Energy Efficiency in Cloud Computing Environments: Early Results of a Tertiary Study

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***Abstract*—This work presents the initial findings from a tertiary study that synthesizes existing research on energy efficiency in cloud computing. Using a systematic methodology including automated search and forward snowballing, the study identified and analyzed 25 literature reviews to explore key research topics and some challenges.**

***Index Terms*—cloud computing, energy efficiency, tertiary study**

I. Introduction

The Information and Communication Technology (ICT) sector has been accounted for approximately 4% of global electricity use and 1.4% of greenhouse gas emissions in 2020 [1]. Projections indicate that global data center energy consumption could double between 2023 and 2028, driven by energy-intensive workloads like artificial intelligence models and cryptocurrency mining [2]. This trend underscores the urgent need for energy efficiency and sustainability in the face of climate change and environmental challenges.

Cloud computing provides a flexible, cost-effective solution for users and businesses to access ICT services, eliminating the need for physical infrastructure investment and maintenance. While using cloud services instead of an on-premise infrastructure can lower energy usage and decrease carbon footprint, the data centers that power cloud services are responsible for a large share of global energy use and greenhouse gas emissions. As such, optimizing energy use in cloud data centers while maintaining or improving performance is critical. Recent research has concerned energy efficiency in cloud environments, including energy-aware strategies and algorithms from hardware and software perspectives [3].

Considering the substantial body of knowledge related to this topic, several secondary studies, such as literature reviews and surveys, have explored the state of the art. Nevertheless, the rapid evolution of the field and the large volume of primary and secondary research highlight the need for a *tertiary study*. A tertiary study can synthesize and consolidate findings from multiple literature reviews to provide a broad overview of the current state of knowledge [4]. On the other hand, existing tertiary studies on energy efficiency in cloud computing are outdated, covering the literature only up to 2017 [5], [6]. Moreover, they have not followed a rigorous procedure to collect, select, and analyze secondary studies.

This work presents early results from a tertiary study offering a high-level synthesis of existing research on energy efficiency in cloud computing across hardware, software, and data centers, while identifying topics for further investigation. To increase the reliability of the results and provide a more comprehensive synthesis of the available evidence, our tertiary study followed a systematic methodology comprising automated search and forward snowballing to retrieve literature reviews related to energy efficiency in cloud computing environments. We have selected and analyzed 25 secondary studies focusing on their main research topics and some of the challenges they discussed.

II. Methodology

A tertiary study addresses broader research questions by identifying and analyzing secondary studies, employing methodologies similar to those used in systematic literature reviews and mapping studies [4]. To synthesize existing research on energy efficiency in cloud computing environments, we formulated the following research questions:

- RQ1: What research topics secondary studies related to energy efficiency in cloud computing environments have addressed?
- RQ2: What are the issues and challenges discussed, and what are the key recommendations for future research on energy efficiency in cloud computing environments?

Some tertiary studies opt to include only secondary studies that follow systematic procedures to ensure high research quality and rigor. However, we have decided not to impose this constraint as our goal was to gather as many relevant secondary studies as possible. Furthermore, we aimed to assess the number of secondary studies that did not adhere to systematic literature review procedures as part of the outcomes from our tertiary study.

Our automated search process for collecting secondary studies (literature reviews, mapping studies, and literature surveys) on energy efficiency in cloud computing environments used the following search string:

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("power consumption" OR "energy efficiency" OR "energy
efficient" OR "energy consumption" OR "energy
utilization" OR "energy-aware" OR green) AND "cloud
computing" AND ("systematic literature review" OR
"systematic review" OR "systematic mapping study" OR
"systematic mapping" OR "literature review" OR
"literature survey" OR survey)
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We defined specific criteria to filter search results for relevance to our tertiary study. The exclusion criteria included: (i) studies that did not primarily focus on energy efficiency

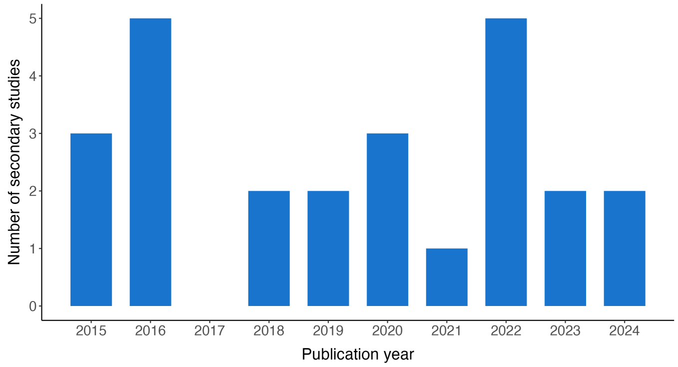

Fig. 1. Temporal distribution of the selected secondary studies

in cloud computing, such as those where energy efficiency was a secondary goal or incidental outcome of strategies, frameworks, or architectures; (ii) non-peer-reviewed studies; (iii) studies with unavailable full text; (iv) studies written in languages other than English; and (v) studies that were themselves tertiary research.

We carried out the automated search in October 2024 in Scopus,[1] a well-known database that covers major computing-related publishers such as IEEE, Elsevier, Springer, and ACM. We set the search string to the paper title field, yielding an initial set of 40 results. Applying the exclusion criteria to these entries resulted in 18 secondary studies. To enhance the comprehensiveness of our tertiary study, we used forward snowballing [7] to identify additional relevant secondary studies. Using Google Scholar,[2] we searched for studies that cite those retrieved by the automated search. This process resulted in seven more studies. Our final dataset consisted of the 25 secondary studies listed in the appendix.

III. Results

A. Demographics the Selected Studies

Fig. 1 shows the temporal distribution of the selected secondary studies, with an average of 2.5 publications per year. We observed that 52% (13 out of 25) were published in the last five years, highlighting the relevance of energy efficiency in cloud computing amid rising ICT energy demands and the urgent need for solutions to address energy consumption.

We also analyzed the selected secondary studies concerning their rigor. Nearly two-thirds (64%) of the studies lack systematic methodologies in their literature reviews, omitting key elements such as clearly defined research questions, a structured search strategy, proper selection criteria, or documented data extraction processes. This lack of a systematic process undermines the reliability of their findings and limits their contribution to accurately representing the research landscape on energy efficiency in cloud computing.

Finally, only 64% of the secondary studies explicitly reported the number of primary studies analyzed and the timespan covered, reviewing an average of 98 studies (median = 110, max = 294, min = 9). Moreover, we observed that the literature on energy efficiency in cloud computing spans 15 years (2008—2022), with most primary studies concentrated between 2010 and 2016.

B. Main Research Topics

The selected secondary studies we analyzed broadly discuss several factors contributing to energy consumption in cloud computing, especially underutilized servers and inefficient resource allocation. To meet high availability and other Quality of Service (QoS) requirements, cloud data centers often over-provision servers and resources, resulting in low utilization rates, or rely on suboptimal allocation strategies. Furthermore, most address energy efficiency in data centers supporting cloud services, focusing on three levels: physical, resource, and software. At the physical level, energy efficiency is concerned with optimizing power usage for hardware components such as memory, CPUs, and storage. The resource level involves the energy-aware management of virtualized resources, particularly virtual machines (VMs). At the software level, the emphasis is on implementing strategies and algorithms within cloud service operations to reduce energy consumption.

Our analysis revealed that almost all the studies propose various taxonomies and categorization schemas to organize and classify existing primary research. More than half of the secondary studies focus on techniques for achieving energy efficiency in cloud computing environments (S2, S3, S6, S7, S8, S9, S12, S16, S19, S21, S22, S23, S24), including optimization methods, scheduling, machine learning, VM migration, and server consolidation, with the latter two appearing recurrently. In addition, energy-aware resource and service allocation is a key topic in 20% of the studies (S1, S5, S7, S13, S16), where strategies aim to enhance allocation efficiency to reduce energy consumption. Some studies also emphasize the need for trading off energy efficiency and other quality attributes, such as reliability (S11), security (S12), fault tolerance (S18), and performance and service-level agreements (S14, S16).

Lastly, three studies (S15, S17, S20) focused on green cloud computing. The main concern is minimizing the environmental impact of cloud services while enhancing energy efficiency, reducing e-waste, and adopting renewable energy sources to power cloud data centers.

C. Some Challenges

The selected studies also discuss challenges in implementing energy-efficient solutions in cloud computing, emphasizing the need to reduce energy consumption without compromising application performance or service quality. They noted that existing research often prioritizes one aspect over the other (S11).

We also identified a lack of standardized metrics for measuring energy efficiency in cloud computing. Only one study (S10) focused on metrics, although its scope was beyond cloud environments. This gap calls for further research incorporating metrics into energy-aware and energy-efficient techniques in cloud computing.

[1] https://www.scopus.com
[2] https://scholar.google.com

APPENDIX
SELECTED STUDIES

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