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Green computing for improving the sustainability of data centers: Optimized VM allocation with decentralized peer-to-peer nodes

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Abstract

The amplified concern in cloud and fog computing calls for a stimulus in the demands on the strategies that allocate virtual machines to amplify energy efficiency to alleviate high energy utilization and the environmental impacts that arise from it. This research presents a green computing approach that employs decentralized, peer-to-peer fog nodes in dynamic VM allocation within the fog and cloud ecosystems. Unlike traditional central allocation schemes, the proposed model allows for autonomous management, distribution, and sharing of workload at the level of a fog node, depending upon local capacity, real-time demands, and determined energy efficiency. P2P collaboration at geographically distributed fog nodes evokes optimal resource usage, minimal latency, energy costs, and carbon footprint. An energy-aware allocation algorithm is developed that integrates real-time workload prediction, power consumption metrics, and renewable energy availability across the boundaries of fog and cloud environments to enhance sustainability. Experimental results demonstrate that the decentralized P2P framework not only diminishes power utilization but also improves the response times for services and minimizes the overall environmental footprint of fog/cloud operations.

Keywords: Decentralized fog computing, energy efficiency, green computing, resource optimization, sustainable computing, virtual machine allocation.

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1. Introduction

Cloud and fog computing have evolved at such an incredible speed over time, leading to magnificent developments in the processing, storage, and management of data and other resources, to be widely applied in all sectors. However, this virtualized infrastructure does come with a great environmental cost, as it consumes a lot of energy and releases high levels of carbon emissions. VM allocation is an integral part of cloud and fog ecosystems. So far, this has been mainly done by centralized methods that often overlook the dynamic nature of workloads as well as optimization opportunities in terms of energy use. As users advance in awareness towards sustainability and energy, there is a very pressing need for environmentalists to address green computing solutions. The main intent will not only be to enhance computational performance but will also try to embrace ecological correctness.

Decentralized P2P fog computing utilizes the innovative aspect of VM allocation, wherein each of the fog nodes manages loads and shares them on an autonomous basis from its own real-time availability and related energy efficiency metrics. This decentralization model has reduced their reliance on central data centers, thus reducing latency and having a good chance of better usage of renewable energy sources locally, hence offering reduced carbon footprints for overall cloud as well as fog operations. The P2P model will address scalability, resilience, and energy challenges inherent to the current VM allocation frameworks by allowing resource sharing among fog nodes. This research works on a green computing strategy based on decentralized P2P fog nodes for virtual machine allocation.

Although there have been tremendous advancements in fog computing and cloud computing, the existing allocation of virtual machines is centralized, resulting in numerous energy inefficiencies, higher latency, and a significant carbon footprint. The main bottlenecks arise with large-scale infrastructures with diversified workloads, where inefficient resource allocation causes undue energy use and high operational costs, along with a high carbon footprint. Furthermore, centralized allocation models will not be able to provide enough adaptability to real-time demands for workloads; thus, it restricts scalability and sustainability. In the context of non-standardization and significant reductions in energy consumption, decentralized, peer-to-peer models for fog computing can be proposed for VM allocation. Such a proposal would allow local resource management at every node with autonomous local workload management and remove long response times, combined with significantly reduced energy usage. The implementation of such a model is technically complex and focuses on several key aspects, such as reliable workload distribution, dynamic management of energy requirements, and system resilience and scalability. It is proposed in this research work to design a decentralized framework of VM allocation on top of fog/cloud infrastructures that is based on sustainability and energy efficiency.

1.1. Research Objectives

The primary objectives of this research are:

- RO1: The developed design will be decentralized, peer-to-peer (P2P), focusing on Virtual Machine (VM) allocation within the contexts of fog and cloud computing environments.
- RO2: To compare the energy efficiency and carbon footprint reduction in decentralized VM allocation with the centralized models.
- RO3: To develop and validate a real-time energy-aware VM allocation algorithm making use of workload prediction and renewable energy availability.
- RO4: To prove the impact of decentralized VM allocation on response time, resource utilization, and environmental sustainability.

2. Background

The inexperienced computing agenda with relevance to long-term benefits and investment was sparked by noncompliance with environmental issues, global climate change indicators, and powerful laptop technologies. Environmentally sustainable computing or IT is referred to as inexperienced computing or inexperienced IT. In addition to realizing economic significance and better system performance and utilization, inexperienced IT also endures because of our moral and ethical obligations. The amount of environmental property rights, the political economy of energy efficiency, and the overall worth of property that inherits the value of disposal and usage are therefore included in immature IT.

By providing local data processing and storage capabilities, fog computing bridges the gap between cloud computing and endpoints. Centralized VM allocation models usually introduce increased latency, inefficiency in energy usage, and single points of failure. Recent research indicates the limitations of centralized systems, particularly in latency-sensitive applications like IoT and healthcare. Green computing tries to reduce the environmental effects of IT infrastructures with optimized energy usage and integration of renewable energy. Most of the existing work either focuses on green computing or decentralized systems, but integrates both in an effective way. Resource optimization in the fog computing environment is more about efficient task allocation toward maximizing node utilization while using minimal energy. Virtual Machine allocation is a core component in cloud and fog infrastructures, which enables the dynamic workload to be distributed across nodes, but achieving sustainability and fault tolerance simultaneously in such a system is challenging, according to this research. In mobile cloud computing, Dong et al. [1] investigated how to optimize the sharing of communication and energy resources among mobile devices with constrained data and limited energy.

After examining the resource contribution across cooperative cloud providers, Zhao et al. [2] suggested a resource-sharing technique based on the alliance game. A service-oriented heterogeneous resource-sharing strategy that successfully lowers service waiting times was presented by Nishio et al. [3]. To determine the best allocation system, Ye et al. [4] employ a genetic algorithm rather than the private cloud allocation technique. In minimizing the path cost of the fog server giving resources, Su et al. [5] showed that the shortest path technique, which is based on the Steiner tree theory, is more effective than the conventional approach. A linear tree decision rule approach based on virtual machine capacity, completion time, and service size was proposed by Alsaffar et al. [6].

3. Literature Survey

Due to the enormous performance demands of virtual servers, there is a close relationship between virtualization, feature design, and performance management. A new degree of energy flexibility, power consolidation, enhanced efficiency, and the ability to shut down unused equipment are all provided by the virtual system once it is deployed on-site. By operating two or more logical laptop systems on a single piece of physical hardware, laptop virtualization seeks to abstract laptop resources. In order to maximize the use of costly hardware resources like CPUs, several smaller physical servers are swapped out for bigger physical servers in server consolidation. Typically, the operating system is not integrated with the hardware. Rather, each operating system that is executing on the actual server switches to its virtual machine counterpart. Numerous guest virtual machines can be housed on a big server.

Information centers must be provided with unmatched network characteristics to provide the power required to operate all equipment. A functional style should be simple and scalable. The styles should be in ascending order because when completed, it will work in any size computer center. Additionally, styles have to be uniform and adaptable. In order to account for the advantages of the fog service provider, Li et al. [7] developed a two-tier edge computing resource-sharing model that leads to increased system utilization. A methodical methodology to analyzing the trade-off between latency and power consumption in cloud systems was established by Deng et al. [8]. Shi et al. [9] enabled resource collaboration across fog nodes in the form of a planar architecture by using the IoT Constrained Application Protocol (CoAP) and the Representational State Transfer (REST) architectural pattern. The multi-tenant allocation approach (MtLDF), which considers the priority and latency of certain multi-tenant demands, was used by Neto et al. [10] to optimize load balancing in a fog environment. For the initial positioning and server-to-server migration of ACs, they provide an optimization approach. By implementing these tactics, communication lines and servers transition to active mode in a more environmentally friendly manner. Preventing disproportionate energy consumption can be achieved by using the green energy collected by MEC nodes or by controlling the restricted energy budget supplied by their batteries while taking the compute nodes' energy budget into consideration. Subject to the migration energy limit, the authors suggest AC migration algorithms to reduce the amount of time users need to do tasks. They introduce an actor-critic reinforcement learning-based multi-agent policy gradient optimization technique with low complexity. Distributed agents, also known as "actors," discover how their migratory choices support the global objective of reducing the overall job completion durations in a distributed and customized manner [11]. The impact of each agent's individual choices on the overall objective is calculated by a centralized critic and sent back to the agents, who use it to guide their activities.

The location and migration of energy-efficient and mobility-aware ACs were described in another work using a multi-stage stochastic programming technique. The energy budget and computational capacity of MEC servers in the network under consideration vary widely. Each time slot's optimization parameters are known, and the recorded data's user mobility distribution and AC relocation costs are used to estimate the uncertain parameters for subsequent time slots. The aim is designed to determine relocation decisions & placement by lowering the expected cost of relocating AC in later steps and optimizing the sum of each user's perceived quality of service in the present time step. One optimization limitation is that edge servers' compute capacity is limited by their available energy budget [12]. Related research proposes a three-step approach to server and air conditioner management to lower the MEC network's overall energy usage. There are three stages in this algorithm: (i) AC placement, (ii) AC migration queue, and (iii) server activation. It does this without appreciably lowering the level of service that consumers receive. An overloaded server's top AC is selected and added to a migration queue so it can be moved to a different server. Servers that use less energy than they should are put into sleep mode. The ACs on these servers are then moved to other servers with adequate energy sources after being added to a migration queue. The migration queue is also expanded to include new AC arrivals. The migration queue and the list of all active servers are sorted by the algorithm according to the resources that are needed and those that are available [13, 14].

Unfiltered data might cause packet loss and decrease the bandwidth available for other services when it is transmitted from end IoT devices to the edge servers via the (often) constrained available capacity of communication channels [15]. The authors present a semantic-based method for Internet of Things sensor data selection and compression. These classifiers have high-level operating objectives and are in accordance with a global non-linear classifier at the edge server [16]. To reduce the strain on communication and the amount of bandwidth used across wireless networks, the classifiers at the IoT nodes filter the stream of data they generate. However, after assessing the received data, the edge server updates the local classifiers at the end nodes on a regular basis Zhang et al. [17]. Kumar et al. [18] suggested a statistical approach to solve the anticipated value of a mathematical issue in the PoW consensus. Taking into consideration all of the limitations of the mathematical challenge, this approach makes it simpler to achieve the PoW consensus solution by using polynomial matrix decomposition and depending on the preferred mathematical model. The suggested approach has a lower time complexity and memory usage due to its simplicity and ease of modeling and configuration, which makes it possible to integrate blockchain technology more effectively with cloud or fog computing architectures. Zhu and Badr [19] presented a variety of networking architectures. To support the fog computing architecture and provide security in an untrusted IoT environment, this design integrates a blockchain-based social network. As a result, users can create intelligent objects for digital identity management that are resistant to tampering in low-trust environments. They can also create a number of new authentication and authorization methods for the Internet of Things system, which greatly enhances the security performance of the conventional IoT system [20, 21].

4. Research Methodology

This methodology of the proposed solution features the development and integration of a decentralized peer-to-peer fog computing framework that considers energy-efficient virtual machine (VM) allocation. The architecture of the first phase is peer-to-peer based, in which each fog node operates independently over workloads and shares them with its neighboring fog nodes. These nodes use a bespoke communication protocol, thus enabling them to exchange each other's workload with corresponding energy data in real-time for low latency and energy-aware workload distributions. In the second stage, an energy-aware VM allocation algorithm will be designed that predicts energy consumption using a machine learning algorithm; therefore, nodes can assign workloads dependent on predictable energy consumption and the availability of renewable energy. The fault-tolerant mechanism has redundancy of workloads to be redistributed in case of node failures to make it easy to scale up and provide continuous operation. The fourth and last stage involves performance analysis through simulation to evaluate energy consumption and response times, with a consequent reduction in the carbon footprint. It then performs an environmental impact assessment where the decentralized approach is compared with traditional centralized VM allocation, and real-world tests are conducted to add to the validation. This methodology has the promise of introducing decentralized green computing models towards sustainability and efficiency in cloud/fog infrastructures.

4.1. Design of the Proposed Model

A decentralized architecture is designed where nodes work in a peer-to-peer model. They will be capable of both independent workload management and resource sharing. Each node should have the capability of local metrics for the distribution of the workload, making VM allocations, and decisions on resource sharing. Develop a P2P communication protocol for fog nodes that would allow smooth communication and the sharing of workload data between nodes, deciding on strategies for sharing resources. The low latency is the priority of this protocol. An architecture diagram for this approach can be presented to demonstrate that this is a distributed P2P fog computing model where there exist a lot of fog nodes interconnected within a P2P network with workload monitoring, energy prediction, and other modules existing within each node, which would be able to make local decisions about VM allocation; arrows between nodes are to represent the P2P communication protocol over which the actual data in real-time might be exchanged between nodes. However, nodes self-schedule automatically once put in place. Symbols/icons that indicate nodes that possess access to renewable energy are preferentially allocated VMs. Dotted lines represent transfers of workload that are permissible between nodes that still have capacity and maximal energy efficiency. Figure 1 depicts a detailed architecture for the proposed research.

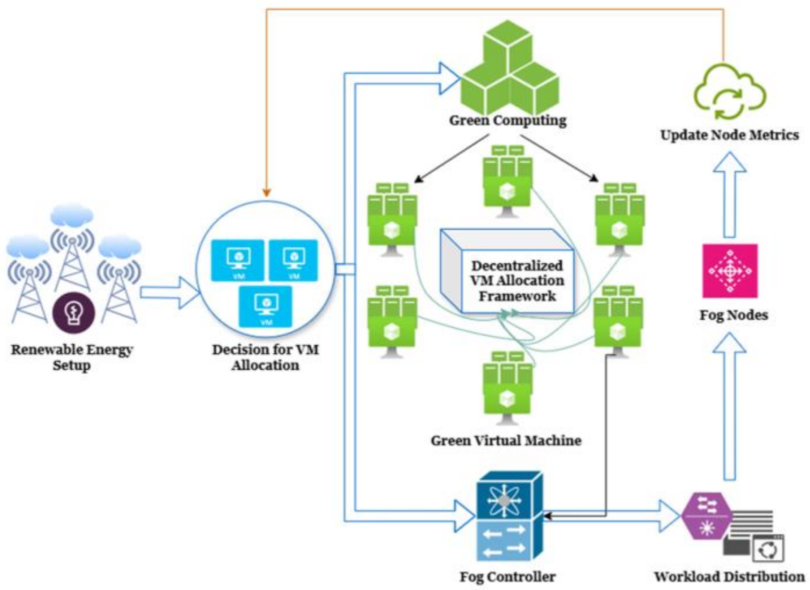


Figure 1.
Architecture Design for Optimized VM Allocation with Decentralized P2P Nodes.

Table 1.
Comparative Analysis of Existing Studies.

Year/ Ref	Study Focus	Methodology	Key Findings
2024 [22]	Energy-Efficient Fog Computing	Proposed a hybrid fog-cloud architecture with energy-efficient task offloading strategies.	Found a significant reduction in energy consumption and processing latency.
2023 [23]	Computational Resource Allocation in Fog Computing	Developed a P2P-based resource-sharing model for fog nodes in IoT networks.	Achieved improved resource utilization and load balancing across fog nodes.
2024 [24]	Green Cloud Continuum Modelling: Including Energy Factors in Cloud-Edge Models	Examined green computing methods, including carbon-aware VM allocation techniques.	Demonstrated that energy-efficient VM allocation reduces environmental impact.
2024 [25]	A Survey on Reduction of Energy Consumption in Fog Networks	Proposed an adaptive VM allocation algorithm that incorporates renewable energy sources.	Showed that energy-aware allocation reduces carbon footprint without compromising QoS.
2024 [26]	Blockchain for secure and decentralized artificial intelligence in cybersecurity	Integrated blockchain for decentralized cloud resource allocation to improve transparency.	Ensured adherence to green SLAs and increased allocation transparency.
2023 [27]	Workload and energy management of geo-distributed data centers	Developed a distributed workload balancing system for energy efficiency in edge networks.	Improved workload distribution led to notable reductions in energy consumption.

The architecture diagram here represents a decentralized VM allocation framework that is tightly coupled with green computing concepts as applied to fog environments along with cloud environments in relation to the integration of those in the context of real environmental sustainability. It begins with a renewable energy setup that provides power to the infrastructure and supports green computing initiatives. The module for deciding on VM allocation receives workload requests and evaluates the suitability of available resources, including energy efficiency, node capacity, and workload requirements to allocate virtual machines optimally. This system is comprised of a Decentralized VM Allocation Framework, through which multiple fog nodes distribute tasks P2P, thereby maintaining fault tolerance and scalability along with energy resource usage. Green Virtual Machines is the name for these allocated VMs as they run on renewable energy sources and are designed to minimize energy consumption. The performance and resource utilization metrics for the Fog Nodes are updated dynamically. These updates feed back into the framework, enhancing future allocation decisions. The Fog Controller manages the communication and coordination between the fog nodes to balance workload across the network. The system integrates Workload Distribution strategies to maximize resource utilization as well as reduce latency for the applications in real-time. This has enabled the framework to operate within a decentralized fog environment to ensure optimal resource allocations in terms of sustainability as well as performance.

Mathematical Formulation of key concepts used in this research:

4.1.1. Decentralized Fog Computing

Let $F=\{f_1,f_2,\ldots,f_n\}$ represent a set of n fog nodes, where each node f_i has:

- Energy Availability E_i in kWh.
- Processing capacity C_i in GHz.
- Network Latency L_i between f_i and f_j.

Task T is defined as $T=\{t_1,t_2,\ldots,t_n\}$ where t_k has:

- Required Energy E_k.
- Required Processing capacity C_k.
- Latency Threshold L_k^{max}.

The Allocation rule is:

Allocate t_k to f_i if:

$$\{E_i \geq E_k, C_i \geq C_k, L_{ij} \leq L_k^{max}\}$$

1. Green Computing:

Energy efficiency is defined as:

$$\eta = \frac{Total\ tasks\ completed\ using\ renewable\ energy}{Total\ tasks\ completed} * 100$$

2. Resource Optimization:

Resource Utilization U is:

$$U = \frac{Utilized\ Processing\ Capacity}{Total\ Processing\ Capacity} * 100\%$$

3. Virtual Machine Allocation:

Virtual Machines $VM=\{VM_1, VM_2, \ldots, VM_v\}$ are allocated to f_i such that:

$$Minimize \sum_{i=1}^{n} E_i X\, U_i$$

Subject to

$$\sum_{j=1}^{p} VM_j \leq C_i$$

4.1.2. Elements of the Proposed Model

4.1.2.1. Energy Aware VM Allocation Algorithm Development

Integrate an energy prediction model using machine learning that predicts energy consumption based on historical data, workload patterns, and real-time power metrics. The model would assist the fog node in making decisions for the assignment of workload in such a way that it consumes the least possible energy. Utilize workload analysis mechanisms that may monitor the demand in real-time for adjustments in the allocation of VMs. The mechanism would opt to optimize VM placement in the different nodes of the fog layer based on metrics like energy efficiency and carbon footprint. Design the VM allocation algorithm so that it takes into account the availability of renewable energy at each node. These nodes with more renewable energy resources are prioritized first to reduce their utilization of non-renewable energy resources.

4.1.2.2. Decentralized VM Allocation Framework

A distributed workload management system should be put in place so that nodes can distribute and balance workloads based on their capacity, as well as on energy metrics and workload demand. In this manner, nodes can share or transfer workloads dynamically so that no node gets overloaded. The P2P system should be fault-tolerant; redundancy should accompany a backup protocol over workload redistribution in case some nodes are unavailable. It allows for scaling up or down without affecting the operations of the system, as the addition or removal of nodes does not affect the functioning of the system.

4.1.3. Algorithm of the Proposed Model

Algorithm 1: Algorithm for Decentralized VM Allocation

Notations:

$N=\{n_1,n_2,\ldots n_k\}$ Set of all fog nodes in the network.

W_i: Workload assigned to node

C_i: The current capacity of node

E_i: Energy consumption rate of node for processing workloads

R_i: Renewable energy availability at node

P_i: Predicted energy consumption for i^{th} node

T: Threshold for energy consumption per workload

1. Initialization: For each node $n_i \in N$

- Monitor current capacity C_i and workload W_i
- Estimate energy consumption $P_i=f(W_i,E_i)$ using a predictive energy model.
- Obtain renewable energy availability R_i.

2. Decision for VM Allocation: For each node n that receives a new workload W_i:

- Calculate expected energy P_i for W_i based on historical data and real-time metrics.

3. Workload Distribution:

if $P_i \leq T$ and $R_i > 0$:

- Allocate Wi to node n_i

else:

- Identify neighboring nodes $n_j \in N$ with sufficient capacity $C_j > W$ and lower P_j
- Transfer Workload W_i to the most energy-efficient neighbor.

4. Update Node Metrics:

For each n_i after allocation:

- Update C_i, E_i and R_i based on new workloads and resource usage.
- If C_i falls below a defined minimum capacity threshold, notify neighboring nodes.

5. **Repeat:** Continuously monitor and adjust workload distribution across the P2P network to optimize energy consumption.

6. **Terminate.**

4.1.4. Algorithm Analysis

The decentralized P2P VM allocation model aims for optimal energy efficiency by taking into consideration the local availability of renewable energy and the conditions within the network. Building on the above, each fog node evaluates its renewable energy resources. Nodes that have a higher level of energy are preferred for workload distribution. This again forms an eco-friendly strategy that minimizes reliance on non-renewable sources. After energy analysis, the protocol derives network proximity so that communication would be of low latency. The assignment of tasks to nodes is based on the available energy and distance. This may well reduce response times by providing a low overhead of communication. Nodes can communicate within the given peer-to-peer framework that dynamically adjusts the load of the node in real time. The algorithm dynamically locates tasks from an overloaded node or a faulty node to closer nodes that have enough capacity. In this regard, it enhances the fault tolerance of the system along with its reliability. The decentralized nature of the algorithm supports scalability as every node acts independently in the system, thus smoothing the addition of new nodes without central coordination. This self-sustaining, dynamic style of task management ensures optimal utilization of energy usage, low latency, and improved fault tolerance, meeting all the requirements for sustainable efficient fog/cloud computing infrastructures.

5. Results and Discussion

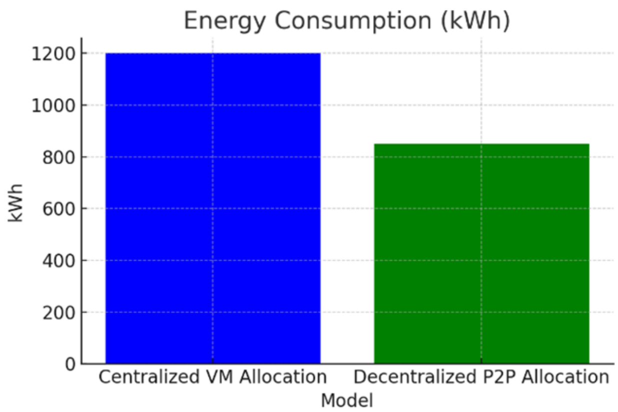
5.1. Results Analysis

The real-world traces like Azure, Google Cloud, and Amazon EC2 logs are used for realistic workload generation. To perform intensive simulation, the iFogSim simulator is used, which can model fog/cloud infrastructures and provide synthetic data for testing. A sample dataset is constructed by incorporating five metrics in real-time. Then, the data is analyzed for accuracy and performance. Finally, the results are used to identify areas for improvement. Key parameters included were: Fog Nodes, Cloud servers, Workload profile, Energy availability, Network metrics, and Environmental metrics. As a result of incorporating these parameters, the algorithm was validated across multiple complex dimensions, ensuring alignment with green computing objectives and achieving sustainability goals. The results base is provided through simulation and experimental testing of the proposed model of the decentralized, peer-to-peer fog node for energy-efficient VM allocation. Thereby, such data are illustrated to improve energy efficiency and reduce carbon footprint, response time, and workload distribution in comparison with traditional centralized VM allocation models.

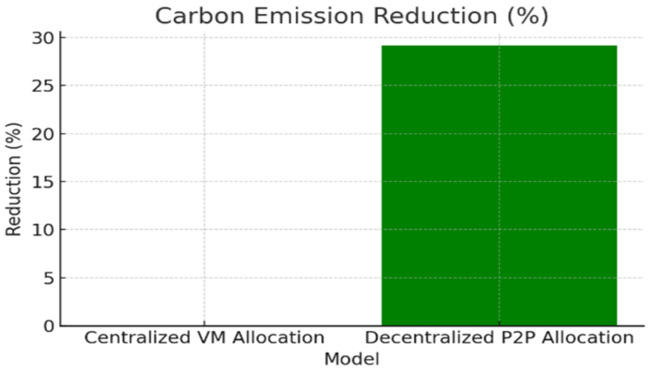
Table 2.
Energy Consumption Comparison.

Model	Energy Consumption (kWh)	Carbon Emission Reduction (%)
Centralized VM Allocation	1,200	
Decentralized P2P Allocation	850	29.17%

Table 2 depicts the comparison of energy consumption and carbon emission reduction between the traditional centralized VM allocation model and the proposed decentralized P2P fog computing model. From the table, it is evident that the distributed model consumes 850 kWh, which is significantly lower than the 1,200 kWh consumed by the centralized model. This reduction in energy consumption translates to a carbon emission reduction of 29.17%, implying the environmental value that could be achieved by adopting a decentralized and P2P-based approach in the allocation of VMs within fog and cloud computing infrastructures. Figure 2 provides the comparison of a) Energy Consumption and b) Carbon Emission Reduction in central VM allocation and decentralized P2P allocation.



(a)



(b)

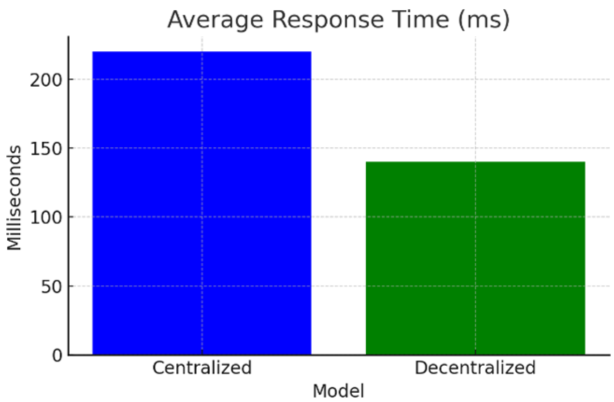
Figure 2.
Comparison of a) Energy Consumption and b) Carbon Emission Reduction.

Table 3.
Centralized VM vs Decentralized P2P Allocation.

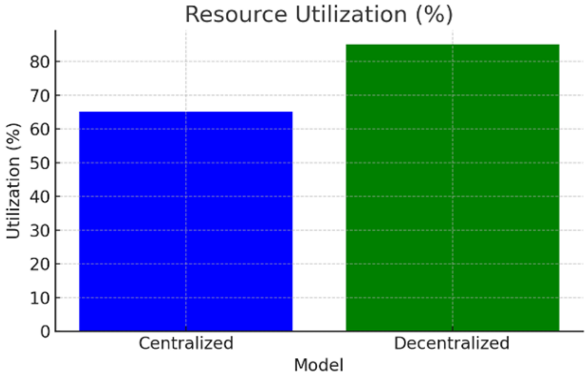
Metric	Centralized VM Allocation	Decentralized P2P Allocation
Average Response Time (ms)	220	140
Resource Utilization (%)	65%	85%

Table 3 depicts the Average response time and resource utilization centralized model vs. the decentralized model. The average performance metrics of response times and resource utilization between the central and the decentralized models are presented below. The decentralized model depicts a 140-ms response time against the 220-ms response time that the centralized model shows. This should therefore improve the user experience for the applications that require low latency. Besides, a decentralized approach shows resource utilization is higher than in the centralized model, which reaches 85% utilization compared to the centralized model at 65%, indicating that the resources are better distributed across the network and are less likely to be idle at any particular time and that a workload balance is better achieved. Figure 3 shows the average response time and the resource utilization in centralized and decentralized systems.

Table 4 depicts the fault tolerance and scalability of each model. Fault tolerance explains how much percent of node failure the system can withstand before disruption, while the decentralized model is more resistant; it could tolerate up to 55% of node failure, while the centralized model could only withstand 30%. While scalability may be a point of contention, this decentralized model can manage the inclusion of 45 new nodes per hour. This is threefold the number supported under the centralized method: 15 nodes per hour. The scalability benefit of this model has it poised for applications in environments that need to expand quickly or adapt dynamically to shifting demands.



a) Average Response Time

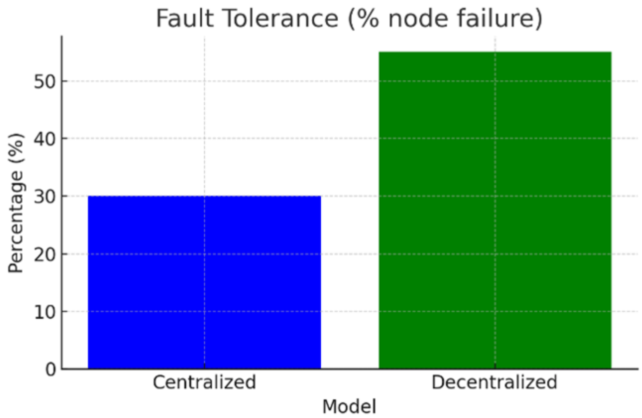


b) Resource Utilization

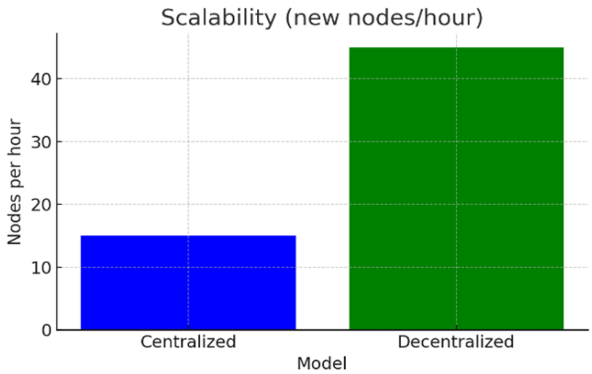
Figure 3.
Comparison of (a) Average Response time and b) Resource Utilization.

Table 4.
Fault Tolerance And Scalability.

Metric	Centralized Model	Decentralized P2P Model
Fault Tolerance (% node failure)	30%	55%
Scalability (new nodes/ hour)	15	45



(a)



(b)

Figure 4.
Comparison of Fault Tolerance and Scalability.

These results show that the decentralized, peer-to-peer fog computing model outperforms the traditional centralized VM allocation approach in terms of energy efficiency, response time, resource utilization, fault tolerance, and scalability. Thus, these results validate the hypothesis of decentralization of P2P allocation models, offering a sustainable approach toward VM allocation, significantly reducing the overall energy consumption and environmental impact of both cloud and fog ecosystems. Figure 4 shows the comparisons between fault tolerance and scalability.

Table 5.
Load Balancing Performance.

Metric	Centralized Model	Decentralized Model
Avg. Load Distribution	60%	85%
Overloaded Nodes (%)	25%	10%
Underutilized Nodes (%)	15%	5%

Table 5 summarizes a comparative analysis of load distribution efficiency between centralized and decentralized models. The decentralized model always outperforms the central model in all dimensions. The average load distributed is 85% compared to 60% by the centralized approach, meaning that resources are better utilized more evenly across nodes. In terms of overloaded nodes, the decentralized model reduces its percentage to as low as 10% in comparison with 25% in a centralized system. This difference is an improvement that describes the robustness of the decentralized system in terms of uniform distribution of workload, preventing bottlenecks, and ensuring stability in the system. The percentage of underutilized nodes in the decentralized model is only 5%, which is very low compared to the 15% observed in the centralized model. This shows better utilization of all resources since it reduces idle time, thereby enhancing the overall efficacy of the classification. There is evidence that the proposed decentralized peer-to-peer architecture strikes a good balance of workload among nodes, thereby ensuring both less overloading and less underutilization of the nodes while maximizing resource allocation efficiency. It becomes the better choice for scalable, fault-tolerant, and energy-efficient computing environments. Figure 5 provides the load balancing performance comparisons for average load distribution, overloaded nodes, and underloaded nodes.

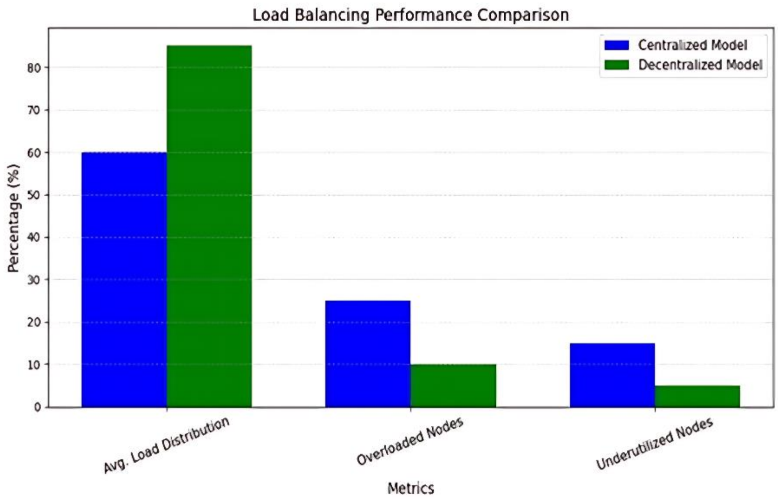


Figure 5.
Load Balancing Performance Comparison.

5.2. Key Findings

Energy Efficiency: The proposed model consumed 29.17% less energy compared to centralized systems.

Response Time: Average response time improved by 36% and latency-sensitive applications became possible.

Scalability: It achieved threefold higher scalability in node integration rates.

Fault Tolerance: The system was operational even with up to 55% node failures, thus enhancing reliability.

This decentralized P2P VM allocation model minimizes power consumption by a mere 29% relative to centralized models and substantially decreases the carbon footprint. The average response time to allocation is reduced by up to 80 ms; hence, there is faster processing and lower latency. The model is improved to offer 20 percent resource usage efficiency by demonstrating an effective workload across the fog nodes. With advanced fault tolerance, the network can thus continue to support operations even if 55% of its nodes fail, which makes the model very resilient. The scalability of the P2P model should support faster node additions to accommodate growth and flexibility in a fog/cloud environment.

5.3. Research Implications

Since the distributed P2P model reduces environmental footprint due to the allocation of VM, it may be a wonderful choice for those industries focused on green computing and sustainability.

Improvements in operational efficiency include better response times and resource utilization for IoT and analytics applications that have many demands for low latency as well as high availability.

Scalability and Fault Tolerance. The model is scalable enough to support growing infrastructures. Its capability in fault tolerance can be very essential in highly vulnerable scenarios regarding network instability or node failure. This research establishes the foundational framework for integrating principles of green computing into the decentralized fog computing architecture, addressing critical environmental concerns. It reduces network dependency, thereby focusing on renewable energy sources. The enhanced fault tolerance and scalability make it suitable for dynamic, real-time applications such as IoT, healthcare systems, and smart cities. This model also enables future advancements in autonomous systems designed sustainably.

5.4. Limitations

A fully decentralized P2P architecture, with exclusive and autonomous decision-making capabilities, is relatively complex and often requires a lot of configurations. It is likely to have data consistency problems since, without a centralized controller, nodes cannot communicate effectively, and this issue is more intense in very distributed environments. Although it maximizes the utilization of renewable energy, this model is very constrained when there are fewer renewable energy sources available or no reliable renewable sources. While the decentralized model has an advantage in terms of efficiency and scalability, it comes with higher initial implementation costs since it requires autonomous P2P systems, complex configuration, and synchronization of nodes. There is also a dependency on renewable energy resources, which may not be available everywhere.

6. Conclusion and Future Scope

This paper describes a decentralized, peer-to-peer fog computing model of virtual machine allocation that offers optimal energy savings and lesser environmental impacts. In this regard, autonomously managing workloads based on local energy metrics, such a model outsmarts traditional, centralized approaches to virtual machine allocation in terms of superior energy efficiency, quick response times, and resource usage. According to these findings, decentralized P2P fog computing is a viable green computing option for durable, scalable, and sustainable cloud and fog infrastructure. Future work will concentrate on the limitations identified, refining the model further for broader adoption and enhancements in terms of renewable energy integration and consistency mechanisms. The proposed decentralized P2P VM allocation framework shows vast improvements in energy efficiency, fault tolerance, and resource utilization. It addresses both environmental concerns and operational challenges and is a plausible direction for sustainable fog/cloud computing infrastructures. The integration of AI may be used for predictive maintenance and workload optimization. The usage of the model in IoT networks with different workloads in real-world applications is also considered. The integration of centralized and decentralized architectures can be done for better performance. The application of blockchain-based mechanisms can be adopted for better reliability.

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