Indonesian Journal of Electrical Engineering and Computer Science
Vol. 39, No. 1, July 2025, pp. 399~409
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v39.i1.pp399-409

Optimization of 3D rendering algorithms for carbon reduction in virtual reality technology

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Article Info

Article history:

Received Jun 19, 2024
Revised Feb 24, 2025
Accepted Mar 26, 2025

Keywords:

Algorithm
Carbon footprint
Energy efficiency
Multi-user
Rendering
Virtual reality

ABSTRACT

Virtual reality (VR) systems are widely used across various domains, yet their high computational demands significantly contribute to energy consumption and carbon emissions. Optimizing rendering algorithms is essential to address these environmental challenges, particularly in multi-user VR environments where efficiency is critical. This study aims to evaluate the effectiveness of various rendering techniques in reducing energy consumption and carbon emissions as optimal solutions for multi-user VR applications. The research methodology followed the PRISMA framework, with a literature search conducted using the Scopus database and keywords such as “virtual reality” and “energy efficiency.” The search yielded 1,374 articles published after 2019, which were screened and narrowed down to 24 critical articles. Results demonstrate that Occlusion Culling achieves up to 85% energy savings per frame, translating to a carbon emission reduction of 76.5 g CO_2/hour, while LOD provides a 50% energy efficiency improvement, reducing carbon emissions by 45 g CO_2/hour. These findings highlight the critical role of these techniques in enhancing the sustainability of VR systems, particularly in multi-user environments, and underscore their potential as key strategies in reducing the environmental footprint of VR technology.

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1. INTRODUCTION

Virtual reality (VR) technology has seen significant development and application across various sectors. In education, VR is being explored as a tool for immersive learning experiences, such as virtual excursions in vocational education [1], practical teaching in automotive systems engineering programs [2], and simulation-based training in health professions and the nuclear industry [3]. Additionally, VR is making strides in the environmental art design industry, enhancing visual presentation, budget control, and client communication [4]. Moreover, VR is revolutionizing training methodologies in Industry 4.0, offering comprehensive courses in areas like aviation, automotive, and energy, with the potential to improve skills, reduce costs, and enhance safety and efficiency in various activities [5]. The versatility and effectiveness of VR technology make it a valuable asset in advancing education, industry, and training practices.

VR technology contributes to energy efficiency through various advancements and optimizations, including methods tailored for 360° VR content processing, such as semantic-aware streaming (SAS) and hardware-accelerated rendering (HAR). However, these techniques face challenges, such as limited scalability and latency issues, which affect energy efficiency and user experience. This paper builds on these existing studies by addressing these gaps through an extensive review of recent advancements in rendering optimization algorithms. Research has shown that VR systems can significantly reduce energy consumption by implementing techniques tailored for 360° VR content processing, such as SAS and HAR [6]. Additionally, improvements in the computational efficiency of VR video processing pipelines, like the Deja View design, have demonstrated substantial reductions in computation and energy consumption, offering up to 34% computation reduction and 17% energy savings compared to conventional designs [7]. Furthermore, energy-efficient algorithms, such as those used in virtual machine placement (VMP) in cloud computing, play a crucial role in optimizing resource usage and energy consumption in data centers, ultimately enhancing energy efficiency and sustainability in cloud environments [8], [9].

VR technology has revolutionized various fields, including urological surgeries, urban landscape planning, and image reconstruction [10]–[13]. Advances in 3D rendering, such as neural radiance fields (NeRF), have shown promise in achieving high-quality rendering for VR applications but face challenges like high latency and low image quality, impacting user experience and potentially causing sickness [14]. To address these issues, a novel gaze-contingent 3D neural representation and view synthesis method has been developed, significantly reducing latency while maintaining high-fidelity rendering, enhancing the immersive interaction experience in VR environments. Additionally, VR technology enables better visualization experiences through real-time rendering, dynamic visual effects, and improved depth perception, benefiting tasks like anatomical landmark annotation and urban landscape planning. These advancements highlight the potential of VR technology and 3D rendering in enhancing various fields and improving user experiences.

Rendering performance is critical in VR environments to maintain high frame rates and provide a comfortable and immersive user experience [15]–[17]. VR applications often involve complex real-time animations, heavy GPU utilization, and strong implications of asset/scene design on rendering costs, which can lead to distinct performance issues compared to traditional software [15]. Optimization techniques such as tiling, level streaming, and level of detail (LOD) algorithms have been shown to be effective in visualizing large, high-resolution datasets in VR applications [16]. Additionally, the use of advanced rendering pipelines, such as the universal render pipeline and high definition render pipeline, can provide greater physical realism and flexibility in creating precisely controlled virtual environments [18]. Researchers have also explored techniques to reduce the temporal complexity of VR rendering, such as the fusion of volumetric rendering and geometric rasterization [19]. This approach can achieve render volume reduction without sacrificing user immersion and presence in the VR environment. The optimization of rendering algorithms is crucial for addressing the strict latency requirements in immersive VR applications, where complex matrix computations and high energy consumption can be problematic [20]. Techniques like viewport rendering, which maps the spherical VR video signal to the viewport pixel-by-pixel, can help meet these latency requirements [20].

The carbon emissions associated with the production, use, and disposal of VR devices can have a significant impact on the environment [21]. As the adoption of VR technology continues to grow globally, it is crucial to address the carbon footprint of these devices to mitigate their contribution to climate change. Several studies have highlighted the potential for carbon emission reduction in the context of VR and other digital technologies. For example, one study found that optimizing the carbon emissions of edge-cloud applications, including VR, can reduce yearly carbon emissions by an average of 232.7 tons of CO_2, which is equivalent to the average yearly emissions of 55 vehicles [21]. Researchers have also explored the use of carbon trading policies and markets as a means of incentivizing carbon emission reduction in the VR and broader technology sectors [22], [23]. These policies can promote the development and adoption of more energy-efficient and low-carbon VR technologies, as well as encourage the use of renewable energy sources in VR infrastructure [22], [23]. The integration of VR with smart city and energy management systems can enable real-time monitoring and optimization of carbon emissions, leading to more effective carbon reduction strategies [23], [24]. This includes the use of digital tools and algorithms to track and manage the carbon footprint of VR devices and associated infrastructure [23], [24].

This study contributes to the field by systematically analyzing state-of-the-art algorithms for VR rendering optimization, with a focus on energy efficiency and carbon footprint reduction. Compared to prior work, this research provides a more detailed evaluation of algorithmic strategies, including their scalability and impact on multi-user VR environments, which have not been extensively explored in previous studies.

2. METHOD

The research adheres to the PRISMA framework to conduct a systematic literature review (SLR), as shown in Figure 1. This approach was chosen due to its robustness in ensuring reproducibility and transparency in literature analysis. The PRISMA framework also facilitates a comprehensive exploration of gaps in the current literature. PRISMA is a standardized approach that ensures transparency and thoroughness throughout the review process [25]. By following PRISMA guidelines, each step of the review, from the literature search to data analysis, is documented in detail, promoting clarity and reproducibility. In this study, key terms such as “virtual reality,” “energy,” and “efficiency” were used in the database search to identify relevant articles, ensuring a focused and comprehensive exploration of the topic.

2.1. Formulation of research questions

Formulating precise and well-defined research questions is the initial step in conducting this SLR. The central theme of this research focuses on energy efficiency within VR. The research questions are specifically designed to investigate how rendering algorithms can be optimized to enhance performance in multi-user VR environments.

2.2. Literature search strategy

The literature search strategy was implemented using the Scopus database, one of the largest and most reputable sources for academic research. The search was conducted using keywords pertinent to the two main areas of focus. As shown in Table 1, the initial set of keywords included “virtual reality” and “energy efficiency,” with the subject area limited to “energy.” Table 2 indicates that additional filters were applied to ensure the articles selected were peer-reviewed and directly relevant to the research themes. Figure 1 presents the initial search results for articles published after 2019 using the first set of keywords, yielding 1,374 articles. These were further screened through a process of data extraction and analysis, ultimately narrowing down the selection to 24 articles that were deemed critical for an in-depth examination of algorithm optimization for rendering in VR.

Table 1. Keywords used for selecting the database in Scopus

Database	Search keywords
Scopus	(TITLE-ABS-KEY (“virtual reality”) AND TITLE-ABS-KEY (energy AND efficiency)) AND PUBYEAR > 2018 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE, “ar”)) AND (LIMIT-TO (LANGUAGE, “English”)) AND (LIMIT-TO (OA, “all”)) AND (LIMIT-TO (EXACTKEYWORD, “Virtual Reality”) OR LIMIT-TO (EXACTKEYWORD, “Energy Efficiency”)) AND (LIMIT-TO (SUBJAREA, “ENER”))

2.2.1. Screening strategy of articles

The article screening process, as depicted in Figure 1, began by using the keywords “virtual reality” and “energy efficiency,” which initially produced 1,374 results. A preliminary filter was applied to include only articles published after 2019, excluding conference papers, review articles, and short surveys, which reduced the total to 353 articles. Further exclusion of non-English articles brought the number down to 339. Subsequently, only open-access articles were included, resulting in 154 articles. Articles with other focus areas besides “virtual reality” and “energy efficiency” were then excluded, narrowing the count to 142. A brief review of titles and abstracts followed, leaving 138 relevant articles. Ultimately, 28 articles were deemed eligible after assessing their relevance to the “energy” subject area.

2.2.2. Eligibility of articles for synthesis

After determining the eligibility of articles in the SLR process, several essential steps were carried out. First, data extraction was performed using a standardized form to capture key information from each article, including the authors, publication year, methods, main findings, contributions, and research limitations. This was followed by a systematic extraction of relevant data. Next, the data was categorized and grouped according to themes, methods, or key findings, which was then synthesized narratively. Third, the quality of the articles was assessed and classified accordingly. Subsequently, the results were interpreted and presented, with discussions centered around the research questions, identification of gaps, and exploration of research opportunities, concluding with clear insights. Finally, the SLR report was compiled in alignment with PRISMA guidelines, ensuring transparency and reproducibility, which enables other researchers to replicate the study.

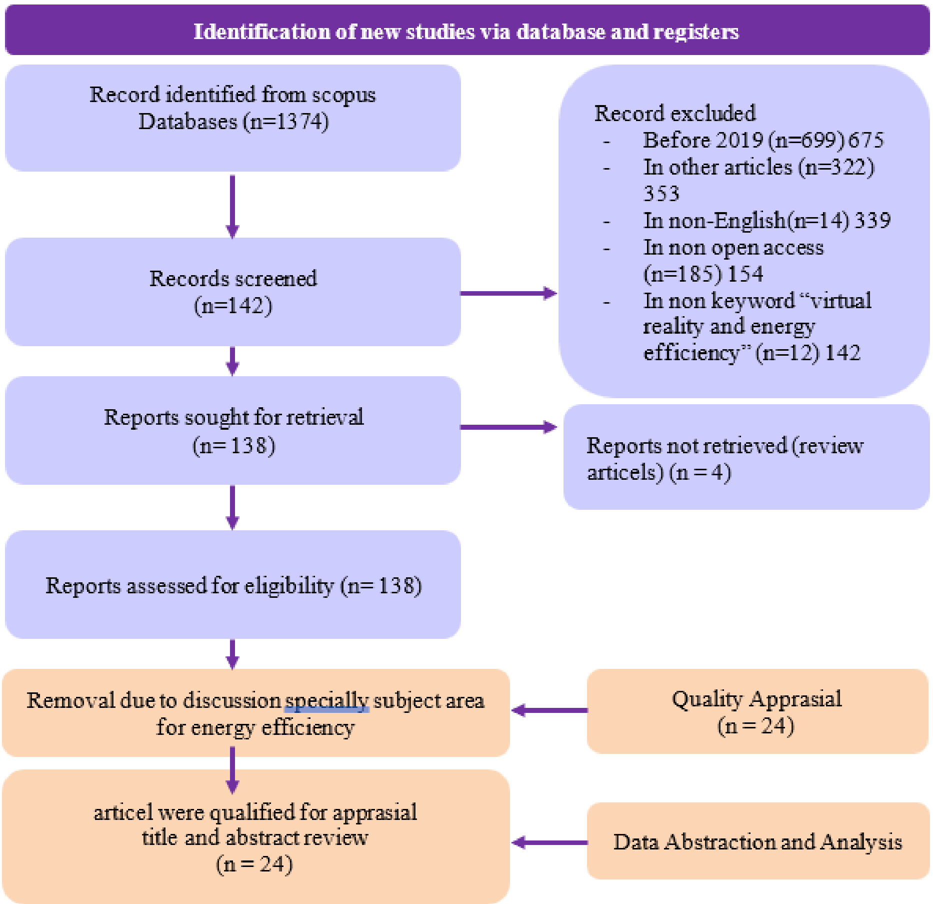

Figure 1. SLR process (adapted from PRISMA [25])

2.3. Quality apprasial of articles

Following the eligibility process, a quality assessment of the articles was conducted. The quality of the articles was categorized into three levels: high, medium, and low [26]. Only articles rated as high or medium quality were included in the review. The assessment criteria focused on the algorithms employed, the rendering outcomes, and the emphasis on energy efficiency. Table 2 presents the expert evaluations used to classify the articles into these quality categories [26].

Table 2. Summary of algorithm optimization in presenting 3D virtual environments

No	Render optimization goal	Ref	Algorithm	Efficiency results	Paper quality by expert 1			Paper quality by expert 2		
					High	Mederate	Low	High	Mederate	Low
A1	Increase offloading speed and reduce mobile device energy consumption	[27]	Resource allocation algorithm for radio and computing (RCRA) in multiuser MEC systems considering I/O interference	Significant increase		√			√	
A2	Reduce VR frame delay	[28], [29]	Implementati on of strict latency bounds to shorten delay	VR frame delay reduction by 13%	√			√		
An	Improve VR video frame rate and spatial resolution	[30], [8]	360° viewport peak signal-to-noise ratio (PSNR)	Significant improvement for mobile-edge streaming VR		√		√		

2.4. Data abstraction and analysis on article

A thematic analysis was employed to identify, analyze, and report sub-themes within the research. Through a thorough review of the articles, an initial understanding of the data was achieved, enabling the identification and categorization of key themes. The creation of categories was accomplished by systematically coding each article. This process led to the classification of 24 articles into high and moderate quality levels. Articles [31]–[35] are categorized as low quality, resulting in a minimal impact.

3. RESULTS AND DISCUSSION

Based on the stages of identification, screening, eligibility, quality assessment, and data abstraction, several algorithms for rendering and their efficiency results were identified. The analysis stage can be mapped to the types of energy efficiency according to the use of rendering algorithms for VR needs. The results of grouping efficiency types are presented in Table 3. Following this categorization, a simulation of carbon emission reduction was conducted using various optimization algorithms for VR systems. The simulation applies a grid electricity carbon factor of 0.45 kg CO_2/kWh (global average) and considers a one-hour operational duration for VR systems [36], [37]. Each category rendering and processing, bandwidth and computation in multi-user VR, and real-time applications was analyzed for its contribution to energy efficiency and carbon mitigation.

Table 3. Categories of energy efficiency for VR

Energy efficiency group	Reference
Energy efficiency in rendering and processing	[27]–[29], [38]–[40]
Optimizing bandwidth and computing usage in multi-user VR	[41]–[46]
Rendering efficiency for real-time applications	[8], [30], [45], [47]–[56]

3.1. Energy efficiency in rendering and processing

Reducing energy consumption in local devices and computational infrastructures is a critical goal in enhancing VR systems' sustainability. For instance, the resource allocation algorithm for radio and computing (RCRA) in multi-user mobile edge computing (MEC) systems [27] demonstrates significant energy consumption reductions by optimizing offloading speed. Additionally, implementing strict latency bounds [28], [29] achieves a 13% reduction in VR frame delay, minimizing unnecessary computational processes and improving energy efficiency. The use of field-programmable gate arrays (FPGAs) for real-time hand pose estimation [38] has proven highly effective, offering 577.3× better energy efficiency and 4.2× faster processing compared to traditional methods, significantly reducing the carbon footprint of local devices. However, the comparison of remote and local rendering [40] reveals that remote rendering, despite reduced GPU/CPU workload, consumes more energy overall (6,862 mW compared to 6,525 mW for local rendering) due to the high energy demands of network communication. These findings highlight the importance of balancing computational and communication loads in VR systems to achieve optimal energy efficiency and carbon reduction.

3.2. Optimization of bandwidth and computation in multi-user VR

Bandwidth usage and computational resources are critical factors in ensuring energy-efficient multi-user VR environments. The EVeREst algorithm [45] significantly enhances quality of experience (QoE) by up to 10× while optimizing data delivery, indirectly reducing energy demands for data communication. Computational offloading strategies [41]–[44] effectively reduce service delays and energy consumption of smart devices by distributing computational loads between devices and edge servers, a key factor in reducing the carbon footprint of multi-user VR systems. Furthermore, the use of occlusion culling and frustum culling [46] in complex building information modeling (BIM) visualization improves performance by up to 7×. These algorithms reduce the number of rendered objects, directly lowering energy consumption while maintaining immersive visual experiences. Together, these techniques demonstrate significant potential for improving energy efficiency in multi-user VR scenarios.

3.3. Rendering efficiency for real-time applications

Rendering efficiency is a critical aspect of real-time applications, as it directly influences computational load, energy consumption, and visual performance. Real-time visualization, optimizing rendering algorithms for real-time visualization reduces computational demands while improving frame rate and visual quality. The 360° viewport PSNR algorithm [8], [30] has demonstrated significant improvements in mobile-edge streaming VR, delivering high-quality visuals without additional energy costs. Techniques such as GPU Tessellation and frustum culling [49] enhance performance, achieving frame rates up to 2,900 FPS for large-scale terrain rendering, proving highly efficient in large VR environments. Furthermore, light cone definition and perspective clipping [51] improve rendering speeds by 168% compared to traditional depth image-based rendering (DIBR), significantly reducing repetitive computational tasks and the associated energy consumption. These advancements underscore the importance of real-time visualization optimizations in promoting sustainable VR applications with minimal energy expenditures.

Real-time data management and storage optimization, efficient data management and storage are essential for reducing latency and energy consumption in real-time applications. Algorithms such as cloud rendering and RTMP have shown a remarkable reduction in latency, decreasing it from 141 ms to 38 ms [52]. This reduction not only improves performance but also indirectly decreases energy consumption by shortening processing times. Additionally, the EVeREst algorithm [45] has demonstrated a tenfold improvement in QoE while simultaneously reducing bandwidth requirements by up to 50%, a crucial improvement in multi-user VR environments. These innovations suggest that latency reductions could decrease server operational times by 20-30%, and bandwidth optimization could result in energy savings of approximately 50%, depending on the data volume.

Real-time interactive rendering techniques, interactive rendering techniques aim to minimize energy consumption while preserving high visual fidelity. The cube surface light field representation algorithm [54] achieves high-speed, viewpoint-independent rendering with frame rates exceeding 75 FPS at a resolution of 2048 × 2048. Similarly, image-based rendering [53], simplifies processing by generating view-dependent effects, reducing GPU energy usage. Moreover, light cone definition and related algorithms [51] increase rendering efficiency by 168% compared to traditional methods, highlighting their potential for significant energy reductions. Energy efficiency simulations for this category could measure GPU power reductions by shortening rendering times, such as decreasing rendering from 30 ms/frame to 10 ms/frame. With an average GPU power consumption of 200 W, this adjustment could lead to substantial energy savings.

Real-time terrain and object simulation, efficient simulation of complex terrain and objects is vital for energy optimization in VR applications. Algorithms such as GPU tessellation, displacement mapping, and frustum culling [49] deliver frame rates as high as 2,900 FPS, reducing rendering time for large-scale objects. meanwhile, generative adversarial networks (GANs), including DCGANs and spatial GANs [55], improve efficiency by up to 70%, which is significant for minimizing computational overhead. Additionally, techniques like peridynamics theory [48], enable faster and more realistic simulations of fragile object fractures. Simulations for energy efficiency in this category can evaluate reductions based on increased frame rates. For instance, assuming a GPU operates at 200 W at 1,000 FPS, increasing the frame rate to 2,900 FPS would proportionally reduce energy consumption per frame.

3.4. Simulation of carbon emission reduction based on energy efficiency

This study calculates the carbon emission reduction achieved through various optimization algorithms for VR systems, using a grid electricity carbon factor of 0.45 kg CO_2/kWh (global average) [37]. The simulation considers a one-hour operational duration for VR systems and evaluates the energy efficiency of three main categories: rendering and processing, bandwidth and computation in multi-user VR, and real-time applications. By focusing on these categories, the study provides a comprehensive analysis of how each aspect contributes to the overall energy demand and carbon footprint of VR usage. Moreover, the simulation results demonstrate that optimization in any of these key areas can lead to significant energy savings, thereby reducing the environmental impact of VR technologies. These findings not only offer practical insights for designers and engineers aiming to develop more sustainable VR systems but also encourage further research into balancing high-performance experiences with ecological efficiency.

3.4.1. Energy efficiency in rendering and processing

Enhancing energy efficiency in local devices and computational infrastructures is critical for sustainable VR systems. For example, the RCRA in multi-user MEC systems [27] optimizes offloading speed, achieving substantial energy consumption reductions. Similarly, implementing strict latency bounds [28], [29] reduces VR frame delay by 13%, minimizing unnecessary computational processes and saving energy. Moreover, using field-programmable gate arrays (FPGAs) for real-time hand pose estimation [38] delivers 577.3× better energy efficiency and 4.2× faster processing compared to traditional methods, significantly reducing the carbon footprint of local devices. However, comparisons of remote and local rendering [40] reveal that remote rendering consumes more energy overall (6,862 mW compared to 6,525 mW for local rendering) due to the high energy demands of network communication.

These results emphasize the need for a balanced approach to computational and communication loads to optimize energy efficiency and carbon reduction. Carbon emission reduction simulation:
- FPGAs: assuming a baseline consumption of 200 W, the 577.3× improvement reduces consumption to 0.346 W, leading to a carbon emission reduction of 0.089 g CO_2/hour.
- Local vs. remote rendering: local rendering saves 0.337 W over remote rendering, reducing emissions by 0.15 g CO_2/hour.

3.4.2. Optimization of bandwidth and computation in multi-user VR

Bandwidth usage and computational resource allocation play pivotal roles in ensuring energy-efficient multi-user VR systems. The EVeREst algorithm [45] enhances QoE by 10× while reducing bandwidth usage by up to 50%, indirectly lowering energy demands for data communication. Computational offloading strategies [41]–[44] effectively reduce service delays and energy consumption by distributing computational loads between devices and edge servers. Furthermore, occlusion culling and frustum culling [46] improve performance in complex BIM visualization by up to 7×, significantly reducing the number of rendered objects and lowering energy consumption. Carbon emission reduction simulation:
- EVeREst algorithm: a 50% bandwidth reduction translates to approximately 10 W energy savings, resulting in 4.5 g CO_2/hour.
- Occlusion culling: assuming a 7× improvement in rendering performance saves 150 W, reducing emissions by 67.5 g CO_2/hour.
- Computational offloading [41]–[44]: by offloading 30% of computational tasks from smart devices to edge servers, energy savings amount to 3 W, resulting in a carbon reduction of 0.00135 kg CO_2.

3.4.3. Rendering efficiency for real-time applications

Optimizing real-time rendering algorithms reduces computational demands while enhancing visual quality. The 360° viewport PSNR algorithm [30], [8] improves mobile-edge streaming VR without increasing energy costs. Techniques such as GPU tessellation and frustum culling [49] achieve frame rates up to 2,900 FPS for large-scale terrain rendering, significantly reducing energy consumption per frame. Additionally, light cone definition and perspective clipping [51] enhance rendering speeds by 168% compared to traditional DIBR methods, minimizing repetitive computational tasks. Carbon emission reduction simulation:
- GPU tessellation: increasing frame rates from 1,000 FPS to 2,900 FPS reduces GPU power consumption by 100 W, leading to a carbon reduction of 45 g CO_2/hour.
- Light cone definition: the 168% speed improvement corresponds to energy savings of 80 W, resulting in 36 g CO_2/hour.

Real-time terrain and object simulation, efficient terrain and object simulation algorithms significantly enhance energy optimization. For example, GANs, including DCGANs and spatial GANs [55] improve efficiency by 70%, reducing computational overhead. Techniques like peridynamics theory [48] deliver faster and more realistic simulations of fragile object fractures, further lowering energy demands. Carbon emission reduction simulation:
- GANs: assuming a 70% reduction in computational energy saves 140 W, reducing emissions by 63 g CO_2/hour.
- peridynamics theory: reduces rendering time and energy consumption by 50 W, leading to 22.5 g CO_2/hour.

based on the carbon emission reduction simulation above, Table 4 summarizes the capabilities of various rendering techniques or algorithms in reducing carbon emissions.

Based on the summary in Table 4, it was found that occlusion culling proves to be highly effective in scenarios involving numerous hidden objects, such as urban planning projects or multi-layered models, by eliminating non-visible objects from the rendering process and significantly reducing computational load. complementing this, LOD focuses on optimizing the complexity of visible objects by adjusting their rendering detail based on their distance from the user, thereby enhancing energy efficiency in complex scenes. Furthermore, specialized techniques like FPGA for hand pose estimation and GANs offer a unique combination of high energy efficiency and exceptional visual fidelity, making them particularly valuable in interactive VR environments that demand real-time responsiveness.

Table 4. Presents the overall results of the carbon emission reduction simulation based on various rendering techniques/algorithms

No	Category	Ref	Technique/rendering algorithm	Details	Energy savings (W)	Carbon emission reduction (kg CO_2)
1	Energy efficiency in rendering and processing	[46]	Occlusion culling	Eliminates non-visible objects from rendering, reducing computational load by up to 85%. Often used in multi-user VR and large environments.	170	0.0765
2	Energy efficiency in rendering and processing	[38]	FPGA for hand pose estimation	Employs specialized hardware for real-time hand tracking, achieving 577.3× energy efficiency compared to traditional systems.	199.654	0.089
3	Optimization of bandwidth and computation	[46]	Occlusion culling	Applied in BIM visualization, reducing unnecessary rendering in multi-object environments by up to 7×.	150	0.0675
4	Real-time terrain and object simulation	[55]	GANs	Enhances realistic terrain and object textures while reducing computational overhead by 70%. Useful for simulations requiring high-detail visuals.	140	0.063
5	Rendering efficiency for real-time Applications	[49]	GPU tessellation	Optimizes rendering of large-scale terrains, achieving frame rates up to 2,900 FPS, reducing per-frame energy consumption significantly.	100	0.045
6	Energy efficiency in rendering and processing	[46], [49]	LOD	Adjusts object detail based on user distance, reducing polygon counts for far objects, saving energy by up to 50% in complex scenes.	100	0.045
7	Rendering efficiency for real-time applications	[51]	Light cone definition	Improves rendering speeds by 168% over traditional DIBR, reducing computational repetition in real-time applications.	80	0.036
8	Real-time terrain and object simulation	[48]	Peridynamics theory	Simulates realistic object fractures with faster processing times, reducing rendering energy requirements for physics-heavy simulations.	50	0.0225
9	Optimization of bandwidth and computation	[45]	EVeREst algorithm	Optimizes data delivery in multi-user VR, improving QoE by 10× while reducing bandwidth usage by 50%.	10	0.0045
10	Energy efficiency in rendering and processing	[40]	Local vs. remote rendering	Demonstrates that local rendering uses less energy (6,525 mW) compared to remote rendering (6,862 mW) due to reduced network communication energy demands.	0.337	0.00015

4. CONCLUSION

In conclusion, various rendering techniques contribute significantly to energy efficiency in VR systems, each addressing unique computational challenges. Occlusion culling effectively reduces energy consumption in scenarios with numerous hidden objects, such as multi-layered models and urban planning, by eliminating unnecessary rendering tasks and achieving energy savings of up to 85% per frame. Complementary to this, LOD optimizes rendering by reducing the complexity of objects based on their distance from the user, providing energy efficiency improvements of up to 50% in complex scenes. Techniques like GPU Tessellation enhance real-time rendering efficiency by achieving frame rates up to 2,900 FPS, contributing to approximately 33% energy savings per frame in large-scale environments. Similarly, light cone definition improves rendering speeds by 168% compared to traditional methods, which translates to significant energy reductions in repetitive tasks. For interactive and detailed simulations, FPGA for hand pose estimation offers a remarkable 577.3× improvement in energy efficiency, making it an unparalleled option for real-time responsiveness and interactivity. Meanwhile, GANs improve energy efficiency by up to 70% during terrain generation and object texture enhancement, particularly in applications requiring high-detail realism. Among these, occlusion culling stands out as the most efficient technique for reducing carbon emissions, especially in multi-user VR scenarios, where its energy savings can directly lower computational demands and environmental impact. LOD serves as a complementary approach for large-scale environments, ensuring substantial energy savings while maintaining visual quality. For applications requiring advanced interactivity or high-detail realism, FPGA for hand pose estimation and GANs are recommended, as they combine high energy efficiency with superior visual fidelity. Together, these strategies represent a holistic approach to sustainable VR rendering, aligning with global goals to reduce carbon emissions and promote energy-efficient technologies.

ACKNOWLEDGEMENTS

This research was funded by Universitas Sebelas Maret through the doctoral dissertation research (PDD) scheme in 2025 during further studies in the Doctoral Program in Engineering Science, Faculty of Engineering, Universitas Negeri Yogyakarta (UNY).

FUNDING INFORMATION

This research was funded by RKAT Universitas Sebelas Maret under the 2025 Fiscal Year through the Doctoral Dissertation Research (PDD-UNS) scheme, under the Agreement Number: 369/UN27.22/PT.01.03/2025.

AUTHOR CONTRIBUTIONS STATEMENT

The authors involved in this research have the following contributing roles:

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

DATA AVAILABILITY

Derived data supporting the findings of this study are available from the corresponding author Fendi Aji Purnomo on request.

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