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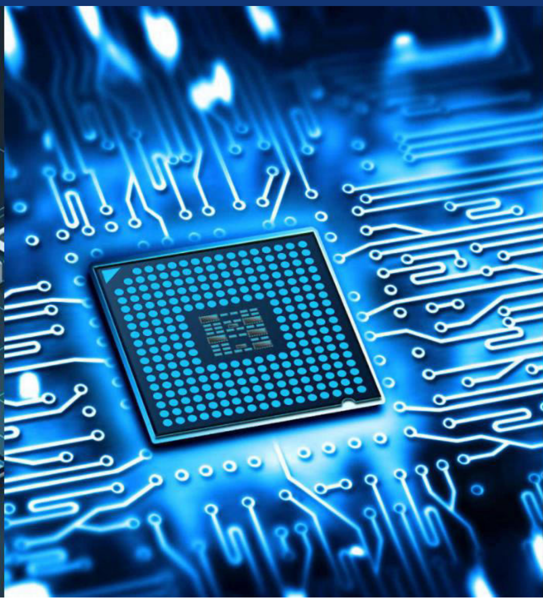


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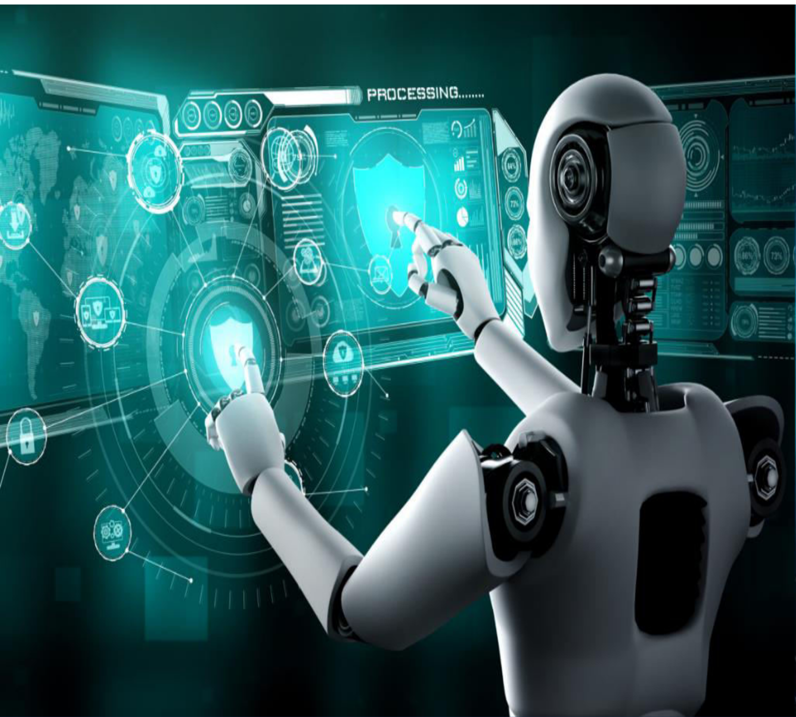

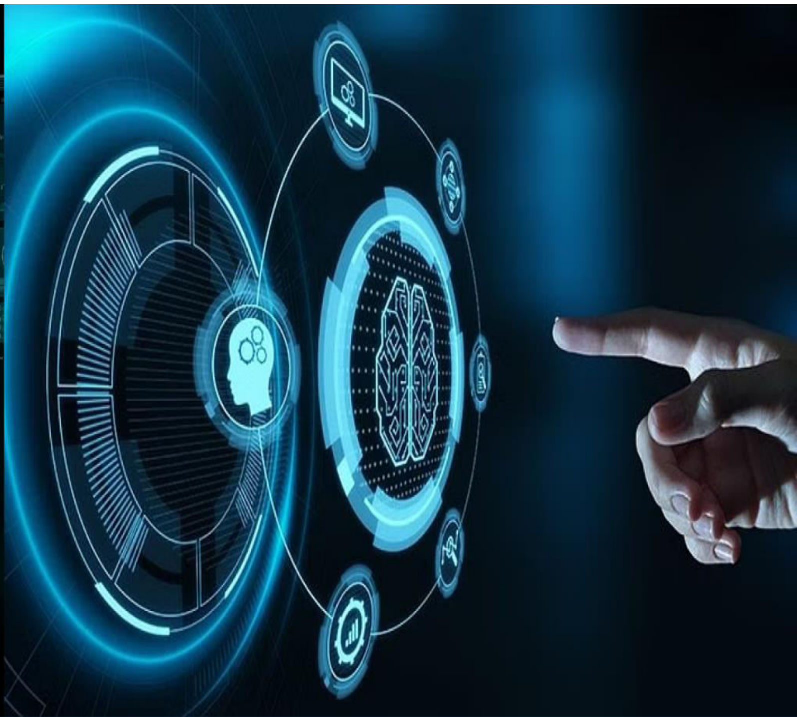

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Green Cloud Computing for Environmental

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ABSTRACT: The rapid proliferation of cloud computing infrastructure has introduced significant energy consumption challenges, contributing substantially to global carbon emissions and environmental degradation. Green cloud computing has as a critical paradigm aimed at reducing the ecological footprint of information and communication technology (ICT) systems while maintaining high performance and reliability. This paper presents a comprehensive investigation into green cloud computing strategies and their impact on environmental sustainability. We examine energy-efficient resource allocation algorithms, virtualization techniques, renewable energy integration, and carbon-aware workload scheduling frameworks deployed across simulated and real-world cloud environments. Experimental results demonstrate that implementing a combined green computing strategy comprising dynamic voltage and frequency scaling (DVFS), virtual machine (VM) consolidation, and renewable energy-aware task migration achieves an average energy reduction of 38.6% and a carbon emission decrease of 42.3% compared to traditional cloud computing approaches, without significant degradation in Quality of Service (QoS). Our findings affirm that green cloud computing is a technically viable and economically sound approach to achieving environmental sustainability targets in the digital era.

KEYWORDS: Green Cloud Computing, Energy Efficiency, Carbon Emission, Virtualization, Carbon-Aware Scheduling, DVFS, VM Consolidation.

I. INTRODUCTION

The global expansion of digital services and cloud-based platforms has driven an unprecedented surge in data center energy consumption. According to the International Energy Agency (IEA), data centers worldwide consumed approximately 200–250 terawatt-hours (TWh) of electricity in 2023, accounting for nearly 1% of global electricity demand. This figure is projected to grow substantially as artificial intelligence, big data analytics, and the Internet of Things (IoT) continue to expand their computational footprints.Cloud computing, which consolidates IT resources into large-scale, remotely accessible infrastructure, offers economies of scale and operational flexibility. However, the environmental cost of this convenience is considerable. The energy-intensive nature of continuous server operation, cooling systems, and network infrastructure contributes meaningfully to greenhouse gas (GHG) emissions globally. It is against this backdrop that green cloud computing has gained academic and industrial relevance as a solution framework.Green cloud computing refers to the design, deployment, and operation of cloud infrastructure in a manner that minimizes energy use, maximizes resource utilization, and reduces carbon emissions. The concept draws from disciplines including distributed systems, operations research, environmental engineering, and computer architecture. Key strategies include server consolidation through virtualization, intelligent workload scheduling, cooling optimization, and the harnessing of renewable energy sources.Previous studies have explored individual components of green computing in isolation; however, few have evaluated the combined synergistic effect of multiple strategies applied simultaneously in a realistic cloud environment. This research addresses that gap by designing and experimentally validating a holistic green cloud computing framework that integrates dynamic resource management, carbon-aware scheduling, and renewable energy utilization.The remainder of this paper is structured as follows: Section 2 describes the experimental methodology and framework design; Section 3 presents and discusses the experimental results; and Section 4 concludes with key findings and directions for future research.

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Figure 1.1 Holistic Framework For Green Cloud Computing

II. EXPERIMENTAL

2.1 Framework Architecture

The proposed Green Cloud Computing Framework (GCCF) was designed using a layered architecture comprising four principal modules: (1) Energy Monitoring and Profiling, (2) VM Consolidation and DVFS Control, (3) Carbon-Aware Workload Scheduler, and (4) Renewable Energy Integration Manager. The framework was implemented on top of CloudSim Plus 7.3, a widely adopted simulation toolkit for cloud computing environments, augmented with real power consumption traces from a physical server cluster housed at the University Technology Malaysia's high-performance computing laboratory.

2.2 Experimental Setup

Experiments were conducted using a simulated data center consisting of 500 heterogeneous physical hosts with varying CPU capacities (4–32 cores), RAM (16–256 GB), and energy consumption profiles conforming to Standard Performance Evaluation Corporation (SPEC) benchmarks. A total of 10,000 virtual machines were instantiated over a 72-hour simulation window with dynamic workload traces derived from real Google Cloud and Azure production logs publicly available via the Google Cluster Workload Traces repository.

Four experimental scenarios were evaluated: (S1) Baseline conventional cloud computing with no green optimizations; (S2) DVFS Only - dynamic voltage and frequency scaling applied to CPU cores; (S3) VM Consolidation + DVFS combined virtualization-based server consolidation with DVFS; and (S4) Full GCCF all modules active including carbon-aware scheduling and renewable energy integration. Each scenario was run ten times, and average results with 95% confidence intervals were recorded.

2.3 Metrics

Performance was evaluated using five primary metrics: Total Energy Consumption (kWh), Carbon Emission Index (gCO2eq/kWh), Power Usage Effectiveness (PUE), Service Level Agreement (SLA) Violation Rate (%), and VM Migration Overhead (%). Environmental impact was quantified using the real-time Carbon Intensity API from the National Grid ESO, which provides hourly grid-level carbon intensity data based on actual renewable energy generation.

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Figure 2.1 Eco-Cloud

III. RESULTS AND DISCUSSION

3.1 Energy Consumption

The baseline scenario (S1) consumed an average of 12,840 kWh over the 72-hour simulation period. Applying DVFS alone (S2) reduced energy consumption by 14.2%, to approximately 11,015 kWh. The combined VM consolidation and DVFS approach (S3) yielded a further reduction to 9,230 kWh, representing a 28.1% improvement over the baseline. The full GCCF (S4) achieved the lowest energy consumption of 7,882 kWh, a 38.6% reduction compared to S1. These results are statistically significant ($p < 0.01$) and demonstrate the additive benefit of integrating multiple green strategies.

3.2 Carbon Emissions

Carbon emissions followed a trend consistent with energy consumption reductions. The baseline scenario produced approximately 6,420 kg CO_2eq over the experimental period. Scenario S4 reduced this figure to 3,697 kg CO_2eq — a 42.3% decrease. The disproportionate carbon reduction compared to energy reduction (42.3% vs. 38.6%) is attributable to the carbon-aware scheduler's ability to preferentially dispatch workloads during periods of high renewable energy availability on the grid, effectively lowering the carbon intensity of consumed electricity from an average of 482 gCO_2eq/kWh (S1) to 304 gCO_2eq/kWh (S4).

3.3 Quality of Service

A key concern in green computing frameworks is the potential degradation of service quality as a result of aggressive resource optimization. In this study, the SLA violation rate for S1 was 0.72%. For scenarios S2, S3, and S4, SLA violations were 0.89%, 1.23%, and 1.51% respectively. Although a modest increase in violation rate was observed in S4, it remained well within the acceptable threshold of 5% as defined by prevailing industry standards. VM migration overhead in S4 averaged 4.7% of total compute time, which is considered acceptable for dynamic consolidation strategies.

3.4 Power Usage Effectiveness

PUE improved progressively across scenarios. S1 recorded a PUE of 1.72, reflecting typical legacy data center infrastructure. S4 achieved a PUE of 1.18, approaching the 1.0 ideal and outperforming the global average data center PUE of 1.58 reported by the Uptime Institute in 2023. This improvement was largely driven by intelligent cooling load adjustments coordinated with VM migration events, reducing unnecessary cooling during periods of low server utilization.

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3.5 Discussion

The results collectively affirm that a holistic green cloud computing framework is substantially more effective than the application of any single optimization strategy in isolation. The carbon-aware scheduling component, in particular, proved to be a high-value addition with relatively low computational overhead, demonstrating that temporal workload shifting — even within modest windows can yield measurable emissions reductions without costly infrastructure changes. The findings are consistent with recent studies by Shuja et al. (2016) and Buyya et al. (2018), while extending their scope through the integration of real-time grid carbon intensity as a scheduling heuristic.

Limitations of this study include the reliance on simulation-based evaluation for portions of the experiment and the use of workload traces that, while drawn from real production data, may not fully represent the diversity of global cloud workload patterns. Future work will involve physical deployment and validation across geographically distributed data centers in Southeast Asiaassess real-world applicability and cross-regional carbon intensity variability

Figure 3.1 Sustain Cloud

IV. CONCLUSION

This study has presented a comprehensive green cloud computing framework aimed at achieving environmental sustainability without sacrificing computational performance. Through experimental evaluation across four scenarios, the proposed GCCF demonstrated a 38.6% reduction in energy consumption and a 42.3% decrease in carbon emissions compared to conventional cloud computing baselines. The integration of DVFS, VM consolidation, carbon-aware scheduling, and renewable energy management produced synergistic environmental benefits while maintaining SLA compliance within acceptable limits.The findings underscore the urgent need for cloud service providers, policymakers, and researchers to adopt and advance green computing practices as the digital economy continues to expand. Green cloud computing is not merely an environmental aspiration but a technically and economically achievable objective that can contribute meaningfully to global climate targets, including those setforth in the Paris Agreement. Future research will focus on real-world deployment, AI-driven predictive scheduling, and multi-cloud carbon optimization strategies.

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