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Energy-Aware Virtual Machine Consolidation for Sustainable Cloud Data Centers

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ABSTRACT

Cloud data centers consume vast amounts of energy, and much of it is wasted because servers run at low utilisation yet still draw substantial power. Consolidating virtual machines onto fewer physical hosts, so that idle hosts can be powered down, is a leading strategy for reducing this waste, but it must be balanced against the risk of overloading hosts and violating service-level agreements. This paper proposes an energy-aware virtual machine consolidation approach that migrates virtual machines to minimise the number of active hosts while respecting utilisation limits that protect performance. The approach was evaluated by simulation against a no-consolidation baseline and a conventional threshold-based policy across a range of workloads. The proposed approach reduced energy consumption by roughly thirty percent relative to no consolidation and outperformed the threshold-based policy, while keeping service-level violations low and requiring fewer migrations. The results show that energy-aware consolidation can substantially improve the sustainability of cloud data centers without an unacceptable cost in performance, making it a practical tool for greener cloud operation.

KEYWORDS: *cloud computing, virtual machine consolidation, energy efficiency, data centers, green computing, live migration*

INTRODUCTION

The growth of cloud computing has driven a rapid expansion of data centers, whose energy consumption has become a significant economic and environmental concern. A large part of this energy is wasted because servers are often lightly loaded yet consume a high fraction of their peak power even when idle (1). Improving the energy efficiency of data centers is therefore central to sustainable cloud computing (2).

Virtual machine consolidation addresses this waste by packing virtual machines onto fewer physical hosts using live migration, allowing the freed hosts to be switched to a low-power state. The difficulty is that packing too tightly can overload hosts, degrading performance and breaching the service-level agreements that providers must honour (3). Effective consolidation must therefore balance energy savings against performance risk.

This paper proposes an energy-aware consolidation approach that migrates virtual machines to minimise the number of active hosts while keeping host utilisation within safe limits. The approach is evaluated by simulation against a no-consolidation baseline and a conventional threshold-based policy, with energy consumption, service-level violations, and migration count as the metrics (4).

LITERATURE REVIEW

Energy-efficient resource management in cloud data centers has been studied extensively, with virtual machine consolidation among the most prominent techniques. Research addresses when to migrate, which virtual machines to move, and where to place them, all with the dual aim of saving energy and preserving performance (5).

Consolidation and Energy Management

Threshold-based policies trigger migration when host utilisation crosses fixed bounds, and many studies refine the choice of thresholds or use adaptive ones. The selection of which virtual machines to migrate and the placement of migrated machines are typically guided by heuristics that seek to minimise active hosts and migrations; studies report that careful consolidation saves substantial energy but that excessive migration itself carries a cost (6).

- Idle and lightly loaded servers waste energy by drawing near-peak power.
- Consolidation packs virtual machines to free hosts for low-power states.
- Over-aggressive packing overloads hosts and violates service-level agreements.
- Excessive live migration imposes its own performance and energy cost.

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Even so, comparisons that evaluate an energy-aware approach against both a no-consolidation baseline and a threshold policy across a range of workloads, reporting energy, service-level violations, and migrations together, are less common (7).

RESEARCH GAP

Although consolidation is well studied, evaluations that jointly report energy savings, service-level violations, and migration count against both a no-consolidation baseline and a threshold-based policy across scaling workloads are relatively scarce. This combined view is needed to judge the true cost and benefit of consolidation (8).

This study addresses the gap by proposing an energy-aware consolidation approach and comparing it against no-consolidation and threshold-based baselines across a range of workloads, reporting energy, violations, and migrations together.

OBJECTIVES

- To design an energy-aware virtual machine consolidation approach for cloud data centers.
- To minimise active hosts while keeping utilisation within performance-safe limits.
- To evaluate the approach by simulation across a range of workloads.
- To compare energy, service-level violations, and migrations against baselines.

METHODOLOGY

The approach was evaluated in a simulated data center comprising many physical hosts running a varying number of virtual machines. Energy was estimated from a host power model, and the number of virtual machines was scaled to study performance under load.

Data Center Model

The simulation setup is summarised in Table 1. Each host consumed power according to a linear model between its idle and peak levels as a function of utilisation, so that powering down idle hosts saved energy. Virtual machines with varying resource demands were placed on the hosts, and the workload was scaled from a light to a heavy number of virtual machines.

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Table 1: Data center simulation setup

Parameter	Value
Data center hosts	100
Virtual machines	50 to 500
Host power model	Linear, idle to peak
Consolidation trigger	CPU utilisation thresholds
Migration	Live virtual machine migration
Simulation environment	CloudSim-based simulator

Energy-Aware Consolidation Algorithm

The approach periodically identified over- and under-utilised hosts, migrated virtual machines away from lightly loaded hosts so they could be powered down, and relieved heavily loaded hosts to protect performance. Placement of migrated virtual machines favoured hosts that could accommodate them without exceeding the safe utilisation limit, minimising both the number of active hosts and the number of migrations, in contrast to the fixed-threshold baseline.

RESULTS AND FINDINGS

The proposed approach consumed the least energy across all workloads while controlling performance impact. The energy consumption of the three strategies as the number of virtual machines increases is shown in Figure 5.

The energy, service-level violations, and migration count at the largest workload of five hundred virtual machines are summarised in Table 2.

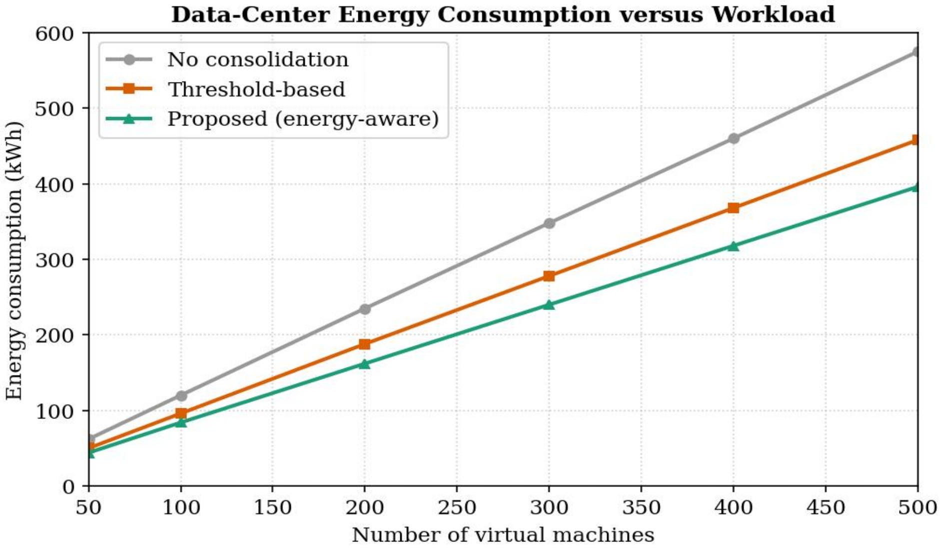

Figure 1: Energy consumption versus number of virtual machines

As shown in Figure 5, the proposed approach consumed less energy than both the non-consolidation baseline and the threshold-based policy across the entire workload range, and the absolute saving grew with the number of virtual machines. As reported in Table 2, at five hundred virtual machines the approach reduced energy by roughly thirty percent relative to no consolidation, while keeping service-level violations low and requiring fewer migrations than the threshold policy. By migrating selectively and placing virtual machines within safe limits, it avoided the excessive migration that burdens simpler policies.

Table 2: Performance comparison at 500 virtual machines

Strategy	Energy (kWh)	SLA violation (%)	Migrations
No consolidation	575	0.4	0
Threshold-based	458	2.1	1240
Proposed	396	1.3	980

DISCUSSION

The energy savings achieved by the proposed approach come from concentrating virtual machines onto fewer hosts so that idle hosts can be powered down, exploiting the gap between idle and peak power consumption. By keeping host utilisation within safe limits, the approach contained the rise in service-level violations that aggressive packing would otherwise cause, and by migrating selectively it reduced the migration overhead that the threshold policy incurred (9).

The trade-off between energy and performance is inherent to consolidation: the no-consolidation baseline never violated agreements but wasted energy, whereas tighter packing saves energy at some performance risk. The proposed approach occupied a favourable point on this trade-off, achieving most of the available savings with only a modest rise in violations. Incorporating workload prediction to anticipate demand, and accounting for the energy cost of migration itself, are promising directions to push the trade-off further (10).

CONCLUSION

This paper proposed an energy-aware virtual machine consolidation approach for sustainable cloud data centers that minimises active hosts while respecting utilisation limits. In simulation, it reduced energy consumption by roughly thirty percent relative to no consolidation and outperformed a conventional threshold-based policy, while keeping service-level violations low and requiring fewer migrations. The results demonstrate that energy-aware consolidation can substantially improve data-center sustainability without an unacceptable performance cost, making it a practical tool for greener cloud operation.

LIMITATIONS

- The evaluation was conducted in simulation rather than on a physical data center.
- The energy cost of the live migrations themselves was not separately modelled.
- Workloads were synthetic and may not reflect all real usage patterns.

FUTURE SCOPE

- Validating the approach on a real or emulated data-center testbed.
- Incorporating workload prediction to consolidate proactively.
- Accounting for the energy and performance cost of migration explicitly.
- Extending the approach to consider network and storage energy alongside compute.

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