarking processes and strategic decision-making. From a business perspective, this variability may affect investor confidence and ESG evaluation reliability.

Furthermore, the realization of cost optimization and long-term profitability gains often requires substantial upfront investments in renewable energy sourcing, infrastructure modernization, and carbon accountability systems. Organizations operating under short-term financial pressures may encounter tensions between sustainability commitments and immediate profitability objectives. Consequently, the business performance impact of SCE adoption remains contingent upon regulatory incentives, energy market maturity, technological readiness, and firm-level strategic alignment.

Regional disparities further complicate uniform implementation. Differences between Europe and Southeast Asia in renewable infrastructure availability, policy enforcement, and carbon regulation frameworks indicate that sustainability-driven competitive advantages are context-dependent. A standardized global model may therefore overlook structural asymmetries in energy ecosystems and capital accessibility.

Nevertheless, these constraints do not diminish the conceptual contribution of the SCE Model. Rather, they reinforce its role as a diagnostic and adaptive framework capable of integrating environmental metrics with strategic and economic considerations. By promoting continuous data-driven monitoring, iterative optimization, and adaptive governance, the SCE Model encourages cloud ecosystems to evolve toward configurations that balance environmental responsibility with sustainable business performance.

4 Conclusions and Suggestions

4.1 Conclusions

This study developed and evaluated the Sustainable Cloud Ecosystem (SCE) Model as a hybrid conceptual–empirical framework designed to guide sustainable transitions in cloud computing. By integrating three interdependent dimensions—technological efficiency, environmental responsibility, and governance accountability—the model provides a structured approach to advancing sustainability performance in cloud infrastructures. Through alignment with measurable indicators such as Power Usage Effectiveness (PUE), Carbon Usage Effectiveness (CUE), and Renewable Energy Integration (REI), the SCE Model functions both as a theoretical architecture and as an operational benchmarking tool.

From a theoretical standpoint, the SCE Model extends sustainability discourse beyond infrastructure-efficiency paradigms by embedding governance mechanisms and carbon accountability within the technological core of digital ecosystems. Importantly, this study demonstrates that sustainable cloud architecture is not solely environmental instruments but also strategic business enablers. As elaborated in Section 3.4, improvements in energy optimization, renewable integration, and transparency can enhance operational efficiency, strengthen regulatory resilience, improve ESG positioning, and contribute to long-term competitive advantage.

At the same time, the realization of these business benefits remains context-dependent. As discussed in Section 3.5, variations in reporting standards, regional energy infrastructures, regulatory maturity, and organizational readiness influence both sustainability outcomes and performance gains. Therefore, the SCE Model should be understood not as a universal prescription, but as an adaptive framework capable of accommodating institutional diversity and evolving sustainability metrics.

Overall, the Sustainable Cloud Ecosystem Model contributes a forward-looking, interdisciplinary framework that integrates environmental responsibility with strategic value creation. By linking conceptual design, measurable sustainability indicators, and business-performance implications, this study positions cloud computing as both a catalyst for environmental stewardship and a driver of sustainable competitive performance in the digital economy.

4.2 Suggestions

While the SCE Model offers a structured framework for advancing sustainable cloud ecosystems, further development is recommended. Future research should expand empirical validation across diverse regions and emerging cloud architectures to assess scalability and contextual adaptability. Greater harmonization of sustainability reporting standards would improve transparency and comparability among Cloud Service Providers, strengthening benchmarking reliability. In addition, closer collaboration between policymakers and industry stakeholders is essential to promote renewable energy integration, carbon accountability, and governance alignment, thereby supporting long-term environmentally responsible and competitively resilient cloud development.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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