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Analysis Of Increasing Power Usage Effectiveness (PUE) Through Renewable Energy Integration In Data Center Electrical Systems

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Abstract

The rapid growth of digital technologies, including cloud computing, artificial intelligence, and big data analytics, has significantly increased the demand for data center infrastructure, resulting in higher energy consumption and environmental concerns. This study aims to evaluate the effectiveness of electrical infrastructure optimization and renewable energy integration in reducing Power Usage Effectiveness (PUE) within mission-critical data centers. A quantitative explanatory approach was employed using Single Line Diagram (SLD)-based analysis as the primary source of technical data. Electrical specifications, including transformer efficiency, Uninterruptible Power Supply (UPS) performance, power distribution systems, and cooling plant characteristics, were extracted and analyzed to estimate facility energy losses and baseline operational efficiency. Simulation modeling was then conducted to assess the impact of renewable energy integration under various penetration scenarios while maintaining system stability and reliability. The findings indicate that cooling systems, UPS modules, and transformer losses represent the major contributors to non-IT energy consumption. The baseline analysis produced a PUE value of 1.67, whereas the implementation of renewable energy integration combined with electrical infrastructure optimization reduced the PUE value to 1.47, representing an improvement of approximately 12%. In addition, renewable energy penetration significantly reduced dependence on grid electricity and lowered estimated carbon emissions without compromising operational continuity. The study demonstrates that SLD-based electrical analysis provides a practical and cost-effective framework for evaluating energy efficiency and renewable energy

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readiness in data centers. These findings contribute to the development of sustainable digital infrastructure aligned with energy transition goals, ESG principles, and long-term carbon reduction strategies.

Keywords: Data Center, Power Usage Effectiveness (PUE), Renewable Energy Integration, Electrical Infrastructure Optimization.

INTRODUCTION

The rapid advancement of digital technologies, including cloud computing, artificial intelligence, big data analytics, Internet of Things (IoT), and edge computing, has significantly increased the demand for data center infrastructure worldwide. Data centers have become the backbone of modern digital ecosystems because they provide essential computing, storage, networking, and information-processing capabilities that support government services, financial transactions, industrial automation, healthcare systems, educational platforms, and e-commerce activities. Indonesia, as one of the fastest-growing digital economies in Southeast Asia, is experiencing an unprecedented expansion of data center facilities driven by increasing internet penetration, digital transformation initiatives, and national policies promoting digital sovereignty. According to recent studies, the growth of hyperscale and colocation data centers has generated substantial increases in electricity consumption, making energy management one of the most critical challenges in contemporary data center operations (Zhang et al., 2023; Kumar & Singh, 2024).

The operation of modern data centers requires a highly reliable and continuous power supply characterized by a constant baseload profile. Unlike conventional commercial buildings, data centers operate twenty-four hours a day and seven days a week, requiring uninterrupted electrical power to maintain service availability and operational resilience. The electrical demand originates not only from servers, storage devices, networking equipment, and computing clusters but also from supporting infrastructure such as cooling systems, lighting, security systems, and power distribution networks. Research indicates that cooling systems alone can account for approximately 30–50% of the total facility energy consumption, particularly in tropical countries where ambient temperatures remain relatively high throughout the year (Rahman et al., 2023; Li et al., 2024). Consequently, the increasing number of digital services directly translates into higher electricity consumption and greater pressure on national power systems.

One of the most significant concerns associated with data center expansion is the

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continued dependence on fossil-fuel-based electricity generation. Although digital technologies are often portrayed as enablers of sustainable development, the environmental footprint of data center operations remains substantial. Global data center electricity consumption continues to rise annually, contributing to greenhouse gas emissions and climate change challenges. Scholars have emphasized that the rapid growth of computational demand associated with artificial intelligence and machine learning applications may further increase energy requirements if efficiency improvements are not simultaneously implemented (Jones et al., 2024; Patel & Roy, 2023). Therefore, achieving a balance between digital transformation and environmental sustainability has become a strategic priority for governments, technology companies, and infrastructure operators worldwide.

To evaluate energy performance, the data center industry widely adopts Power Usage Effectiveness (PUE) as the primary indicator of operational efficiency. PUE represents the ratio between the total facility energy consumption and the energy consumed directly by information technology equipment. A PUE value approaching 1.0 indicates that nearly all electrical energy is utilized for productive computing purposes, while minimal energy is wasted by supporting systems. Recent technological innovations, including advanced cooling architectures, airflow optimization, artificial intelligence-based energy management systems, and modular infrastructure design, have significantly contributed to lowering PUE values across modern facilities (Brown et al., 2024; Wang et al., 2023). Consequently, PUE has become not only a technical performance metric but also an important benchmark for environmental accountability and operational excellence.

The urgency to reduce PUE values is no longer motivated solely by financial considerations related to operational expenditure (OPEX). In recent years, regulatory pressures and sustainability commitments have become equally influential drivers of energy-efficiency initiatives. Governments around the world are introducing stricter environmental regulations, carbon disclosure requirements, and renewable energy targets that directly affect large-scale energy consumers, including data centers. Furthermore, global commitments under the Paris Agreement require organizations to actively reduce greenhouse gas emissions and transition toward low-carbon energy systems. Simultaneously, investors and stakeholders increasingly evaluate organizations based on Environmental, Social, and Governance (ESG) principles, making energy efficiency and sustainability critical components of corporate competitiveness and reputation (Anderson & Miller, 2024; Garcia et al., 2023).

In response to these challenges, many organizations have begun integrating renewable

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energy sources into data center power infrastructures. Renewable technologies such as solar photovoltaic systems, wind power generation, battery energy storage systems, and hybrid microgrids are increasingly being considered as viable alternatives to conventional electricity supplies. Previous studies have demonstrated that utility-scale wind power installations dedicated to supporting data center operations can be economically feasible while substantially reducing carbon emissions (Chen et al., 2023). Similarly, renewable-powered microgrids have shown significant potential for improving energy resilience, reducing grid dependency, and supporting long-term sustainability objectives. As a result, renewable energy integration is now recognized as one of the most promising pathways toward achieving carbon-neutral data center operations.

At the operational level, numerous researchers have proposed innovative strategies to maintain electrical stability while incorporating renewable energy sources. Since renewable generation is inherently variable, maintaining power quality and frequency stability becomes a major technical challenge. Dynamic synchronization mechanisms involving Uninterruptible Power Supply (UPS) systems, intelligent power electronics, and adaptive server workload management have demonstrated considerable effectiveness in mitigating power fluctuations and preserving system reliability (Ahmed et al., 2024; Lee & Choi, 2023). These technological advancements enable data centers to absorb intermittent renewable energy inputs while ensuring uninterrupted service delivery, which is essential for mission-critical applications.

Beyond technical efficiency, the adoption of green infrastructure innovations has also been linked to broader organizational performance improvements. Studies indicate that environmentally sustainable facilities contribute positively to operational reliability, stakeholder trust, regulatory compliance, and overall business competitiveness. Green data center initiatives often involve integrated approaches that combine energy-efficient equipment, renewable energy adoption, advanced monitoring systems, and sustainability-oriented management practices (Santos et al., 2024). Furthermore, international sustainability frameworks increasingly require organizations to measure, verify, and transparently report energy performance indicators using precise monitoring instruments and standardized methodologies. Accurate reporting not only enhances accountability but also facilitates benchmarking and continuous improvement efforts.

Despite these advantages, renewable energy integration does not automatically guarantee improvements in PUE performance. The intermittent nature of solar and wind power introduces substantial complexity into electrical distribution systems. Variations in renewable generation can cause voltage fluctuations, frequency instability, and operational uncertainties that may compromise the reliability of critical infrastructure if not properly managed. Several studies have

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identified inadequate electrical infrastructure readiness as one of the primary factors contributing to unsuccessful renewable energy integration projects within mission-critical facilities (Nguyen et al., 2024; Ferreira & Costa, 2023). Consequently, detailed engineering analysis is required to ensure that renewable energy deployment enhances rather than undermines overall system performance.

Another challenge relates to the implementation of energy auditing and performance assessment processes. Although smart metering technologies and Building Management Systems (BMS) provide valuable operational insights, their deployment often involves substantial capital investments and technical expertise requirements. In many facilities, limited accessibility to detailed analytical data constrains the effectiveness of energy optimization programs. This situation is particularly relevant in developing countries, where budget limitations and technological barriers may hinder comprehensive monitoring initiatives. As a result, alternative analytical approaches that utilize existing engineering documentation and operational records become increasingly important for supporting efficiency evaluations and strategic decision-making processes.

Based on these research gaps, the present study focuses on optimizing the analysis of electrical equipment specifications contained within Single Line Diagram (SLD) documentation as a foundation for evaluating strategies to reduce PUE values. The study proposes the development of an electrical efficiency estimation model capable of assessing power distribution performance and identifying opportunities for integrating renewable energy sources without compromising operational stability. By utilizing SLD-based electrical analysis, the research seeks to provide a cost-effective and technically robust approach for supporting energy-efficiency improvements in mission-critical facilities. The findings are expected to contribute to the advancement of sustainable data center design and operation, particularly in Indonesia, where the rapid expansion of digital infrastructure must be balanced with national commitments toward energy transition, carbon reduction, and sustainable development goals.

RESEARCH METHODOLOGY

This study employed a quantitative explanatory research design to investigate the influence of electrical infrastructure configuration and renewable energy integration on Power Usage Effectiveness (PUE) performance in mission-critical data center facilities. Quantitative explanatory research was selected because it enables researchers to examine causal relationships among technical variables through objective measurement, mathematical modeling, and

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simulation-based analysis (Creswell & Creswell, 2023). The study focused on Tier-3 and Tier-4 data center architectures due to their high availability requirements and widespread adoption in modern digital infrastructure. Rather than relying on operational data obtained directly from Building Management Systems (BMS), which are often inaccessible because of security and confidentiality constraints, this research utilized engineering documentation in the form of Single Line Diagrams (SLDs) as the primary source of technical data. The SLD approach has increasingly been recognized as an effective method for evaluating electrical performance, identifying energy losses, and supporting infrastructure optimization in critical facilities (Wang et al., 2024).

The data collection process involved systematic extraction of electrical specifications from the SLD documentation. Key parameters analyzed included transformer rated capacity and efficiency, nominal current ratings of circuit breakers, Uninterruptible Power Supply (UPS) topology and conversion efficiency, power distribution unit characteristics, cable distribution routes, and cooling plant compressor power requirements. These parameters were selected because previous studies have identified them as major contributors to energy losses within data center electrical systems (Zhang & Liu, 2023). To improve analytical reliability, all technical specifications were validated against industry standards and manufacturer nameplate data. The collected information was then organized into a structured database consisting of electrical input variables, load characteristics, operational efficiency coefficients, and estimated thermal loads generated by information technology equipment and supporting infrastructure.

The analytical phase employed electrical engineering calculations and simulation modeling techniques to estimate baseline facility performance. First, theoretical power losses were calculated for each component of the electrical distribution chain, including transformer losses, UPS conversion losses, cable losses, and auxiliary mechanical loads. Subsequently, the total facility power demand and IT equipment power consumption were determined to establish the baseline PUE value. The mathematical model was developed based on established power system analysis methodologies and energy auditing principles commonly applied in mission-critical infrastructure assessments (Ahmed et al., 2024). Simulation modeling was chosen because it enables the evaluation of multiple operating scenarios without disrupting actual facility operations, thereby reducing operational risks while maintaining analytical accuracy (Garcia et al., 2023).

The next stage involved integrating renewable energy variables into the established electrical model. Renewable energy injection scenarios were simulated using representative intermittent generation profiles derived from wind and solar energy production patterns. Multiple penetration levels were evaluated to determine the impact of renewable energy integration on

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electrical stability, facility efficiency, and overall PUE performance. The simulation incorporated load-balancing mechanisms, UPS battery support functions, and dynamic power compensation strategies to assess the resilience of the electrical infrastructure under fluctuating renewable generation conditions. Scenario-based simulation has been widely recommended in recent energy systems research because it allows researchers to evaluate system responses under varying environmental and operational conditions while identifying potential reliability risks before implementation (Kim et al., 2025; Fernandez & Torres, 2024).

To ensure the validity and reliability of the findings, the simulation outputs were subjected to comparative and sensitivity analyses. Baseline and post-integration PUE values were compared to determine the magnitude of efficiency improvement achieved through renewable energy adoption. Furthermore, sensitivity analysis was conducted by varying key parameters such as transformer efficiency, UPS performance, renewable energy penetration rates, and cooling system power demand. This approach enabled the identification of critical variables that most significantly influence overall energy performance and operational stability. The final results were interpreted within the framework of sustainable data center management, emphasizing the balance between energy efficiency, carbon emission reduction, and operational reliability. Through this methodological framework, the study provides a validated technical assessment model capable of supporting future decision-making processes regarding electrical infrastructure optimization and renewable energy integration in modern data centers (Brown et al., 2024).

FINDINGS AND DISCUSSION

Finding

1. Analysis of Existing Electrical Infrastructure Based on Single Line Diagram (SLD)

The first stage of the analysis focused on evaluating the existing electrical infrastructure represented in the Single Line Diagram (SLD) of the data center facility. The SLD review revealed that the electrical architecture follows a Tier-3/Tier-4 design philosophy, consisting of dual utility feeders, medium-voltage transformers, redundant UPS systems, Power Distribution Units (PDUs), and centralized cooling plant facilities. The analysis identified that the largest proportion of energy consumption originated from IT equipment and cooling systems, while additional losses occurred during power conversion and distribution processes. These findings are consistent with previous studies indicating that transformers, UPS modules, and HVAC systems are the primary contributors to non-IT energy consumption in modern data centers.

The extracted technical specifications demonstrated that transformer efficiencies

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exceeded 97%, while UPS conversion efficiencies ranged between 94% and 97% depending on operating load conditions. Although these values are considered acceptable according to industry standards, the cumulative effect of conversion losses significantly affected overall facility energy performance. Furthermore, the cooling plant required substantial electrical input due to the continuous operation of chillers, pumps, and air-handling systems necessary to maintain server operating temperatures.

The SLD evaluation also revealed that several electrical components operated below their optimal loading conditions. Underutilized transformers and oversized UPS modules reduced operational efficiency because energy losses remained present even when actual IT loads were lower than rated capacities. Such inefficiencies contribute directly to higher PUE values and indicate opportunities for infrastructure optimization.

Table 1. Existing Electrical Infrastructure Characteristics

Component	Quantity	Rated Capacity	Average Efficiency (%)	Estimated Loss (%)
Transformer	2 Units	2500 kVA	97.8	2.2
UPS Module	4 Units	1200 kVA	95.4	4.6
PDU System	12 Units	250 kVA	98.5	1.5
Cooling Plant	6 Units	850 kW	88.2	11.8
Distribution Cables	Multiple	-	99.0	1.0

Table 1 indicates that the cooling plant exhibited the lowest efficiency among all major facility systems. The cooling infrastructure contributed the highest percentage of energy losses, followed by UPS conversion losses. These findings suggest that efficiency improvement strategies should prioritize mechanical cooling systems and power conversion equipment.

2. Baseline Power Usage Effectiveness (PUE) Assessment

The second stage involved calculating the baseline PUE value using the extracted electrical specifications and estimated operational loads. Total facility power consumption was determined by aggregating IT equipment demand, cooling system demand, UPS losses, transformer losses, and auxiliary facility loads. The analysis showed that the total incoming power exceeded the actual IT load due to unavoidable energy losses throughout the electrical distribution chain.

The simulation results indicated that the data center achieved a baseline PUE of 1.67. While this value remains within the acceptable range for many conventional enterprise data centers, it is still considerably higher than the industry benchmark of highly efficient hyperscale

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facilities, which often operate at PUE values below 1.30. The relatively high PUE can primarily be attributed to the substantial energy demand of the centralized cooling infrastructure.

Further analysis demonstrated that approximately one-third of total facility energy consumption was utilized by non-IT support systems. This finding highlights the importance of optimizing supporting infrastructure rather than focusing exclusively on server efficiency. Improvements in cooling technology, power distribution architecture, and renewable energy integration therefore represent viable pathways toward achieving better energy performance.

Table 2. Baseline Facility Energy Consumption and PUE

Energy Component	Power Consumption (kW)	Percentage (%)
IT Equipment Load	4,500	59.9
Cooling System	2,100	28.0
UPS Losses	350	4.7
Transformer Losses	180	2.4
Lighting and Auxiliary Systems	380	5.0
Total Facility Load	**7,510**	**100**

Table 2 demonstrates that IT equipment represented approximately 60% of total energy consumption, whereas cooling infrastructure consumed 28%. The calculated baseline PUE value of 1.67 indicates significant opportunities for efficiency improvement through infrastructure optimization and renewable energy adoption.

3. Renewable Energy Integration Simulation

The third phase of the study evaluated the impact of renewable energy integration on overall facility performance. Renewable power injection scenarios were modeled using intermittent generation profiles derived from utility-scale wind energy and photovoltaic systems. Three renewable penetration levels were simulated: 20%, 40%, and 60% of total facility demand.

Simulation results revealed that renewable integration reduced dependence on utility-grid electricity and significantly lowered facility carbon emissions. However, increasing renewable penetration introduced greater variability into the electrical system. Consequently, UPS battery systems and load-balancing mechanisms played a critical role in maintaining operational stability and preventing power-quality disturbances.

The simulation further demonstrated that renewable integration alone did not automatically improve PUE. Instead, measurable PUE improvements occurred only when

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renewable energy deployment was accompanied by infrastructure optimization measures such as UPS synchronization enhancement, transformer load balancing, and cooling system efficiency upgrades. This finding supports previous research suggesting that renewable energy implementation must be integrated with broader energy-management strategies.

Table 3. Impact of Renewable Energy Integration on Facility Performance

Scenario	Renewable Penetration (%)	Grid Energy Reduction (%)	Carbon Emission Reduction (%)	PUE
Baseline	0	0	0	1.67
Scenario A	20	16.5	18.3	1.61
Scenario B	40	34.2	37.6	1.54
Scenario C	60	52.8	57.9	1.47

Table 3 illustrates a progressive reduction in PUE as renewable energy penetration increased and supporting infrastructure optimization measures were implemented. The highest renewable penetration scenario achieved a PUE value of 1.47, representing an improvement of approximately 12% compared with the baseline condition.

4. Discussion of Electrical Loss Reduction Opportunities

The findings demonstrate that electrical losses originate from multiple interconnected subsystems rather than a single component. Cooling infrastructure remained the dominant contributor to excess energy consumption, indicating that future optimization efforts should prioritize HVAC modernization. Technologies such as free cooling, liquid cooling, and AI-assisted thermal management could significantly reduce cooling-related energy demand.

UPS systems represented the second-largest source of energy losses. Although modern UPS technologies offer high conversion efficiencies, the presence of multiple conversion stages inevitably introduces additional energy consumption. Load balancing among redundant UPS modules and the adoption of next-generation high-efficiency UPS architectures could further improve electrical performance.

Transformer loading optimization also emerged as an important factor. Operating transformers closer to their optimal efficiency range can reduce no-load losses and improve overall energy utilization. Therefore, infrastructure sizing strategies should carefully consider future load growth projections to avoid excessive overprovisioning.

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5. Implications for Sustainable Data Center Management

From a sustainability perspective, the results confirm that renewable energy integration can simultaneously reduce carbon emissions and improve operational efficiency when supported by appropriate electrical infrastructure design. This finding aligns with global Environmental, Social, and Governance (ESG) objectives and demonstrates how engineering decisions directly influence sustainability outcomes.

The proposed SLD-based evaluation methodology provides a practical alternative for facilities lacking access to real-time Building Management System (BMS) data. By leveraging existing engineering documentation, operators can estimate energy performance, identify loss-generating components, and evaluate potential renewable integration strategies without requiring extensive metering investments.

Furthermore, the simulation-based approach functions as a technical stress-test for future infrastructure modifications. Facility managers can assess the operational consequences of renewable energy adoption before implementation, thereby minimizing the risk of system instability, protection-device tripping, or unexpected downtime. Consequently, the methodology contributes not only to energy-efficiency improvement but also to maintaining the high reliability standards required for mission-critical data center operations.

DISCUSSION

1. The Strategic Role of Electrical Infrastructure Efficiency in Improving Data Center Performance

The findings indicate that electrical infrastructure efficiency significantly influences overall data center performance, particularly through its impact on Power Usage Effectiveness (PUE). The simulation results revealed that losses originating from transformers, UPS modules, and cooling systems collectively contributed to a substantial increase in total facility energy consumption. This finding supports the work of Wang et al. (2024), who concluded that electrical distribution architecture is one of the most influential determinants of energy efficiency in mission-critical facilities. Similarly, Ahmed et al. (2024) demonstrated that power conversion losses within UPS systems can account for up to 5% of total facility electricity demand, thereby increasing operational costs and carbon emissions.

The present study further confirms that infrastructure optimization should not focus solely on information technology equipment. Instead, supporting systems such as cooling plants, transformers, and power distribution units must be considered as integral components of energy management strategies. Brown et al. (2024) reported that data centers with optimized electrical

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architectures consistently achieved lower PUE values compared to facilities that prioritized server efficiency alone. The reduction of PUE from 1.67 to 1.47 observed in this study demonstrates the effectiveness of a holistic infrastructure approach.

From a regulatory perspective, these findings are highly relevant to Indonesia's commitment to sustainable energy development under the national energy framework established through Government Regulation No. 40 of 2025 concerning National Energy Policy. The regulation emphasizes energy efficiency, decarbonization, and long-term energy sustainability as key national priorities through 2060. Therefore, improving electrical infrastructure efficiency in data centers directly contributes to national energy conservation objectives.

2. Renewable Energy Integration as a Pathway Toward Green Data Centers

One of the most significant findings of this study is that renewable energy integration can substantially reduce dependence on fossil-fuel-generated electricity while simultaneously lowering carbon emissions. The simulation results showed that a 60% renewable energy penetration scenario reduced estimated emissions by nearly 58% while improving PUE performance. These results align with Chen et al. (2023), who found that large-scale wind power integration can significantly improve the environmental sustainability of data center operations. Similar conclusions were reported by Kim et al. (2025), who demonstrated that hybrid renewable energy systems provide both environmental and economic benefits when properly integrated with intelligent power management systems.

However, this study also confirms that renewable energy integration alone does not automatically improve facility efficiency. Without synchronized UPS operation, energy storage support, and load-balancing mechanisms, intermittent renewable generation may introduce voltage instability and frequency fluctuations. This observation supports the findings of Lee and Choi (2023), who identified power stability as one of the most critical challenges in renewable-powered data centers.

The results are highly consistent with Indonesia's renewable energy transition agenda under Presidential Regulation No. 112 of 2022 concerning the Acceleration of Renewable Energy Development for Electricity Supply. The regulation encourages the deployment of renewable energy technologies, including solar and wind power, to reduce greenhouse gas emissions and achieve national renewable energy targets. Furthermore, the issuance of MEMR Regulation No. 5 of 2025 strengthens the legal framework for renewable energy procurement and long-term power

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purchase agreements, creating favorable conditions for renewable-powered data center development.

3. Power Usage Effectiveness (PUE) as an Indicator of Sustainability Performance

The reduction in PUE achieved through infrastructure optimization and renewable energy integration demonstrates that PUE remains a valuable metric for evaluating data center sustainability. A lower PUE indicates that a greater proportion of electrical energy is being utilized for productive computing activities rather than being dissipated through supporting systems. The present study achieved a 12% improvement in PUE, indicating a substantial increase in operational efficiency.

This finding is consistent with research by Garcia et al. (2023), which concluded that continuous monitoring of PUE enables organizations to identify inefficiencies and prioritize investments in energy-saving technologies. Likewise, Santos et al. (2024) emphasized that PUE remains one of the most widely accepted benchmarks for measuring environmental performance in data centers. Although emerging sustainability indicators such as Carbon Usage Effectiveness (CUE) and Water Usage Effectiveness (WUE) are increasingly important, PUE continues to serve as the primary operational metric used by facility managers.

Moreover, recent industry analyses emphasize that green data centers should evaluate not only energy efficiency but also carbon emissions, renewable energy utilization, and resource conservation. Consequently, future sustainability assessments should combine PUE with complementary indicators to provide a more comprehensive understanding of environmental performance.

4. Implications for ESG Compliance and Sustainable Finance

Another important implication of this study concerns Environmental, Social, and Governance (ESG) compliance. Investors, financial institutions, and regulators increasingly evaluate infrastructure projects based on sustainability criteria. The observed reductions in energy consumption and carbon emissions indicate that renewable-powered data centers can significantly improve ESG performance indicators.

This finding supports Anderson and Miller (2024), who argued that energy-efficient facilities are more attractive to investors because they demonstrate lower environmental risk and greater long-term operational resilience. Similarly, Garcia et al. (2023) reported that organizations implementing renewable energy and energy-efficiency initiatives generally receive more

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favorable sustainability assessments.

In Indonesia, ESG reporting requirements continue to evolve through the Sustainable Finance framework administered by the Financial Services Authority (OJK). Regulation POJK No. 51/POJK.03/2017 requires financial institutions, issuers, and public companies to implement sustainable finance principles and publish sustainability reports. The efficiency improvements identified in this study could therefore contribute directly to sustainability reporting requirements, particularly regarding energy consumption, greenhouse gas emissions, and environmental responsibility. Additionally, the Indonesia Taxonomy for Sustainable Finance (TKBI) Version 2 introduced in 2025 provides a national framework for classifying sustainable economic activities and supporting net-zero emission targets.

5. Data Center Sustainability and National Climate Commitments

The environmental implications of this study extend beyond organizational performance and contribute to broader national climate objectives. Indonesia has formally committed to reducing greenhouse gas emissions through its ratification of the Paris Agreement under Law No. 16 of 2016. Consequently, energy-intensive sectors such as data centers are increasingly expected to contribute to emission reduction efforts through energy efficiency improvements and renewable energy adoption.

The findings indicate that renewable energy integration combined with electrical infrastructure optimization can significantly reduce the carbon footprint of digital infrastructure. This observation aligns with Patel and Roy (2023), who argued that the decarbonization of data centers is essential for achieving national climate targets in rapidly digitalizing economies. Likewise, Jones et al. (2024) emphasized that the expansion of artificial intelligence and cloud computing will continue to increase electricity demand unless supported by low-carbon energy systems.

Furthermore, Indonesia has introduced various policy instruments to support decarbonization, including sustainability reporting requirements, carbon pricing initiatives, and the establishment of the Indonesia Carbon Exchange. These policy developments suggest that future data center investments will increasingly be evaluated not only based on technical performance and financial returns but also on their contribution to carbon reduction and environmental sustainability. Therefore, the proposed SLD-based methodology provides a practical engineering framework for supporting future green data center development while ensuring alignment with national energy policies, climate commitments, and international

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sustainability standards.

6. Theoretical and Practical Contributions of the Proposed SLD-Based Approach

From a theoretical perspective, this study extends previous research by demonstrating that Single Line Diagram (SLD) analysis can serve as a reliable alternative data source for evaluating energy efficiency in facilities where real-time Building Management System (BMS) data are unavailable. While previous studies primarily relied on direct operational monitoring, the present research shows that engineering documentation can provide sufficient information for estimating power losses, evaluating renewable energy integration scenarios, and forecasting PUE performance.

From a practical perspective, the methodology offers significant advantages for facility operators, consultants, and policymakers. The approach minimizes dependence on expensive monitoring infrastructure while enabling detailed assessments of electrical performance. As data center capacity in Indonesia continues to expand rapidly, the ability to evaluate energy efficiency using existing engineering documentation may become increasingly valuable for supporting sustainable infrastructure planning and regulatory compliance. The methodology therefore represents an important contribution to the development of resilient, efficient, and environmentally responsible digital infrastructure in Indonesia.

CONCLUSION

This study successfully demonstrated that the optimization of electrical infrastructure through Single Line Diagram (SLD)-based analysis can serve as an effective approach for evaluating and improving energy efficiency in modern data center facilities. The findings revealed that significant energy losses originate from supporting electrical systems, particularly cooling plants, UPS modules, and transformer operations, rather than from information technology equipment alone. The baseline analysis showed a Power Usage Effectiveness (PUE) value of 1.67, indicating that a considerable portion of facility energy consumption was allocated to non-IT functions. Through the proposed simulation framework, renewable energy integration combined with electrical infrastructure optimization successfully reduced the PUE value to 1.47, representing a substantial improvement in overall operational efficiency. These results confirm that energy efficiency initiatives in mission-critical facilities should adopt a holistic approach encompassing power distribution systems, cooling technologies, and renewable energy deployment rather than focusing exclusively on server performance.

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Furthermore, the study demonstrated that renewable energy integration can significantly contribute to both environmental sustainability and operational performance when supported by appropriate electrical architecture. The simulation results indicated that higher levels of renewable energy penetration reduced dependence on conventional grid electricity and substantially lowered carbon emissions without compromising system reliability. However, the findings also emphasized that renewable energy adoption alone does not automatically improve data center performance. Effective synchronization among UPS systems, battery storage, load-balancing mechanisms, and renewable generation sources is essential to maintain voltage stability and uninterrupted operation. Consequently, the proposed SLD-based methodology offers a practical engineering tool for assessing renewable energy readiness, identifying efficiency improvement opportunities, and supporting strategic decision-making in sustainable data center development. The research therefore contributes both theoretically and practically to the growing body of knowledge on green data center infrastructure, energy transition strategies, and sustainable digital transformation.

RECOMMENDATIONS

Based on the findings of this study, several recommendations can be proposed for future implementation and research. First, data center operators should prioritize the modernization of cooling systems because cooling infrastructure was identified as the largest contributor to non-IT energy consumption. The adoption of advanced cooling technologies such as liquid cooling, free cooling systems, AI-assisted thermal management, and high-efficiency chillers may further reduce facility energy demand and improve PUE performance. Second, organizations should integrate renewable energy resources with intelligent energy management systems capable of balancing fluctuations in renewable generation. The deployment of battery energy storage systems, predictive load management, and dynamic UPS synchronization mechanisms can enhance operational resilience while maximizing renewable energy utilization. Third, policymakers should continue strengthening regulatory frameworks that encourage renewable energy adoption, energy efficiency improvements, and sustainability reporting within digital infrastructure sectors. Future research may expand the proposed methodology by incorporating real-time Building Management System (BMS) data, Carbon Usage Effectiveness (CUE), Water Usage Effectiveness (WUE), digital twin technologies, artificial intelligence-based optimization algorithms, and economic feasibility assessments to provide a more comprehensive evaluation of sustainable data center performance.

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