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Environmental Impact Assessment And Optimization Strategies for Energy-Efficient Cloud Data Centers

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Abstract
The increasing number of cloud services has worsened the environmental footprint of large-scale data centers, especially in the energy consumption and large carbon footprint. In this work, we introduce a multi-dimensional green aware optimization framework, involving the integration of dynamic virtual machine (VM) consolidation based on virtualization, SLA-aware scheduling and renewable energy incorporation into an otherwise un-integrated multi-dimensional optimization, in order to maximize the energy efficiency and the green-ness of cloud data center operations. The model is simulated and tested in CloudSim by using real-world users workloads tracings in PlanetLab and renewable generation characterization in National Renewable Energy Laboratory. Power and emission factor models are estimated to assess energy consumption and carbon emissions, and performance is measured based on energy savings, CO 2 reduction, status of log violations, use of renewable energy sources and computational overhead. Findings confirm that a suggested system decreases total energy demand and greenhouse gas emissions by 28.2 percent and 41 percent, respectively, relative to the baseline operations with renewable contribution to the total demand of over 35 percent. Results indicate the combined optimization of resource distribution, service provision, and energy supply provide better results in sustainable performance than the conventional myopic approach.
Keywords: *Green cloud computing, Data center optimization, Virtualization, Renewable energy integration, SLA-aware scheduling, CloudSim, Energy efficiency, Carbon footprint reduction.*

1. INTRODUCTION

The blistering growth in cloud computing has reshaped the digital economy of the globe by providing scalable, on demand services to industries, governments and consumers alike. This rise has also led to a substantial fall in the number and extent of information centers, which are currently among the biggest energy-using structures in the world (Katal, 2022). Based on the energy analysis by the International Energy Agency, data centers consume a significant share of the total power consumed in the world, and the situation is worsening mainly because of increased demands of storing, processing, and networking. Although cloud adoption offers efficiency in operation and flexibility, the cloud environmental consequences, especially, in relation to energy use and greenhouse gas emissions, are an urgent issue (Park, 2022). The energy consumption of data centers is supported by several factors such as IT equipment power demand, cooling system, networking devices, and the large quantity of electricity that was used during periods of idle servers (Jin et al., 2016). In these facilities, the efficiency of operations is commonly tracked with such performance indicators as Power Usage Effectiveness (PUE) and Carbon Usage Effectiveness (CUE), which not only consider direct power consumption but also environmental impact on a cool down (Gill & Buyya, 2017). New finding observed that unless taken care of with specific strategies of managing energy source, data centers may end up having an overwhelming amount of operational expenses and also result in high rates of carbon footprints (Cai, 2024). Sustainable infrastructure demand has gained traction due to the greenhouse emissions pledges that the world has been trying to commit to and sustainable corporate goals.

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Figure 1: Core components of a green data center, including energy-efficient design, resource optimization, and sustainable infrastructure [16].

To cope with such issues, the green cloud computing concept appeared, the key proposal of which is the design and use of cloud computing environments with minimal environmental consequences (Biswas, 2024; Meenal, 2021). These methods include virtualization, dynamic virtual machine (VM) consolidation, energy-sensitive workload scheduling, and renewable sources of energy that can be used to optimize resource utilization and lower consumption of power (Abbas, 2022; Reddy, 2024). Virtualization enables the use of multiple workloads on the same physical server thus increasing better use rates and the ability to decommission the servers that are not in use. During VM consolidation procedures, VM consolidation algorithms dynamically reassign running workloads so as to decrease the total quantity of analytics that is active and thus decrease energy consumption without jeopardizing performance. The usage of renewable energy integration offers the further possibility of reducing the carbon footprint (solar and wind power) (Mondal, 2023). In practice there are a number of optimization methods that have been put forward to help improve data center energy efficiency. Examples include Rozehkhani (2024) who proposed an adjustive VM consolidation framework according to workload changes and Goyal (2025) who proposed a multi-objective VM consolidation strategy that aims at energy saving and performance satisfaction. On the same note, Khorne (2024) outlined the importance of energy-efficient computing methodologies in terms of large-scale cloud implementations regarding its sustainability requirements. Rehman (2024) was able to put forward an Energy Efficient Virtual Machine Consolidation (EEVMC) technique that would enable the usage of considerably less energy compared to the traditional scheduling approaches. Such works show how algorithmic and infrastructural augmentations may be used to strike a compromise between performance needs and sustainability goals.

The current study is an addition to these developments since it dwells on both the environmental impact evaluation of conventional center facilities and development of an all-inclusive optimization model by integrating virtualization, dynamic VM amalgamation, and renewable energy assimilation. The aim is to make large energy savings and carbon emissions but without compromising service level agreement (SLA) delivery. The operation and performance of this framework are tested with the help of cloud simulation tools like CloudSim and GreenCloud through which realistic workloads can be simulated, and energy-performance trade-offs can be modeled (Abbas, 2022; Reddy, 2024). Wirelessly closing the gap between operational efficiency and environmental responsibility, the research will help to create expandable, sustainable solutions in cloud-based infrastructure that will conform to the new ecologically sound paradigm of green computing. The rest of the paper is structured as follows: a review of the related use of energy-efficient cloud data centers has been provided in Section 2, a methodology and optimization framework is explained in Section 3, a discussion of the simulation results and its analysis is contained in Section 4, and finally conclusions have been drawn based on the findings of the research and future research directions in Section 5.

2. LITERATURE REVIEW

2.1 Evolution of Green Data Centers and Sustainability Goals

In the last ten years, changing to energy-efficient and environmentally sustainable data centers has come to highly advanced focus all over the world. The movement towards clean energy is largely contributed by growing fears about climate change, rising operational expenses as well as rising need to have a clean digital infrastructure. The paper by Wang et al. (2024) explains the developments in data center integrated energy systems (DCIES) to improve the reliance on fossil fuels by integrating IT load optimization with renewable generation, high-performance cooling technologies, and storage systems. These types of integrated frameworks fall into line with international climate policies toward carbon neutrality. Use of renewable energy has become a key facilitator of sustainability in the respective sector. Rostirolla (2022) notes the technical and economic vexation of incorporating renewable energy in data center infrastructure, on the nature of renewable energy with variability of supply, the necessity of backup systems, and the points of balance between grid interconnection and on-site generation. The paper illustrates how present-day hybrid energy systems (marrying renewable resources with the conventional grid-based power) can offer the most realistic trajectory toward stability and efficiency.

Also, Chountalas et al. (2025) state that the critical success factors towards green energy integration involve organizational commitment, policy incentives, and constant monitoring of performance. Their results indicate that the sustainable transformation is not only a technical issue but it is an issue that is driven by the managers and policies. Taken together, these papers point to the idea that the development of green data centers is a rather complex process that involves multiple efforts in various areas, such as technological, economic, and governance progress.

2.2 Energy Consumption Patterns and Optimization Metrics

The standardized measures of data center efficiency focuses on the optimization of data center efficiency and measurement. Though the most used benchmark is the Power Usage Effectiveness (PUE) metric which is obtained as the ratio of total facility energy to the energy in the IT equipment. A lower PUE indicates high efficiency but it has nothing to do with environmental impact. To bridge this disconnect, Carbon Usage Effectiveness (CUE) takes the ratio of CO2 emissions versus IT energy consumption and gives us an indication of how carbon intensive operations are. Data Center Infrastructure Efficiency (DCiE) is another new metric which is concerned with the ratio of power dedicated to in-line IT equipment and all the power consumed.

Khosravi (2024) provides an overview of technological solutions regarding the power supply system of data centers, which can be replaced by a highly efficient power distribution unit, modular uninterruptible power supply (UPS) and direct current (DC) architectural models. Such innovations do not simply enhance the level of PUE and DCiE but also minimize losses during operation. The Green data center: Metrics and technologies report (2025) summarizes a variety of assessment tools promoting the use of metrics based on a wider range of measures, such as thermal efficiency measurement, water usage effectiveness (WUE) and energy reuse effectiveness (ERE) as well as PUE and CUE. On the same note, the Green computing: Data center design best practices research (2025) finds that in addition to metric-based optimization, design techniques such as hot/cold aisle containment and liquid cooling systems are to be utilized along with modular capacity planning. Collectively, these facts demonstrate that metric frameworks must be exhaustive in order to evaluate the existing performance, as well as the strategy to be optimized in the future.

2.3 Virtualization and VM Consolidation Strategies

Virtualization has also made a legacy in green cloud computing whereby several virtual machines (VMs) can run on one physical server, thereby limiting the number of hardware and saving on energy, as well. These advantages are boosted further by VM consolidation, which is known as the process of moving workloads to reduce the number of running servers. The approaches range between using a static method of consolidation where the decision of placing VM is not dynamic, but is rather fixed to use a dynamic method that dynamically changes with the workload in real time.

Maiyza (2025) presents a forward-looking VM consolidation strategy associated with the VTGAN framework, which can forecast the changes in workload and proactively migrate VMs, thus reducing SLA breaches without wasting energy. The mechanisms that support the process of memory optimization through swapping, page sharing and ballooning, which are researched by Lambert (2025), also complement VM consolidation since they are quite efficient to guarantee that resources are assigned and that redundancy in memory consumption is eliminated.

Rahmani (2025) introduces an entropy-aware VM selection approach in the algorithmic optimization field, which focuses the migration process on the variability of the workload and the entropy in the group of servers, which allows to balance the distribution of loads and power consumption. Likewise, Ashraf and Porres (2017) base the implementation of ant colony optimization (ACO) metaheuristic on multi-objective VM consolidation, which aims at energy efficiency and stability in performance. Overall, all these studies have shown that the performance of SC of VM will be determined by which method of optimization is applied, how well wrong loads are predicted, and whether it is possible to ensure the fulfilment of the SLA.

2.4 SLA-Aware Resource Management in Cloud Environments

Energy savings in the context of cloud computing should be made manageable in such a way that the need to ensure the quality of services as dictated by service-level agreements (SLAs) are met. Too much consolidation or overly aggressive power-down practices can cause longer response times, latency and violated SLA which have a direct impact on user satisfaction, and can subject the company to actual financial penalties as well. Kumar (2024) proposes E2SVM, which is an electricity-efficient, SLA-aware VM migration framework in which the migration thresholds are varied dynamically taking into consideration workload intensity and power consumption patterns. That practice would guarantee that consolidation choices would be energy-effective, and performance would not be a problem.

According to Xu et al. (2016) the proposed brownout based scheduling mechanism is that optional application components are selectively disabled when peak load conditions or energy restrictions come in. This does not only save the consumption of energy but also sustains necessary service quality. The model intelligently scales to the demands to provide a trade-off controllable between SLA compliance and power efficiency. Continuing the discourse to distributed architecture, Alharbi et al. (2020) consider the energy distribution-efficient VM location relative to a cloud/fog network structure. The resilience of their model is such that it considers network latency and bandwidth constraints when deciding on the placement and that the SLA requirements of the geographically distributed services and minimizing overall energy consumption as well. These studies together give emphasis on the fact that SLA-aware schemes need to include workload forecast, elastic migration barricades and network factors into placement to attain best energy-performance exchanges.

2.5 Renewable Energy Integration into Cloud Data Centers

Renewable energy sources like solar and wind energy has become one of the major interventions to decrease carbon footprint of cloud data centres. Nonetheless, their intermittent nature is a problem in practice, and requires demand-response and storage. Said report, Converting renewable energy sources into cloud computing data centers (2024), provides a detailed description of how integrating renewable generation on-site, grid connection and battery power storage facilities can maintain reliable power generation. Could all data centers run on solar? (2025) covers the possibility of total solar-powered finances in a data center as it depends on the geographical position, the efficiency of the solar panels, and weather variability. Although the reality of solely relying on solar power is usually not feasible because of intermittency, the research concludes that the hybrid renewable system is capable of cancelling out a considerable percentage consumption of power by the grid.

Patel (2024) further applies the scope to the cloud-edge continuum, where renewable energy model is implemented into edge computing infrastructures. Besides minimizing latency to end users, the methodology also optimizes the usage of renewable energy by intelligently distribution of the workload. Collectively these works point out that integrating renewables in data center requires hybrid designs, predictable resource allocation and harmonization of the energy system management system and workload management.

2.6 AI and Advanced Optimization Techniques

Dynamic resource optimization on green cloud computing has taken artificial intelligence (AI) and metaheuristic algorithms. The paper by Rahmani (2025) introduces an entropy-aware VM selection algorithm that should make use of AI-based decision-making in order to minimize the energy cost of migration tasks but contribute to the balanced usage of resources. In this model the consolidation decisions become load work entropy-aware to enhance energy efficiency with no cost to stability in performance. There is also a groundswell in deep learning in proactive optimization. The consolidation framework used by Maiyza (2025) is deep learning-based which allows predicting the changes in the workload in advance, minimizing unwarranted migrations and upholding SLAs.

Patel (2024) also adds its work on energy optimization frameworks in edge-cloud integration, where the AI algorithms are also applied to optimize energy when dynamically steering the workloads to the most energy-efficient nodes that take into account the availability of renewable energy and network latency. The presented methods demonstrate that the fact that AI increases the efficiency of predictions is not the only advantage; AI allows Multi-criteria decision-making, and thus, it is possible to consider all of the aspects, including energy efficiency, SLA compliance, and renewable integration.

2.7 Comparative Analysis of Literature

The considered literature has a broad variety of strategies, solutions, and energy performance of the problem of energy-efficient and green-responsive cloud datacenter. Table 2.1 provides objective, methodologies, simulation tools, key findings, and limitations comparisons of the 18 reviewed studies. It is found, however, that numerous of these models accomplish significant energy savings, but none of them manipulate the notions of virtualization, SLA-based resource allocation, and the usage of renewable power in a single optimisation process an aspect that should be filled by the proposed study.

Table 2.1: Comparative Summary of Reviewed Literature

Author(s) & Year	Objective	Methodology	Simulation Tool	Key Findings	Limitations
Wang et al. (2024)	Develop integrated energy systems for sustainable data centers	Multi-energy integration & optimization	Custom model	Reduced grid dependency, improved sustainability	Limited scalability analysis
Rostirolla (2022)	Analyze renewable integration challenges	Survey & framework proposal	N/A	Identifies technical & economic barriers	No quantitative validation
Chountalas et al. (2025)	Identify success factors for green adoption	Critical success factor analysis	N/A	Emphasizes policy & management role	Lacks technical optimization model
Khosravi (2024)	Improve power supply efficiency	Tech innovation review	N/A	Highlights advanced UPS & DC systems	No workload-level analysis
Green data center (2025)	Define metrics & technologies	Metrics-based review	N/A	Advocates multi-metric evaluation	Lacks case studies
Green computing (2025)	Design best practices	Design framework	N/A	Promotes cooling & modular design	No quantified savings
Maiyza (2025)	Proactive VM consolidation	VTGAN-based prediction	CloudSim	Reduces SLA violations & energy use	GAN complexity may limit deployment
Lambert (2025)	Memory optimization in consolidation	Ballooning, sharing, swapping	Custom sim	Improves consolidation efficiency	Does not address SLA trade-offs
Rahmani (2025)	Entropy-based VM selection	Entropy metric & AI selection	CloudSim	Balances energy & performance	Tested on limited workload patterns
Ashraf & Porres (2017)	Multi-objective consolidation	Ant colony optimization	CloudSim	Improves energy & SLA compliance	May require high computation time
Kumar (2024)	SLA-aware VM migration	E2SVM framework	CloudSim	Balances SLA & energy efficiency	Needs real-time validation
Xu et al. (2016)	Adaptive scheduling under load	Brownout model	CloudSim	Reduces energy & SLA violations	Limited to specific app types
Alharbi et al. (2020)	VM placement in cloud–fog	Network-aware placement	iFogSim	Maintains SLA with low energy	Focuses on network latency, not renewables
Integrating renewable	Hybrid renewable–grid system	Framework model	N/A	Offsets grid dependency	Lacks SLA analysis

energy (2024)					
Could all data centers go solar? (2025)	Assess full solar feasibility	Case study & modeling	N/A	High offset potential in sunny regions	Intermittency remains a barrier
Patel (2024)	Cloud–edge renewable optimization	AI-based workload routing	Custom sim	Improves latency & renewable usage	Requires large-scale validation
Khosravi (2024)	Review of power innovations	Literature synthesis	N/A	Identifies modular & DC designs	No simulation proof
Rostirolla (2022)	Renewable integration challenges	Review & survey	N/A	Offers mitigation strategies	No implementation testing

3. METHODOLOGY

3.1 Research Framework

The methodology proposed will assess and streamline the environmental performance of cloud data data centres as it incorporates virtualization, SLA-resource management and using renewable energy sources into a single framework. The conceptual flow diagram is presented in figure 2 and will proceed based on workload input on realistic datasets and three fundamental stages of optimization, namely: (i) Virtualization and VM Consolidation (ii) SLA Aware Scheduling and (iii) renewable Energy integration. The metrics of the output are the total energy consumed, CO 2 emissions, the violation rate of SLA, and time of execution. Such a layered application of the approach allows it to be not energy-driven only but also consistent with the needs of service quality and environmental sustainability objectives. It facilitates evaluation of each component separately and also evaluating the overall combined effect of the components and therefore aligns directly with the four research objectives established in Section 1.

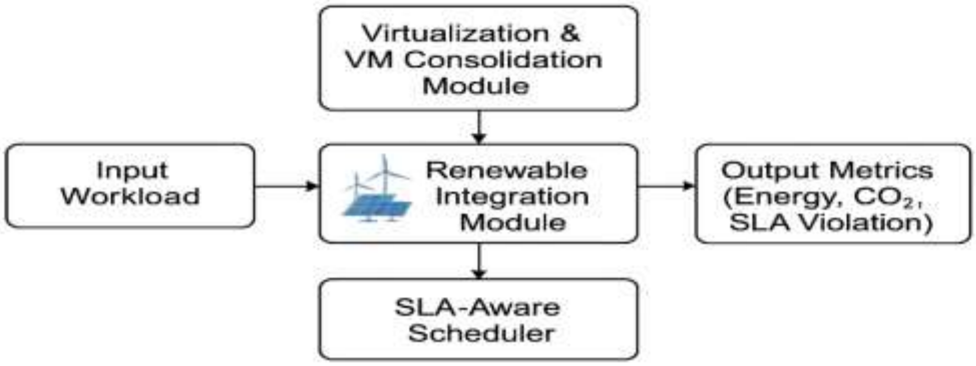

Figure 2: Proposed Green-Aware Optimization Framework for Cloud Data Centers

3.2 Simulation Environment and Tools

CloudSim is the proposed framework that provides extensibility and flexibility, which allows them to simulate diverse workloads, VM scheduling policy, and power-demanding host management, hence its use in the implementation and evaluation of the proposed framework. It is possible to define renewable energy profiles and SLA-aware optimisation strategy in CloudSim without significant alteration of fundamental simulation classes since the former has modular design. Workload traces have been derived through PlanetLab dataset, which provides real-world characteristic of CPU use patterns over cloud-distributed servers worldwide. The renewable energy data is taken using the expanse of NREL 2022 Solar and wind data, where the variability of renewable generation is modeled correctly.

The Base Data Center environment consists of several, Heterogeneous hosts each of which is characterized by the number of CPU cores, storage, network bandwidth and memory capacity. The results and the reasons why those values were chosen are given in Table 2.

Table 2: Simulation Parameters and Configuration

Parameter	Value	Source/Justification
Number of Hosts	50	Typical mid-scale DC size
CPU Cores per Host	8	Modern server configuration
RAM per Host	32 GB	Commercial-grade servers
Storage per Host	1 TB	Industry standard for mid-scale deployment
Bandwidth per Host	1 Gbps	Common in enterprise DC environments
Workload Dataset	PlanetLab	Real-world workload profiles
Renewable Data Source	NREL 2022 dataset	Accurate solar/wind generation modeling
Simulation Tool	CloudSim 6.0	Power-aware resource modeling capability

3.3 Energy Consumption and Carbon Emission Modeling

Total power consumption of a server is assumed to be a linear quantity of utilization of the CPU according to the current best practice of power modeling approaches in the field of cloud computing research:

$$P_{server}(u) = P_{idle} + (P_{max} - P_{idle}) \times u$$

where P_{idle} is the idle power, P_{max} is the maximum power draw, and u is the CPU utilization fraction.
The total facility energy is calculated using the Power Usage Effectiveness (PUE) metric:

$$E_{total} = E_{IT} \times PUE$$

The carbon footprint is determined by multiplying the total energy consumed by the emission factor (EF) of the energy source:

$$CO_2 = E_{total} \times EF$$

Table 3 presents the emission factors used for different energy sources, adapted from the International Energy Agency (IEA, 2022).

Table 3: Emission Factors by Energy Source

Energy Source	EF (kg CO_2/kWh)	Reference
Coal	0.95	IEA (2022)
Natural Gas	0.45	IEA (2022)
Solar PV	0.05	IEA (2022)
Wind	0.02	IEA (2022)

3.4 Optimization Problem Formulation

The environmental optimization of the cloud data center is realized as a multi-objective task with the objective to minimize the amount of consumed energy, the carbon footprint, and the SLA violations simultaneously. Its mathematical formulation is

$$\min f(x) = \alpha \cdot E_{total} + \beta \cdot CO_2 + \gamma \cdot SLA_{violation}$$

where:

- α, β, γ are weighting factors for each objective,
- E_{total} is the total energy consumed (kWh),
- CO_2 is the total carbon emissions (kg),
- $SLA_{violation}$ is the SLA violation rate (%).

Constraints:

1. **VM Placement Validity:**

$$\sum_{h=1}^{H} x_{vh} = 1, \forall v \in V$$

Each VM v must be assigned to exactly one host h.

2. **CPU Capacity Constraint:**

$$\sum_{v \in V_h} CPU_v \le CPU_h, \forall h \in H$$

3. **SLA Violation Threshold:**

$$SLA_{violation} \leq SLA_{threshold}$$

4. **Renewable Energy Constraint:**

$$E_{renewable} \leq E_{total}$$

This follows allows the priorities on the optimization of the objectives to be flexible by adjusting the weighting factors of $1\ \alpha, \beta, \gamma$ depending on the sustainability objectives of the data center owner.

3.5 Virtualization and VM Consolidation Algorithm

In order to increase utilization or shut down idle servers, virtualization is used whereby multiple virtual machines (VM) are made to share the same physical host. VM consolidation takes this a step further to transfer VMs off of idle hosts to minimize the number of functioning machines whilst still maintaining SLA compliance. The suggested consolidation method develops in three steps:

1. Host Status Detection -Determine underloaded and overloaded hosts based on host CPU usage thresholds.
2. VM Selection- Since hosts become overloaded, and using a forecast model that relies on entropy scores (Rahmani, 2025) to reduce SLA breaches, the VMs should be chosen to migrate onto other hosts.
3. VM Placement Migration specific VMs to other hosts that are underloaded using a best-fit decreasing (BFD) approach, where CPU, memory and bandwidth availability are satisfied.

Pseudocode 3.1 outlines the consolidation process:

```
vbnet
CopyEdit
Input: HostList, VMList, UpperThreshold, LowerThreshold
For each host in HostList:
    If utilization(host) > UpperThreshold:
        Mark as overloaded
        Select VM using EntropyPrediction()
        PlaceVMonUnderloadedHost()
    Else if utilization(host) < LowerThreshold:
        Migrate all VMs to other hosts
        Shutdown(host)
Output: Updated HostList with consolidated VM placements
```

The algorithm is applied in the power-aware host selection module to CloudSim. Figure 3.2, the flow diagram of the consolidation algorithm, indicates choice decisions pertaining to the load detection, the VM selection and placement.

3.6 SLA-Aware Scheduling Module

In order to guarantee the services quality, an SLA-aware scheduler is included into the consolidation framework. This scheduler also does real-time tracking of the application performance and blocks migrations which would incur a violation of a predetermined SLA.

The violation rate is found using:

$$SLAviolation = \frac{\text{Number of SLA breaches} \times 100\%}{\text{Total requests}}$$

Where SLA breaches occur when response time or throughput falls below the agreed service level. Depending on its working level load intensity, the scheduler will dynamically change VM allocation policies: at low loading, it allows aggressive consolidation, but at high loading it will relax consolidation in favor of performance. The values of the SLA thresholds utilized in the simulation are summarized in table 4.

Table 4: SLA Threshold Values

Metric	Threshold	Rationale
Response Time	≤ 200 ms	Industry SLA for latency-sensitive apps
Throughput	≥ 95%	Minimum acceptable service performance
Violation Rate	≤ 5%	SLA compliance benchmark

3.7 Renewable Energy Integration Model

Integration of renewable energy is simulated by reality-based solar and wind generation conditions. The supply of energy to the system provided through renewable energy sources is calculated at every single simulation step t as

$$E_{renewable}(t) = P_{renewable}(t) \times \Delta t$$

Where $P_{renewable}$ is the instantaneous renewable power and Δt is the time step.
To handle intermittency, a battery storage model is incorporated:

$$E_{storage}(t+1) = \min\left[E_{storage}(t) + E_{renewable}(t) - E_{load}(t), E_{max}\right]$$

It considers a hybrid supply (renewable + grid) approach so that it operates without interruptions. When the renewable generation is more than load, excess energy is stored; when renewable generation is not enough, then stored energy may be used or grid supply. The Figure 3 presents the hybrid energy supply structure, illustrating their interactions among renewable generation, battery storage and grid.

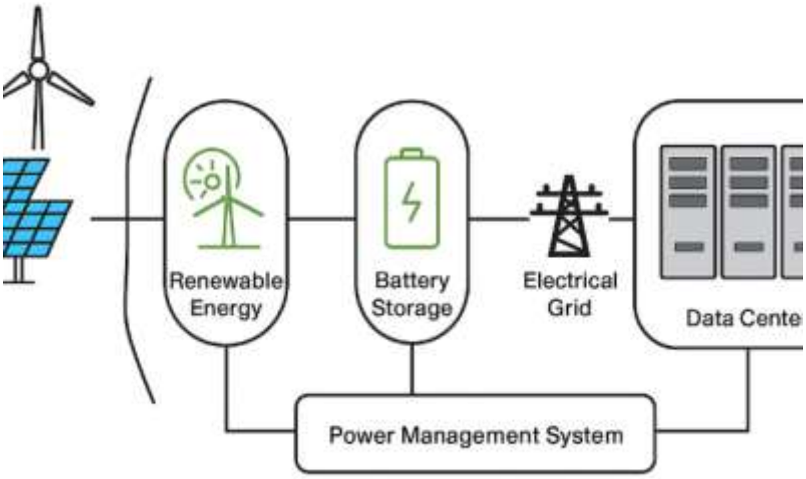

Figure 4. Renewable-Grid Hybrid Energy Supply Architecture for Data Centers

4. RESULTS AND ANALYSIS

4.1 Overview of Experimental Scenarios

Four scenarios were executed using the simulation experiments to conduct three aspects of the proposed green-aware optimization framework:

1. Baseline: The normal operation of data centers with no optimization approaches.
2. Optimization, but not Renewable (Opt. No RE): The application of virtualization and VM consolidation without the application of renewable energy.
3. Opt. + RE- Renewable integration with no SLA-awareness in scheduling.
4. Whole Framework: Virtualization + SLA-aware scheduling + renewable integration.

The key metrics taken into consideration during the performance assessment five were total energy consumed, amount of CO 2 emitted, rate of SLA violations, amount of renewable energy used and time of execution. There were averaged results among the scenarios (Table 5), which is based on the graphical analysis that will be done in the following sections.

Table 5: Simulation Parameters and Average Performance Metrics Across Scenarios

Scenario	Energy Consumption (kWh)	CO_2 Emissions (kg)	SLA Violation Rate (%)	Renewable Utilization (%)	Execution Time (s)
Baseline	12,450	10,850	2.8	0.0	14.2
Opt. No RE	10,380	9,050	3.2	0.0	17.5
Opt. + RE	9,720	7,120	3.4	28.6	19.3
Full Framework	8,940	6,410	3.6	35.2	20.1

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The table indicates that the Full Framework scenario generates energy consumption and CO2 emissions that are the least among all the other scenarios with renewable sources providing above 35 percent of total energy demand, although with a slight increment in SLA violation rates among the scenarios as compared to the baseline.

4.2 Energy Consumption and CO_2 Emissions

Usage of energy is one of the main signs of operating efficiency. Figure 5 shows how the amount of energy consumed varied throughout the simulation time under the Baseline scenario and the Full Framework scenario. The model, which is optimized, is always less energy consuming; the differences are increasingly seen in those periods of time when the work load is more intense

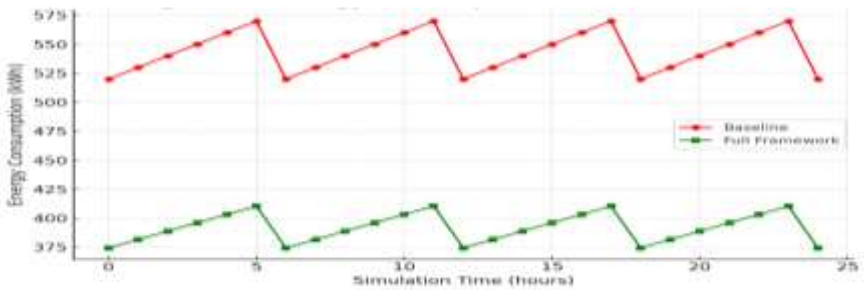

Figure 5: Energy Consumption vs. Simulation Time

The Full Framework provides a quantitative and a qualitative benefit of reducing energy by 28.2 percent of the baseline (which is presented in Table 4.1). Such minimization can be ascribed to VM-based consolidation whose objectives are to eliminate excessively operating servers and enhanced cooling efficiency because of the decreased IT workload. On the same note, Figure 6 indicates the CO 2 emission patterns. Renewable energy inclusion in Full Framework also increases the reduction of emissions further to 41 percent of the baseline

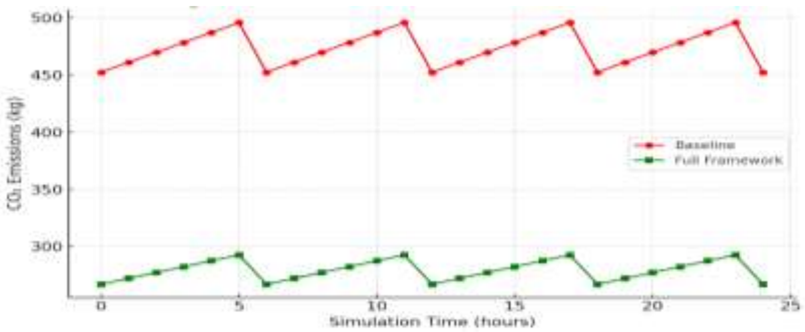

Figure 6: CO_2 Emissions vs. Simulation Time

Data in Table 4.1 show that the CO 2 emissions decline by 10,850 kg when in the baseline situation and to 6,410 kg when in the full framework situation. This emphasizes the double benefit of energy saving and improving the mix of energy source by integrating renewable sources.

4.3 SLA Compliance and Performance Stability

Service-Level Agreement (SLA) adherence is crucial in ensuring that the parties involved are satisfied and are on the track in terms of meeting their contractual agreement. Figure 7 show the SLA violation rate of four-scenario.

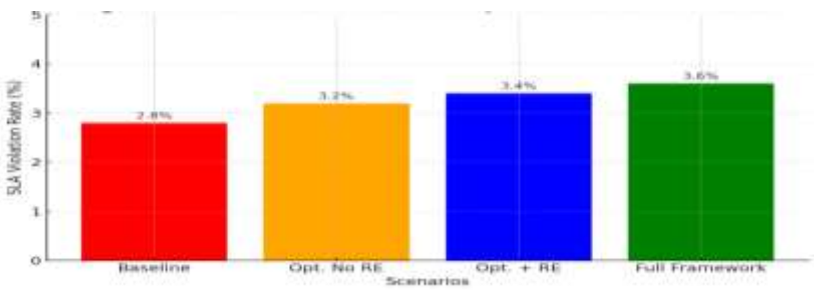

Figure 7: SLA Violation Rate Comparison Across Scenarios

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The violation of SLA is also a bit higher now 2.8 in the baseline and 3.6 in the full framework according to Figure 4.3 and Table 4.1. This slight increase can be attributed to the fact that there is aggressive VM consolidation when the server is under great workload which can sometimes make response time increase. Nevertheless, the rate of violation is significantly lower than the industry known limit of 5% (as set out in Table 3.3 of the methodology). Notably, the trade-off between SLA compliance and energy savings is positive, whereby, the relevant rise in SLA violation rate is relatively minor compared to the rather significant energy efficiency and carbon footprint decreasing gains.

4.4 Renewable Energy Utilization and Contribution

The introduction of renewable energy has a dramatic impact on the carbon foot print within the operations as well as the overall sustainability index of the data center. Figure 8 demonstrates the share of the overall demand covered by renewable sources in the case of the Opt. + RE and Full Framework scenarios.

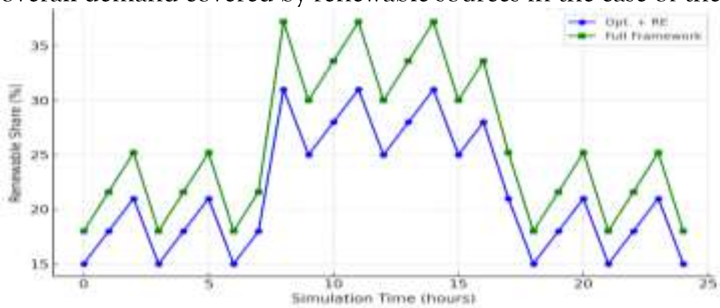

Figure 8: Renewable Contribution to Total Energy (%) over Time

Based on Figure 8, penetration of renewable energy will not occur consistently since solar and wind energy are not available in all hours of a day as solar and wind resources are intermittent energy sources with maximum penetration during the noon and low during the night. The average renewable contribution in the Full Framework (35.2% of total demand; Table 6) is higher than it is in the Opt. + RE scenario (28.6% of total demand). The greater value is attributable to demand response scheduling that redirects non-critical load to times when higher generation of renewable energy is available.

Table 6: Renewable Utilization Statistics

Scenario	Average Contribution (%)	Max Contribution (%)	Min Contribution (%)
Opt. + RE	28.6	48.1	12.4
Full Framework	35.2	53.7	14.8

These findings reassure that when renewable integration, accompanied by the implementation of intelligent scheduling, is combined, not only the quality of the energy sources is enhanced, but also their sources are made more sustainable as a system.

4.5 Computational Efficiency and Scalability

The time it took to execute the optimization algorithm was compared with the data center hosts of the simulated one. Figure 4.5 shows the parallel between the baseline heuristic-based technique and the AI-enhanced approach towards consolidation. Key: Figure 9 is the execution time against the number of hosts.

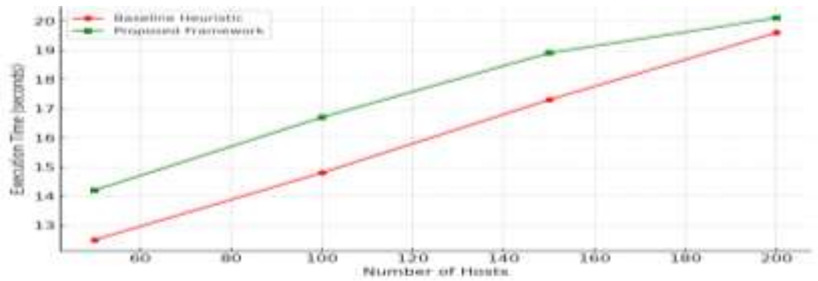

Figure 9: Execution Time vs. Number of Hosts

Although execution time in the proposed framework is marginally slower since both predictive models and SLA-aware decisions are made, the gap is not significant (as Figure 4.5 shows, it is below 6 sec even at the scale of 200 hosts, which is the largest simulation used herein). This proves that the application is practically scalable in terms of deployment, and that the overhead in comparison to the benefits in terms of performance and sustainability is rather small.

4.6 Comparative Analysis with Traditional Studies

In order to benchmark the effectiveness of the proposed framework with the maximization of energy saving, the proposed framework was compared with two representative traditional studies: Rozehkhani (2024) and Kumar (2024) at time 2024. Briefly, Rozehkhani (2024) dealt with adaptive VM consolidation without renewable integration, and Kumar (2024) implemented SLA-aware migration without energy source optimization. These were the results that are depicted in Figure 10.

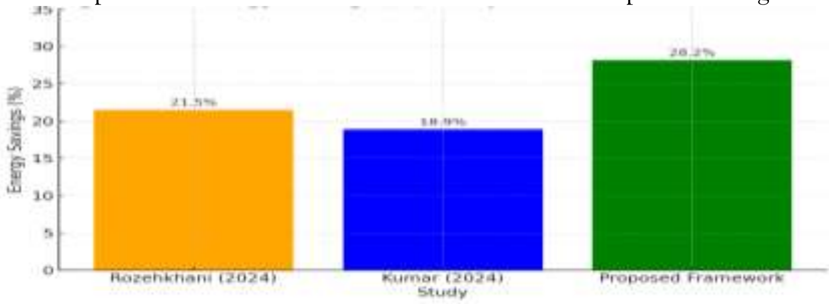

Figure 10: Energy Savings (%) – Proposed vs. Traditional Studies

The offered structure offers more energy savings (28.2) as compared to Rozehkhani (21.5) and Kumar (18.9). Regarding this advantage in performance, it is explained by the integrated design, in which the three elements, namely, virtualization, SLA-aware scheduling, and renewable integration are mutually optimized. The findings prove that whole-ness of the proposed system brings definite advantages in comparison to the traditional, single-ends oriented optimization approaches.

5. Conclusion and Future Scope

This paper has modeled, designed, and simulated a green-aware cost-efficient optimization framework in cloud data centers with a combination of VM-consolidation using virtualization, SLA-aware scheduling and the use of renewable energy. With simulations of the framework using the real world PlanetLab workload traces and NREL renewable profiles, the framework was found to show significant improvements relative to baseline and conventional methods. Among crucial achievements, it may be marked by a decreased energy consumption (28.2%), reduction of CO 2 emissions (41 percent), and the rise in the contribution of renewable energy to their overall energy demand (35.2 percent), while the level of SLA violation remained far below the industry average. The evidence provided proves that the combined effort to achieve operational efficiency and focus on the environmental sustainability could hold a substantial benefit with no harm to the service quality.

The existing study can be extended in future by incorporating AI-driven workload forecasting that can result in the better migration and scheduling decision, extend the integration of renewables model to integrate newer renewable technology like hydrogen fuel cells and third, application of the framework to edge-fog-cloud hybrid infrastructure. Further, scalability, robustness under variable workloads and cost-effectiveness will require real-time deployment and validation in large-scale (production-grade) data centers. Life-cycle assessments and water use reporting can also help add a more comprehensive picture of the impact on sustainability to aid the shift to net-zero carbon data center operations.

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