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# INTEGRATED ARCHITECTURE PROPOSAL FOR THE COLLECTION AND PROCESSING OF ENERGY METRICS IN DATA CENTERS

**Annia Lisbeth Barbán Acea**[1]

[1]Technological University of Havana José Antonio Echeverría
[1]e-mail: annia@tele.cujae.edu.cu

## ABSTRACT

Rising energy consumption in data centers underscores the need for precise energy efficiency evaluation. This article critically examines current metrics for assessing data center energy performance, with particular attention to the limitations of the Power Usage Effectiveness (PUE). Additional metrics are examined to enable a general assessment that links energy consumption to service quality. Commercial and open-source tools for estimating PUE are compared based on their accuracy, usability, and cost-effectiveness. A layered integration architecture is introduced to measure energy efficiency metrics. This approach addresses the heterogeneity of energy data and supports accurate, near real-time presentation measurements for analysis of data center efficiency.

**KEYWORDS:** energy efficiency, PUE, data centers, evaluation tools, energy management.

# PROPUESTA DE ARQUITECTURA INTEGRADA PARA LA RECOLECCIÓN Y PROCESAMIENTO DE MÉTRICAS ENERGÉTICAS EN CENTROS DE DATOS

## RESUMEN

El aumento del consumo energético en los centros de datos pone de relieve la necesidad de evaluar con precisión su eficiencia energética. Este artículo examina de forma crítica los parámetros actuales para evaluar el rendimiento energético de los centros de datos, prestando especial atención a las limitaciones del índice de Eficiencia de Uso de Energía (PUE). Se examinan parámetros adicionales para permitir una evaluación general que vincule el consumo energético con la calidad del servicio. Se realiza una comparativa entre herramientas comerciales y de código abierto para estimar el PUE, basándose en su precisión, usabilidad y rentabilidad. Se introduce una arquitectura de integración por capas para medir las métricas de eficiencia energética. Este enfoque aborda la heterogeneidad de los datos energéticos y permite una medición y un análisis precisos y en tiempo real de la eficiencia de los centros de datos.

**PALABRAS CLAVES:** eficiencia energética, PUE, centros de datos, herramientas de evaluación, gestión energética.

## 1. INTRODUCTION

The rapid expansion of data centers, fueled by cloud computing, artificial intelligence (AI), and digital transformation, is driving significant increases in energy demand and environmental strain [1]. In particular, AI applications currently account for 10%-20% of data center electricity usage, since they are significantly more energy-intensive than traditional queries [2]. The International Energy Agency's 2025 report indicates global energy demand grew by 4.2% from 2023 to 2024, largely due to increasing demand for data center cooling. As data volume expands, that share is projected to rise further (see Fig. 1) [3], [4]. While data centers play a critical role in modern infrastructure, their growing energy footprint poses a serious threat to sustainable development and cost efficiency. This reality highlights the urgent need for innovative solutions to meet their rising energy requirements [5], [6].

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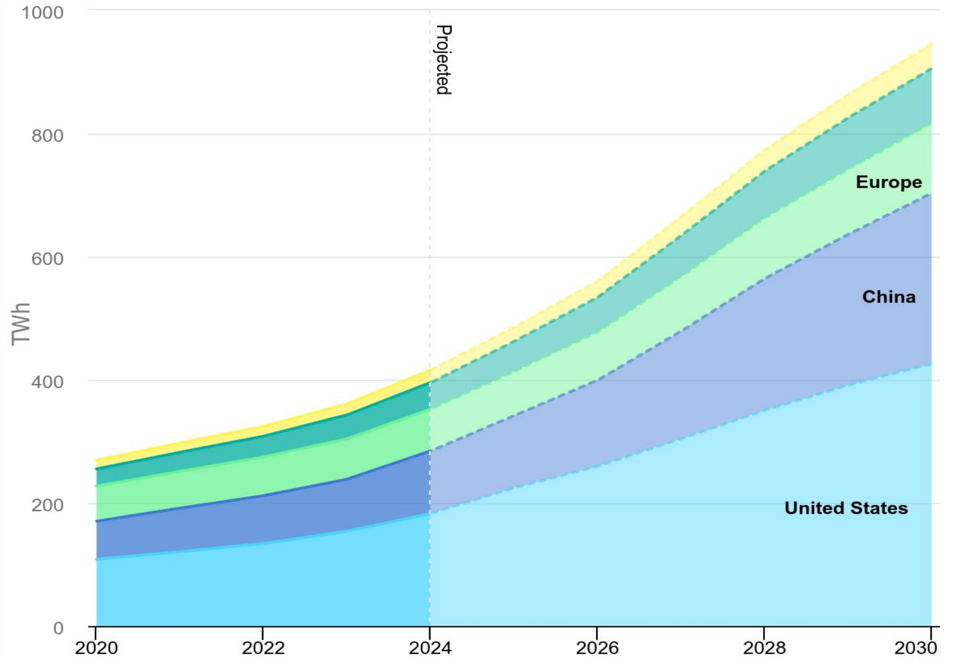


Figure 1: Data center energy consumption by region, 2020-2030 [3].

A significant challenge lies in the complexity and diversity of data center infrastructure. Traditional energy management strategies are frequently insufficient for addressing the heterogeneous characteristics of modern data centers, especially those with legacy infrastructure and limited monitoring capabilities (see Fig. 2) [7]. These limitations impede the accurate measurement and optimization of energy consumption at the IT service level where efficiency gains and losses occur [8].

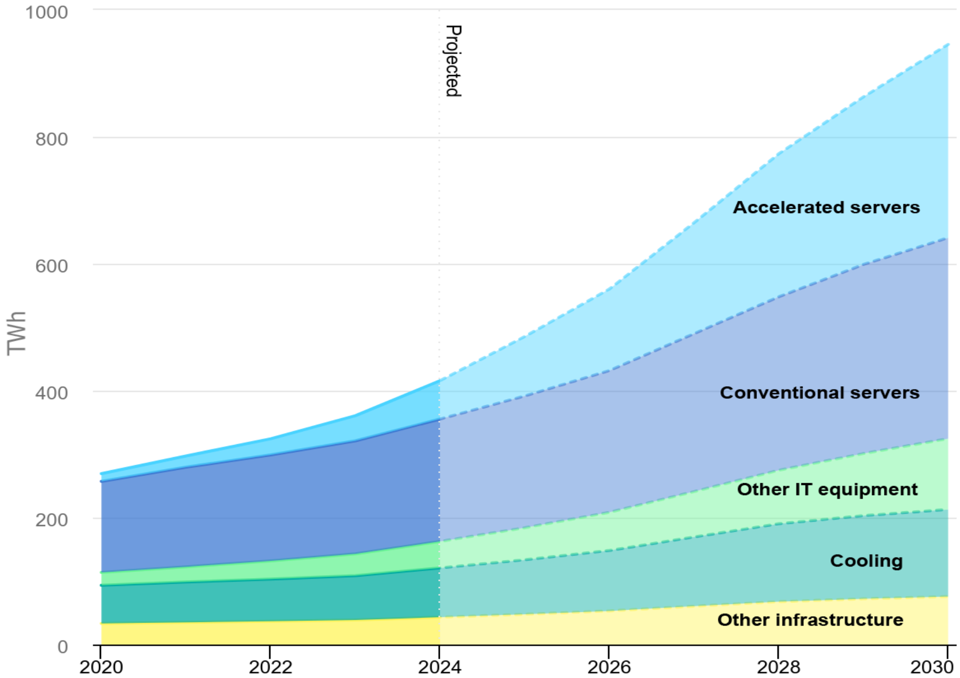


Figure 2: Global data center energy consumption by equipment, 2020-2030 [3].

Advanced platforms have been developed to address these challenges by integrating data collection from multiple sources and applying sophisticated analytics, including machine learning and deep learning, to provide near real-time,

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granular insights into power usage and to predict resource utilization and energy consumption [9], [10], [11]. Automation tools enable dynamic adjustments of workloads, cooling systems, and power distribution, offering energy optimization that manual interventions cannot achieve [12]. For instance, specific frameworks employ AI techniques such as K-means clustering to optimize cooling parameters, while monitoring systems automate power state control of compute nodes to balance energy availability and computational requirements [13]. Such precise and scalable management solutions are crucial for optimizing energy consumption, preventing operational disruptions, and ensuring compliance with increasingly stringent environmental regulations [14].

This article examines the state-of-the-art energy efficiency management in data centers, focusing on integrated solutions and automated monitoring frameworks. It presents a thorough analysis from infrastructure-level sensing to service-level energy attribution, illustrating how modern automation transforms the operational landscape of energy management in data centers, enabling robust, scalable, and eco-friendly IT ecosystems.

## 2. METRICS TO EVALUATE ENERGY USAGE EFFECTIVENESS IN DATA CENTERS

Energy usage effectiveness metrics are fundamental in evaluating and optimizing the operational energy efficiency of data centers. This section provides an overview of the principal energy usage metrics, methodologies, and applicability within modern data center energy management paradigms.

### Power Usage Effectiveness

Power Usage Effectiveness (PUE) is the standard industry metric for evaluating energy efficiency within data center infrastructure [15]. PUE is calculated as the ratio of the total energy consumed by the entire facility ($E_{DC}$) to the energy consumed solely by its Information Technology (IT) equipment ($E_{IT}$) (1). $E_{DC}$ encompasses all critical supporting systems, including cooling, power distribution units (PDUs), and lighting. PUE value is always greater than 1, as the energy consumption of heating, ventilation and air-conditioning (HVAC) systems constitutes a significant portion of the total energy consumption [16].

$$PUE = \frac{E_{DC}}{E_{IT}} = \frac{\sum DC\ energy\ consumption}{energy\ compsution\ of\ IT\ equipment} \quad (1)$$

Developed by the Green Grid Association, the methodologies for calculating PUE are described in several recognized standards such as ISO/IEC 30134-2:2016 and EN 50600-4-2:2016 [17]. Adhering to these standards provides organizations with critical insights into their energy consumption patterns, facilitating the identification of substantial opportunities for energy-efficient operational improvements.

Despite its prevalence, PUE exhibits several critical limitations that undermine its reliability as a comprehensive measure of data center sustainability and operational performance [16]. PUE measurements involve nuanced considerations such as temporal variation, equipment heterogeneity, and site-specific environmental conditions that affect baseline calculations and benchmarking [18]. It overlooks upstream energy losses, including power generation and transmission inefficiencies, and downstream energy use beyond the data center boundary. Additionally, PUE does not consider IT workload efficiency [19]. Two data centers with similar PUE values can exhibit drastically different levels of computing resource utilization, leaving potential energy waste from workloads unmeasured. As a result, PUE does not consistently serve as a clear indicator of energy efficiency. To address these deficiencies, [20] recommends the supplementation of PUE with additional metrics that offer a more detailed evaluation framework.

### Data center infrastructure efficiency

Data Center Infrastructure Efficiency (DCiE) is used to measure the data center's efficiency by determining the ratio of the power consumed by IT equipment to the total power of the entire facility. It functions as the inverse of PUE (2). This metric provides insights into the proportion of energy dedicated to computing tasks versus supporting overheads such as cooling and power distribution. A higher DCiE indicates improved efficiency in directing power towards IT operations [21].

$$DCiE = \frac{1}{PUE} \quad (2)$$

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**IT Equipment Energy Efficiency for servers**

The standard ISO/IEC 30134-4:2017 for IT Equipment Energy Efficiency for servers (ITEEsv) refers to assessing and optimizing energy consumption in server operations within data centers. It describes the maximum power performance of all or a group of servers in a data center, based on a specification or the potential performance of these servers. ITEEsv reflects the energy efficiency capacity of servers, not the energy efficiency in a real server operating situation [22]. The formula (3) determines where SMPE is the maximum performance of a server $i$, and SMPO is the maximum energy consumption in kW [23].

$$ITEEsv = \frac{\sum_{i=1}^{n} SMPE_i}{\sum_{i=1}^{n} SMPO_i} \quad (3)$$

**Cooling Efficiency Ratio**

The Cooling Efficiency Ratio (CER) is a metric designed to quantify the energy efficiency of cooling systems within data centers. Standardized by ISO/IEC 30134-7:2023 and EN 50600-4-7, CER evaluates the effectiveness of cooling infrastructure by comparing the amount of heat removed ($Q_{dissipated}$) from the data center to the electrical energy consumed ($E_{cooling}$) by the cooling systems, measured in kilowatt-hours (kWh) (4). CER complements efficiency metrics like PUE by focusing specifically on the HVAC subsystem, which typically accounts for a substantial portion of a data center's total energy demand [24].

$$CER = \frac{Q_{dissipated}}{E_{cooling}} \quad (4)$$

A higher CER value signifies a more efficient cooling system, indicating more heat removal per unit of electrical energy consumed. Effective measurement and continuous monitoring of CER allow data center operators to identify opportunities for energy optimization. It is important to mention that CER values are context-dependent and can vary based on data center size, climate, and technology used [25]. Integrating CER into a comprehensive monitoring framework alongside complementary metrics such as ITEEsv and PUE provides a complete perspective of energy efficiency in data center.

**Control Process Unit load and energy consumption**

The Central Processing Unit **(**CPU) is one of the most power-consuming components within a server, and its energy usage varies dynamically based on the workload it processes [26]. The power consumption climbs accordingly when the CPU load increases [27]. Conversely, the CPU enters power-saving states at lower loads, which significantly reduces energy use. Modern CPUs use Dynamic Voltage and Frequency Scaling (DVFS) to adjust their operating frequency and voltage based on workload demands [28].

Estimating the energy consumption of a service based on CPU usage involves correlating processor utilization with dynamic power consumption characteristics [29]. The usual method for measuring an application's CPU usage over a specific period involves calculating the percentage of time the processor was actively executing instructions for that application compared to the total time elapsed during that interval (5).

$$CPU_{usage} = \frac{CPU_{Time\ Active}}{t} \times 100 \quad (5)$$

The relationship between CPU load and power consumption is typically nonlinear. Maximizing throughput or minimizing latency may require running CPUs at higher power states. As utilization approaches maximum levels, power rises sharply from idle to moderate loads. Therefore, minor load increases at low utilization can cause more relative power rise than higher loads [30]. Different tasks, such as floating-point operations and integer calculations, also affect power consumption for similar loads, as some instructions require more active circuitry and memory access. Recent research did not reflect substantial improvements in energy consumption reduction and performance optimization for High Performance Computing (HPC) environments when using granular measurement in CPUs and applications in traditional aggregate metrics [31]. Understanding the correlation of energy consumption with performance is crucial for optimizing workload allocation, thereby improving energy efficiency [32].

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**Energy per transaction or request**

Measuring energy consumption at the service level is essential for obtaining an accurate and actionable view of energy efficiency in a data center. Unlike general metrics, such as PUE and DCiE, which only consider total or infrastructure-level consumption, detailed service-level measurement identifies how and where energy is used based on specific workloads, applications, and processes. The Energy per Transactions ($E_{transactions}$) or Megabit per Watts (Mbps/W) indicators address this gap by quantifying the energy efficiency of data transmission and processing at the application or network service level [33].

Energy per Transactions or Request quantifies the energy consumed for a service to process a bit. $E_{total}$ is the total energy consumed during the measurement interval (in Joules per bit), and $N_{transactions}$ is the number of processed transactions or requests in that interval (6). This metric enables the evaluation of operational efficiency and comparison between different service implementations [34]. Megabits or Performance per watt (Mbps/W) are equivalent to $E_{transactions}$ and express how many megabits per second are obtained per watt consumed.

$$E_{transactions} = \frac{E_{total}}{N_{transactions}} \quad (6)$$

Such specific, quantitative metrics empower data center operators to optimize resource allocation, refine workload scheduling, and guide infrastructure improvements, all aimed at reducing overall energy consumption while maintaining service quality. Other metrics for energy consumption analysis are discussed in [35], [36].

## 3. OVERVIEW OF DATA CENTER ENERGY MEASUREMENT

The accurate and comprehensive measurement of PUE requires multiple tools and systems that collect data across all critical layers of a data center. These tools facilitate centralized management and analysis of energy consumption, enabling data center operators to optimize performance and reduce costs. According to IEA definitions and industry standards, a data center can be divided into three main layers for energy evaluation: infrastructure, services, and IT equipment [17] (see Table 1). Each layer requires specialized tools for effective monitoring and management of PUE.

Table 1: Overview of a data center [17], [22].

| | | | | |
|---|---|---|---|---|
| Service Level | User IT service/business process | | | |
| | Applications, VNF, HPC, cloud platforms. | | | |
| | Virtualization and container platforms, hypervisors, Operating System | | | |
| IT equipment Level | Servers | Storage | Networking | PNF |
| Infrastructure Level | HVAC | Power | Lighting | Others |
| Data Center | | | | |

**Infrastructure**

The infrastructure in data centers comprises critical support systems such as HVAC, power distribution, and physical protection equipment. These components contribute significantly to a data center's overall energy consumption, often exceeding half of the overall power usage. HVAC systems, in particular, represent a significant energy demand due to the need to maintain optimal operating temperatures for IT equipment. Power distribution components such as uninterruptible power supply (UPS), transformers, and PDUs contribute to energy use and potential losses.

Furthermore, data center operators could address infrastructure lacking built-in intelligence and native monitoring capabilities by deploying external sensor networks and complementary solutions to provide precise and near real-time data. These sensors can communicate with central monitoring platforms via standard protocols such as Simple Network Management Protocol (SNMP), Modbus, or BACnet.

**IT equipment**

This area encompasses the physical hardware components that execute computing and data storage functions within the data center. The equipment includes servers, storage units, and physical network functions (PNF) such as switches

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and routers. These components are among the largest energy consumers, accounting for a substantial fraction of total power use. Effective energy monitoring at this level requires measuring power consumption at a granular hardware level, often through embedded sensors or inline power meters on racks and devices. This data enables identification of inefficient or underutilized hardware, supporting strategies such as server consolidation, hardware upgrades to more energy-efficient models, and network device optimization. Additionally, ensuring the smooth operation of PNFs reduces unnecessary retransmissions and reprocessing, indirectly contributing to energy savings. Detailed insights into server infrastructure-level power consumption enable comprehensive energy management across the data center's IT infrastructure.

**Services**

The services layer includes the software processes, applications, and computing tasks that run on the IT equipment and directly impact energy consumption. Key resources such as CPU load, memory utilization, and network activity dictate how intensively the servers operate, influencing their power draw. Accurate power measurement at this level enables a more granular and actionable understanding of the total energy consumption in data centers.

Monitoring tools in this layer primarily focus on collecting detailed performance metrics and correlating them with power consumption data to understand the energy cost of specific workloads. This correlation allows for identifying energy-intensive services and predicting energy consumption based on expected service loads, improving overall energy efficiency, and enhancing capacity planning. Therefore, tracking service-level metrics is crucial for maximizing energy efficiency at the hardware level and throughout the operational lifecycle of data center services.

## 4. AUTOMATED TOOLS FOR MEASURING ENERGY EFFICIENCY IN DATA CENTERS

Automated tools for measuring energy efficiency in data centers are essential for enabling continuous monitoring and optimization of resource consumption. Their use supports eco-friendly infrastructure management by identifying inefficiencies and guiding data-driven decisions to reduce environmental impact. When used collectively, they offer a comprehensive view of energy use, enabling operators to calculate more accurate PUE values and devise strategies for efficiency enhancement.

**Data Center Infrastructure Management**

The Data Center Infrastructure Management (DCIM) software is a centralized platform that aggregates, organizes, and interprets data streams from the infrastructure and IT equipment. The standards ANSI/BICSI 002-2024 [37] and ISO/IEC 18598:2016 [38] include a dedicated section for DCIM. The main functions of DCIM include integrating electrical, environmental, and operational data into a unified database, providing live dashboards and visualizations that show energy flow and equipment status across the data center [39]. One of the main advantages of DCIM is that it calculates PUE dynamically by dividing the total energy consumption of the facilities (based on infrastructure data) by the energy consumption of the IT equipment, updated at configurable time intervals. It also allows the configuration of alarms to notify data center operators when energy use deviates from expected ranges, enabling quick response to potential issues [40].

To comprehensively assess and optimize energy efficiency, DCIM systems are integrated with other platforms to facilitate a multidimensional analysis of energy consumption by linking physical infrastructure data with operational IT metrics. This integration enables the correlation of IT resource utilization metrics with the corresponding power consumption [41]. This granular insight aids in pinpointing specific software services or processes that disproportionately contribute to energy consumption. Such automation mitigates the need for manual intervention, enhancing responsiveness and maintaining energy consumption monitoring under dynamic conditions [42].

**Comparison of commercial and open-source platforms for measuring Energy Efficiency in data centers**

Considering commercial and open-source software solutions, it is important to provide a comprehensive perspective on tools for monitoring and improving energy efficiency in data centers. Each offers unique advantages and limitations for measuring energy efficiency and managing infrastructure. These tools differ in cost, functionality, scalability, and integration capabilities. Commercial solutions often provide robust, user-friendly platforms with advanced energy monitoring and predictive analytics designed for large-scale, complex environments, but have significant licensing costs. Alternatively, open-source tools offer flexibility and cost advantages, which are ideal for organizations with

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strong technical resources who are willing to customize and integrate additional energy monitoring tools. Their energy measurement capabilities depend on external devices and require more manual configuration. Choosing between these alternatives depends on the data center's size, budget, technical expertise, and specific energy monitoring requirements (see Table 2).

Table 2: Comparison of commercial and open-source DCIM for measuring energy efficiency in data center.

| Features | Commercial | Open-Source |
|---|---|---|
| Cost | Licensing/subscription fees. | Free, community-supported. |
| Data analytics | Advanced near real-time, AI-driven. | Basic or dependent on external integrations. |
| Ease of use | Intuitive UIs, professional vendor support. | Requires technical proficiency, self-managed. |
| Integration | Broad hardware and sensor compatibility. | Dependent on plugins and custom API usage |
| Scalability | Suitable for large and complex deployments. | Suitable for small to mid-sized or customized setups. |
| Flexibility | Vendor-specific customization limits. | Open codebase enables unlimited customization. |
| Support | Professional support, training and updates. | Community based. |
| Deployment | Cloud, on-premises, hybrid. | On-premises and self-hosted. |
| Granularity | High, near real-time detailed data. | Moderate, relies on external hardware. |

## 5. INTEGRATION ARCHITECTURE FOR ENERGY MEASUREMENT IN DATA CENTERS

Accurate measurement and management of PUE in data centers demand the combination of diverse monitoring technologies. Multiple monitoring tools and platforms to capture, correlate, and analyze energy consumption data at the different proposed layers are needed to achieve this. In this section, the authors propose an integrated system architecture where various monitoring technologies converge within a DCIM platform to provide centralized control of energy consumption (see Fig. 3). This architecture centrally collects, analyzes, and visualizes energy and operational data across multiple layers, enabling informed decision-making, predictive maintenance, and resource optimization.

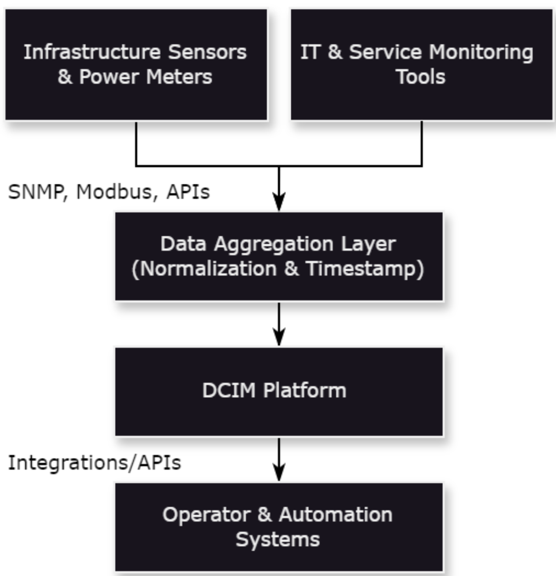


Figure 3: Proposed architecture.

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**Infrastructure sensors and power meters**

This layer consists of an array of electrical and environmental sensors distributed across the data center's critical infrastructure components. The external sensor networks will complement existing equipment to provide detailed energy consumption and environmental data. The energy consumption is monitored in this module using high-precision power meters to capture the actual electrical usage by infrastructure components. Environmental parameters such as temperature and humidity are tracked to correlate with cooling efficiency metrics like CER. This data will directly feed foundational PUE calculations, as total facility energy is aggregated based on measurements in this layer.

**IT and Service Monitoring tools**

This upper layer integrates IT service-level monitoring, capturing CPU usage, network throughput, storage activity, virtualized resources, and application performance metrics. The integration with tools will enable correlating service-level operational data with energy consumption. This granularity helps optimize workload placement and server utilization, which is critical for energy efficiency and cost reduction.

**Data Aggregation Layer**

Sensor outputs are often heterogeneous in protocol and format. Protocols such as SNMP will facilitate collection, while time synchronization will ensure data coherence. The raw data, usually in heterogeneous formats with varying timestamps and measurement units, are converted into a unified, time-synchronized format, such as JavaScript Object Notation (JSON). This results in consistent, comparable data streams suitable for accurate calculations. The layer includes error detection, cleansing, and filtering mechanisms to remove outliers, correct transmission errors, and handle missing data, enhancing data quality. Finally, the system forwards this organized dataset to DCIM platforms.

**DCIM platform**

The DCIM platform serves as the core system unifying all data streams. This module synthesizes infrastructure energy data with IT service metrics, enabling detailed energy attribution and operational insights. Its primary functions include near real-time monitoring dashboards that visualize power flows, thermal maps, rack-level consumption, and equipment status. Automated and configurable PUE calculation engines, continuously compute ratios from the total facility consumption versus IT equipment consumption. Asset management, workflow orchestration, and predictive analytics leverage advanced machine learning algorithms to forecast capacity demand and identify potential failures or inefficiencies. Alerting mechanisms and integration with ticketing systems facilitate proactive maintenance and operational response.

**Operator and Automation Systems**

Finally, operators access the integrated platform through web-based interfaces and mobile apps, enabling remote monitoring and control. Automated feedback loops allow for continuous adjustments in cooling, power provisioning, and IT workload distribution, embodying the principles of intelligent and eco-friendly data center operation.

## 6. ANALYSIS AND DISCUSSION OF THE PROPOSAL

The proposed architecture operates within a heterogeneous data center environment that includes devices and components frequently lacking automated management capabilities. Collecting environmental metrics from multiple sources in such environments introduces significant technical challenges that affect the accuracy, consistency, and utility of the resulting data. Sensor technologies, communication protocols, models, and measurement ranges often vary, particularly among low-cost devices, leading to discrepancies and increased error rates that undermine data reliability. Device heterogeneity also complicates the comparison of metrics across different times and locations. The data aggregation layer serves as the primary component responsible for adaptation and normalization, functioning as middleware between the upper layers and the DCIM platform.

Additional technical challenges include the efficient management of data storage, transmission, and processing requirements. In large-scale data centers with thousands of temperature and humidity sensors, the volume of environmental data generated may exceed several gigabytes per day. Consequently, the communications infrastructure

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must adapt dynamically to changing bandwidth and latency constraints, which depend on the data center's size, the number of sensors, and the frequency of data acquisition.

A further challenge involves the selection of a DCIM tool. The authors propose using a free and open-source software platform to prioritize flexibility and adaptability. Nevertheless, the preceding comparison indicates that such solutions offer reduced functionality relative to licensed alternatives. Notable limitations include incompatibility with certain operating systems or hardware, which complicates integration with other layers of the proposed architecture. Therefore, the availability of up-to-date documentation, the activity level of the development community, ease of integration with multiple protocols, accessible application programming interfaces, and inherent adaptability are critical factors in the selection process.

## 7. CONCLUSIONS

This article examines the established metrics for energy efficiency in data centers, highlighting the limitations of relying exclusively on Power Usage Effectiveness (PUE) as a single performance indicator. Although PUE remains a key indicator of overall energy overhead at the facility level, it does not adequately reflect IT resource utilization, workload-specific energy consumption, environmental impact, and operational behavior. Complementary metrics like CER and service-level indicators such as Energy per Transaction, provide a more refined perspective by linking energy use to service performance and sustainability objectives. The granularity achieved by CPU-level and application-specific energy monitoring is particularly critical in HPC contexts, enabling targeted optimizations that aggregate metrics overlook.

The authors provide a comprehensive evaluation of current tools for measuring energy efficiency in data centers. Analysis showed significant differences in tool performance, underlining the necessity of informed selection based on data center requirements and resource availability. The authors recommend prioritizing tools that balance between precision and adaptability. The proposed layered integration architecture addresses fundamental challenges of heterogeneity, data synchronization, and normalization, turning disparate data into coherent, actionable intelligence. The Data Aggregation Layer plays a pivotal role in ensuring interoperability and scalability across data sources and management platforms. Ultimately, advancing data center energy efficiency demands moving beyond basic metrics and adopting comprehensive, integrated approaches that support intelligent, adaptive management. This research reinforces the imperative need for continuous innovation in energy metrics and monitoring systems, serving as a basis for practical enhancements and academic exploration to build more eco-friendly and efficient digital infrastructures.

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## REFERENCES

[1] V. Milić, “Next-generation data center energy management: a data-driven decision-making framework,” *Front. Energy Res.*, vol. 12, Sep. 2024, doi: 10.3389/fenrg.2024.1449358. Available: https://www.frontiersin.org/journals/energy-research/articles/10.3389/fenrg.2024.1449358/full

[2] “What the data centre and AI boom could mean for the energy sector – Analysis,” *IEA*, Oct. 18, 2024. Available: https://www.iea.org/commentaries/what-the-data-centre-and-ai-boom-could-mean-for-the-energy-sector. [Accessed: Feb. 16, 2025]

[3] “Global Energy Review 2025,” International Energy Agency, Mar. 2025.

[4] A. Capozzoli and G. Primiceri, “Cooling Systems in Data Centers: State of Art and Emerging Technologies,” *Energy Procedia*, vol. 83, pp. 484–493, Dec. 2015, doi: 10.1016/j.egypro.2015.12.168

[5] H. Zhu *et al.*, “Future data center energy-conservation and emission-reduction technologies in the context of smart and low-carbon city construction,” *Sustain. Cities Soc.*, vol. 89, p. 104322, Feb. 2023, doi: 10.1016/j.scs.2022.104322

[6] Q. Clark, F. Acun, I. C. Paschalidis, and A. Coskun, “Learning a Data Center Model for Efficient Demand Response,” *SIGENERGY Energy Inf. Rev*, vol. 4, no. 5, pp. 98–105, Apr. 2025, doi: 10.1145/3727200.3727215

[7] E. Masanet, A. Shehabi, N. Lei, S. Smith, and J. Koomey, “Recalibrating global data center energy-use estimates,” *Science*, vol. 367, no. 6481, pp. 984–986, Feb. 2020, doi: 10.1126/science.aba3758

Received: 10-09-2025, Approved: 11-10-2025
Sitio web:https://revistatelematica.cujae.edu.cu/index.php/tele

[8] S. M. Kak, P. Agarwal, and M. Afshar Alam, "Energy Minimization in a Cloud Computing Environment," in *Intelligent Systems*, A. Sheth, A. Sinhal, A. Shrivastava, and A. K. Pandey, Eds., Singapore: Springer, 2021, pp. 397–405. doi: 10.1007/978-981-16-2248-9_38

[9] W. Khan, D. De Chiara, A. L. Kor, and M. Chinnici, "Advanced data analytics modeling for evidence-based data center energy management," *Phys. Stat. Mech. Its Appl.*, vol. 624, pp. 1–20, Aug. 2023.

[10] M. Smith, L. Zhao, J. Cordova, X. Jiang, and M. Ebrahimi, "Machine Learning-Based Energy-efficient Workload Management for Data Centers," in *2024 IEEE 21st Consumer Communications & Networking Conference (CCNC)*, Jan. 2024, pp. 799–802. doi: 10.1109/CCNC51664.2024.10454842. Available: https://ieeexplore.ieee.org/document/10454842

[11] N. Lei *et al.*, "Generalizable Machine Learning Models for Predicting Data Center Server Power, Efficiency, and Throughput." arXiv, Mar. 09, 2025. doi: 10.48550/arXiv.2503.06439. Available: http://arxiv.org/abs/2503.06439

[12] W. Khan, D. De Chiara, A.-L. Kor, and M. Chinnici, "Advanced data analytics modeling for evidence-based data center energy management," *Phys. Stat. Mech. Its Appl.*, vol. 624, p. 128966, Aug. 2023, doi: 10.1016/j.physa.2023.128966

[13] V. Michalakopoulos *et al.*, "A multi-dimensional unsupervised machine learning framework for clustering residential heat load profiles." arXiv, Nov. 11, 2024. doi: 10.48550/arXiv.2411.16701. Available: http://arxiv.org/abs/2411.16701

[14] S. S. Panwar, M. M. S. Rauthan, and V. Barthwal, "A systematic review on effective energy utilization management strategies in cloud data centers," *J. Cloud Comput.*, vol. 11, no. 1, p. 95, Dec. 2022, doi: 10.1186/s13677-022-00368-5

[15] D. Mukherjee, S. Roy, R. Bose, and D. Ghosh, "A Practical Approach to Measure Data Centre Efficiency Usage Effectiveness," in *Mobile Computing and Sustainable Informatics*, S. Shakya, R. Bestak, R. Palanisamy, and K. A. Kamel, Eds., Singapore: Springer Nature, 2022, pp. 113–122. doi: 10.1007/978-981-16-1866-6_7

[16] G. Fieni, R. Rouvoy, and L. Seinturier, "xPUE: Extending Power Usage Effectiveness Metrics for Cloud Infrastructures," *IEEE Trans. Sustain. Comput.*, pp. 1–13, 2025, doi: 10.1109/TSUSC.2025.3549687

[17] Viegand Maagøe, "Energy Efficiency Metrics for Data Centres," International Energy Agency, Oct. 2022. Available: https://www.iea-4e.org/wp-content/uploads/2022/10/EDNA-Studies-Metrics-for-data-centre-efficiency-Final.pdf

[18] H.-A. Ounifi, A. Gherbi, and N. Kara, "Deep machine learning-based power usage effectiveness prediction for sustainable cloud infrastructures," *Sustain. Energy Technol. Assess.*, vol. 52, p. 101967, Aug. 2022, doi: 10.1016/j.seta.2022.101967

[19] M. Levy and D. Raviv, "A Novel Framework for Data Center Metrics using a Multidimensional Approach," in *Proceedings of the 15th LACCEI International Multi-Conference for Engineering, Education, and Technology: "Global Partnership for Development and Engineering Education,"* Latin American and Caribbean Consortium of Engineering Institutions, 2017. doi: 10.18687/LACCEI2017.1.1.387. Available: http://laccei.org/LACCEI2017-BocaRaton/meta/FP387.html

[20] A. Shaikh, M. Uddin, M. A. Elmagzoub, and A. Alghamdi, "PEMC: Power Efficiency Measurement Calculator to Compute Power Efficiency and $CO_2$ Emissions in Cloud Data Centers," *IEEE Access*, vol. 8, pp. 195216–195228, 2020, doi: 10.1109/ACCESS.2020.3033791

[21] L. Hernandez, G. Jimenez, and P. Marchena, "Energy Efficiency Metrics of University Data Centers," *Knowl. Eng. Data Sci.*, vol. 1, no. 2, p. 64, Aug. 2018, doi: 10.17977/um018v1i22018p64-73

[22] O. Van Geet and D. Sickinger, "Best Practices Guide for Energy-Efficient Data Center Design," National Renewable Energy Laboratory (NREL), Golden, CO (United States), NREL/TP--5R00-89843; DOE/GO--102024-6283, Jul. 2024. doi: 10.2172/2417618. Available: https://www.osti.gov/biblio/2417618

[23] C. Juiz, B. Bermejo, A. Fernández-Montes, and D. Fernández-Cerero, "Towards a General Metric for Energy Efficiency in Cloud Computing Data Centres: A Proposal for Extending of the ISO/IEC 30134-4:," in *Proceedings of the 14th International Conference on Cloud Computing and Services Science*, Angers, France: SCITEPRESS - Science and Technology Publications, 2024, pp. 239–247. doi: 10.5220/0012707600003711. Available: https://www.scitepress.org/DigitalLibrary/Link.aspx?doi=10.5220/0012707600003711

[24] A. A. Alkrush, M. S. Salem, O. Abdelrehim, and A. A. Hegazi, "Data centers cooling: A critical review of techniques, challenges, and energy saving solutions," *Int. J. Refrig.*, vol. 160, pp. 246–262, Apr. 2024, doi: 10.1016/j.ijrefrig.2024.02.007

[25] "Cooling technologies for data centres and telecommunication base stations – A comprehensive review," *J. Clean. Prod.*, vol. 334, p. 130280, Feb. 2022, doi: 10.1016/j.jclepro.2021.130280

[26] X. Yuan *et al.*, "Phase change cooling in data centers: A review," *Energy Build.*, vol. 236, p. 110764, Apr. 2021, doi: 10.1016/j.enbuild.2021.110764

Received: 10-09-2025, Approved: 11-10-2025
Sitio web:https://revistatelematica.cujae.edu.cu/index.php/tele

[27] D. C. Bree and M. Ó Cinnéide, “Weighted Metrics for the Development of Energy Efficient Software,” in *2024 IEEE/ACM International Workshop on Designing Software (Designing)*, Apr. 2024, pp. 64–69. Available: https://ieeexplore.ieee.org/document/10669898

[28] A. Hassan, “Thermal and Energy Efficiency Management of Mobile MPSoC: A Review,” *Arid-Zone J. Basic Appl. Res.*, vol. 4, no. 1, Apr. 2024, doi: 10.55639/607.414039. Available: https://azjournalbar.com/wp-content/uploads/2024/03/121_132_Thermal-and-Energy-Efficiency-Management_090512.pdf

[29] R. Muralidhar, R. Borovica-Gajic, and R. Buyya, “Energy Efficient Computing Systems: Architectures, Abstractions and Modeling to Techniques and Standards,” *ACM Comput. Surv.*, vol. 54, no. 11s, pp. 1–37, Jan. 2022, doi: 10.1145/3511094

[30] V. Saxena, A. Kumar, and V. danwa, “A Review of Cloud Computing CPU Resource Optimization: Methods, Difficulties, and Prospects,” in *Proceedings of the 6th International Conference on Information Management & Machine Intelligence*, in ICIMMI ’24. New York, NY, USA: Association for Computing Machinery, Sep. 2025, pp. 1–5. doi: 10.1145/3745812.3745839. Available: https://dl.acm.org/doi/10.1145/3745812.3745839

[31] E. Suarez *et al.*, “Energy Efficiency trends in HPC: what high-energy and astrophysicists need to know,” *Front. Phys.*, vol. 13, p. 1542474, Apr. 2025, doi: 10.3389/fphy.2025.1542474

[32] B. Kocot, P. Czarnul, and J. Proficz, “Energy-Aware Scheduling for High-Performance Computing Systems: A Survey,” *Energies*, vol. 16, no. 2, p. 890, Jan. 2023, doi: 10.3390/en16020890

[33] T. Hossfeld, S. Wunderer, F. Loh, and D. Schien, “Analysis of Energy Intensity and Generic Energy Efficiency Metrics in Communication Networks: Limits, Practical Applications, and Case Studies,” *IEEE Access*, vol. 12, pp. 105527–105549, 2024, doi: 10.1109/ACCESS.2024.3435716

[34] B. A. Yosuf, M. Musa, T. Elgorashi, and J. Elmirghani, “Energy Efficient Distributed Processing for IoT,” *IEEE Access*, vol. 8, pp. 161080–161108, 2020, doi: 10.1109/ACCESS.2020.3020744

[35] K. M. U. Ahmed, M. H. J. Bollen, and M. Alvarez, “A Review of Data Centers Energy Consumption and Reliability Modeling,” *IEEE Access*, vol. 9, pp. 152536–152563, 2021, doi: 10.1109/ACCESS.2021.3125092

[36] A. Katal, S. Dahiya, and T. Choudhury, “Energy efficiency in cloud computing data centers: a survey on software technologies,” *Clust. Comput.*, vol. 26, no. 3, pp. 1845–1875, Jun. 2023, doi: 10.1007/s10586-022-03713-0

[37] “ANSI/BICSI 002-2024 Data Center Design and Implementation Best Practices.” May 2024. Available: https://it-class.net/wp-content/uploads/2024/07/002_2024_Preview.pdf. [Accessed: Sep. 26, 2025]

[38] “Information technology — Automated infrastructure management (AIM) systems — Requirements, data exchange and applications — Amendment 1,” *ISO*, 2021. Available: https://www.iso.org/standard/82768.html

[39] D. E. Mogahed and A. I. B. E. Seddawy, “Applying the Data Center Infrastructure Management (DCIM) Tool to Enhance the Quality Management of the Data Centers by Decreasing the Unplanned Outage Reasons,” *Int. J. Innov. Res. Comput. Sci. Technol.*, pp. 192–203, Jul. 2022, doi: 10.55524/ijircst.2022.10.4.23

[40] G. Balabanov and N. S. Apostolov, “Data Centre Infrastructure Monitoring,” in *2025 60th International Scientific Conference on Information, Communication and Energy Systems and Technologies (ICEST)*, Jun. 2025, pp. 1–4. doi: 10.1109/ICEST66328.2025.11098186. Available: https://ieeexplore.ieee.org/abstract/document/11098186

[41] M. K. Jackson Ramphela, P. A. Owolawi, T. Mapayi, and G. Aiyetoro, “Internet of Things (IoT) Integrated Data Center Infrastructure Monitoring System,” in *2020 International Conference on Artificial Intelligence, Big Data, Computing and Data Communication Systems (icABCD)*, Durban, South Africa: IEEE, Aug. 2020, pp. 1–6. doi: 10.1109/icABCD49160.2020.9183873. Available: https://ieeexplore.ieee.org/document/9183873/

[42] M. Levy and A. Subburaj, “Emerging Trends in Data Center Management Automation,” in *2021 IEEE 11th Annual Computing and Communication Workshop and Conference (CCWC)*, NV, USA: IEEE, Jan. 2021, pp. 0480–0485. doi: 10.1109/CCWC51732.2021.9375837. Available: https://ieeexplore.ieee.org/document/9375837/

## AUTHORS SECTION

**Annia Lisbeth Barbán Acea,** Telecommunications and Electronics Engineer. Instructor Professor at the Technological University of Habana José Antonio Echeverría (CUJAE). Associate researcher at the Center for Telecommunications and Informatics Studies (CETI). Her research focuses on network management, network functions virtualization (NFV), software defined networking (SDN), cloud computing and High-Performance Computing (HPC). ORCID 0000-0003-2854-8273

## CONFLICT OF INTEREST

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