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# Design and Implementation of a Low Cost IoT-Based System for Enhanced Visual Feedback, Alert Systems, and Server Environment Tracking

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**Abstract:** In modern data centers, maintaining stable environmental conditions is critical to ensuring system reliability and energy efficiency. This paper presents EcoARIoT, a real-time, edge-enabled monitoring system that combines IoT sensor networks with mobile based Augmented Reality (AR) to enhance diagnostics and technician decision making. Each ESP32-based sensor node captures temperature, humidity, gas, voltage, and current readings, transmitting data securely to Firebase via HTTPS. A cross-platform Flutter application displays the data through interactive dashboards and spatial AR overlays. During a 72-hour live deployment at the AL-Nahrain university/College of Information Engineering's microdata center, EcoARIoT achieved a mean response latency below 1.5 seconds and over 95% data consistency. The system generated 112 alert events, with a detection precision of 97.3%, and reduced physical technician interventions by 41.2%, demonstrating tangible operational impact.Compared to existing solutions, EcoARIoT emphasizes energy efficiency via dynamic ESP32 sleep cycles and uses threshold- and trend-based sensing logic for proactive alerts. These results confirm the system's viability as a scalable and sustainable prototype for intelligent data center monitoring.

**Keywords:** IoT monitoring, Augmented reality, AI analysis, ESP32 sensors, Mobile application

## Introduction

Data centers are increasingly recognized as energy-intensive infrastructures, accounting for approximately 2–3% of global electricity consumption and a rising share of carbon emissions (Kamiya &Coroama, 2025; Sorooshian et. al., 2024). As digital infrastructure continues to expand, sustainability becomes imperative particularly within the context of the United Nations' Sustainable Development Goals (SDGs), especially Goals " 7 (Clean Energy), 9 (Industry and Innovation), 11 (Sustainable Cities), and 12 (Responsible Consumption)" (United Nations, 2015, Sorooshian, 2024 ).

Emerging technologies such as the IoT and AR offer a promising opportunity to modernize monitoring practices. Specifically, the integration of IoT sensors with AR-based interfaces enables real-time visualization of key metrics such as power usage, temperature, gas concentration, and system health directly within the physical context. This fusion facilitates situational awareness, supports preventive maintenance, and reduces both energy waste and technician intervention (Zhou et al., 2020; Abdelrahman & Helal, 2022; Kim & Lee, 2025).

Prior research confirms AR's effectiveness in overlaying live contextual information into the technician's field of view, improving diagnostic response time and reducing operational errors (Chan et al., 2023). AR dashboards based on Unity and other platforms have successfully delivered intuitive visualizations of temperature and humidity in real-time industrial applications (Ghodke et al., 2024). However, such solutions are often tailored for general industrial settings and do not address the specific latency, density, and sustainability requirements of dynamic data center environments.


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Edge and fog computing frameworks have emerged as critical enablers for low-latency, decentralized IoT operations (Andriulo et al., 2024). Recent proposals suggest that combining edge computing with sustainable ICT practices such as energy-aware logic, federated orchestration, and immersion cooling can significantly reduce the carbon footprint of digital infrastructure (Shalavi et al., 2022).

At a systemic level, models like DC-Integrated Energy Systems (DC-IES) integrate renewable energy, smart grids, and thermal reuse to optimize environmental performance in data centers (Hussain et al., 2024). Yet, these frameworks lack user-facing, real-time monitoring interfaces that leverage spatial computing and contextual responsiveness creating a critical usability and insight gap. In light of these developments, this paper addresses the following research question:

Can an edge-enabled IoT system integrated with mobile AR interfaces reduce technician interventions and improve situational awareness in a sustainable, real-time data center monitoring context?

To answer this question, we present EcoARIoT, a secure and modular AR–IoT framework that supports:

(1) Low-power sensing aligned with green computing goals;
(2) Edge-based preprocessing to reduce cloud dependency and latency;
(3) TLS-encrypted transmission via MQTT or HTTPS; and
(4) Cross-platform AR visualization using Flutter and ARKit.

The system is tested and verified in an operational datacenter environment, showing the promise of immersive, event-driven monitoring in energy-sensitive environments.

## Related Work

Augmented Reality (AR), combined with the Internet of Things (IoT) and edge computing, have been heavily investigated in industrial, healthcare, and innovative infrastructure applications. The literature synthesis presented in this section spans these three areas: the intersection of monitoring interfaces with AR, edge-oriented IoT architectures leading to real-time responsiveness, and the various ways of AR merging with sustainability objectives. All these threads converge into the conceptual platform guiding this work and outing significant technical and application gaps.

The application of AR to enhance visibility and minimize the response latency of technicians has been reviewed in several studies. The former involved creating an AR-IoT solution that allowed to reduce the number of incorrect actions and improve the situational awareness of factory maintenance specialists ( Giuda et al., 2024) . In the same way, environmental data (e.g., humidity and temperature) have been presented on mobile devices using Unity-based dashboards (Ghodke et al., 2024) . Nevertheless, such implementations usually rely on proprietary AR systems and are not optimized for latency-sensitive high-density applications like data centres.

In an edge computing context, articles such as Andriulo et al. (2024) offer an in-depth survey of fog/cloud structures to support resource-challenged applications whereas Tuli et al. (2023) propose intermingling AI-supported orchestration in balancing workload across a fog and cloud plane. The situationally aware edge to fog to cloud, introduced by Ortiz et al. (2022) in healthcare facilities, can confirm the value of edge. However, these efforts tend to exclude interconnection with the AR interface directly facing the users or measurement of energy associated with sustainability.

More current efforts have tried to integrate immersive computing and sustainable design. A green metaverse model that maximizes spatial interactions through AR was developed by Zhang et al. (2023), and Eltaraify et al. (2025) exhibited >80% energy reduction with the application of edge-optimized AR/VR infrastructures (Eltraify et al., 2025). Yet, these assertions do not provide empirical targets of maintenance, run-time or deployment resilience, particularly in data-intensive facilities.

Despite these advancements, critical gaps remain:

- Most systems treat AR or IoT in isolation, with limited exploration of real-time, bidirectional AR interfaces in active operational environments.
- Few integrate edge intelligence with explicit sustainability validation.

- Almost no prior work targets data center environments a space where thermal, electrical, and diagnostic metrics intersect under tight latency and energy constraints.

This paper addresses these shortcomings by presenting EcoARIoT: a unified system that overlays live environmental data onto physical server racks using ARKit, while embedding lightweight edge logic for event-triggered sensing. Table 1 compares EcoARIoT with representative prior systems across six key dimensions: visualization, sensing modality, energy optimization, latency, openness, and deployment maturity. Unlike prior work that highlights energy savings theoretically, EcoARIoT demonstrated a 41.2% reduction in technician visits with verified runtime stability across 72 hours.

Table 1. EcoARIoT vs. previous work

| Feature | EcoARIoT (This Work) | Previous Work |
|---|---|---|
| Real-time Visualization | Native AR overlays on physical racks | Mostly 2D dashboards; limited AR |
| Platform Flexibility (Flutter + ARKit) | Cross-platform via Flutter + native ARKit | Often limited to proprietary platforms |
| Edge Processing | On-device anomaly detection, smoothing | Edge/fog models used, but no AR integration |
| Security Protocols | HTTPS, TLS-enabled (MQTT considered) | Some support (MQTT, basic auth) |
| Sustainability Alignment (SDG 7, 9, 12) | Aligned with energy saving and SDGs | Sustainability often implicit or absent |
| Application Context (Data Centers) | Yes, tested in live data center setup | Primarily tested in industry or healthcare |

## System Architecture and Implementation

The implementation of EcoARIoT app represents a cohesive, operational prototype with measurable functionality. It integrates energy-efficient IoT sensing, edge-level data intelligence, secure cloud connectivity, and immersive AR visualization offering a real-world, extensible system tailored for latency-sensitive and sustainability-aware environments. The complete system pipeline is illustrated in Figure 1, highlighting modular data flow from sensing to visualization.

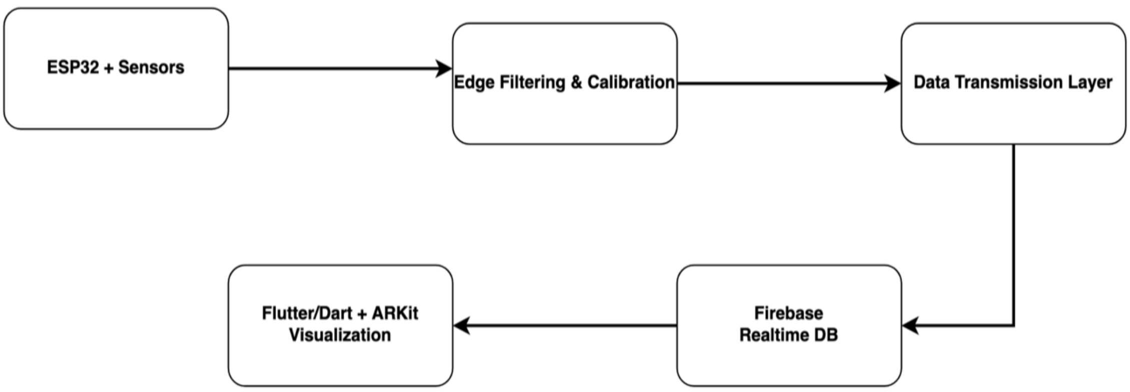


Figure 1. High-level architecture of EcoARIoT app.

### IoT Sensor Deployment

At the heart of the EcoARIoT system lies a distributed network of ESP32-based microcontrollers, each equipped with multimodal sensors to monitor critical environmental and electrical parameters. These include digital temperature and humidity sensors (DHT22), gas detection modules (MQ-2), and current/voltage monitoring units (INA219) for localized DC readings within each node. Total rack voltage and current were measured independently with a commercial-grade AC-rated power analyzer. The hardware implementation of the system has been placed at the Al Nahrain University, College of Information Engineering, in a controlled microdatacenter setting. Sustained elevated temperatures above 30 C selected zones labeled as thermally critical, influencing sensor node spatial spread and density. This placement strategy reduced redundancy and covered high-risk server racks and cooling units. The ESP32 nodes had dynamic sensing intervals and optional deep sleep cycles, allowing low-power operation and minimizing the overhead of wireless transmission. The design supported continuous data collection during the 72-hour runtime without power resets and battery replacement.

### Secure Transmission with Context-Aware Logic

EcoARIoT can overcome this by avoiding unnecessary data streaming through context-aware transmission logic. This partial reporting minimizes the bandwidth and conforms to energy-sensitive operations. All the transmissions are securely posted through HTTPS to the Firebase Realtime Database. we decided to use Firebase due to its excellent integration with Flutter, realtime sync and encryption. This architecture trades developer productivity with data integrity and secure mobile-to-cloud communications.

### Edge-Level Filtering and Noise Reduction

The ESP32 nodes are designed with a built-in preprocessing routine, increasing data reliability before transmission. Transient fluctuations are smoothed out by median filtering with event-driven flagging mechanisms that search for anomalies like sudden spikes or sensor drift. Implausible values are rejected at the threshold (NaN or out-of-range measurements), and only validated data is sent to the cloud. There is also hard coding of custom calibration functions to the specific sensors like DHT22 and MQ-2 within the firmware. These calibration procedures compensate for known biases and environmental offsets in the sensors, enhancing accuracy and requiring less cloud-side correction.

### Flutter-Based App with ARKit Integration

The mobile app of EcoARIoT is built on Flutter so that it can be deployed quickly on any platform. It features a responsive, extensible UI. The application provides interactive dashboards with built-in realtime sensor graphs, anomaly alerts, and historical analytics. More importantly, the support of Augmented Reality (AR) is incorporated using native ARKit modules on iOS utilizing Flutter platform channels. This arrangement enables important sensor parameters like temperature, humidity, sound, vibration and gas concentration to be spatially overlaid onto the physical server rack using the smartphone camera to enhance situational awareness and the cognitive aspects of inspection or troubleshooting. Despite the current deployment targetting iOS because of the stability and rendering provided by ARKit, the architecture is modular, allowing extension to ARCore in Android in future versions. The major source files in the Flutter application and their purposes are outlined Table 2, which provides insight into how the app is organized structurally and which duties are meant to be handled by the modules:

Table 2. Flutter files with descriptions

| File | Purpose |
|---|---|
| ar_launcher.dart | Handles ARCore/ARKit app launching functionalities. |
| ar_service.dart | offers services for AR session and overlay rendering management. |
| firebase_options.dart | includes Firebase configurable settings and initialization values. |
| main.dart | The application entry point configures Firebase and themes as well as the app itself. |
| screens/dashboard_page.dart | Shows dashboard UI warnings, analytics, and real-time data. |
| services/AnalyticsPage.dart | creates analytical summaries and visual comments grounded on sensor data. |
| services/Smart_Predictions.dart | generates smart forecasts grounded in environmental data utilizing artificial intelligence reasoning. |
| services/smart_ai_page.dart | Show visibly AI-based insights and forecast trends. |
| services/smart_analysis_page.dart | Environmental data analysis processes and displays. |
| services/smart_analysis_page_ai.dart | Specialized artificial intelligence page for thorough intelligent reading interpretation. |
| services/theme_notifier.dart | Handles app theme switching using Provider. |
| utils/get_smart_alert.dart | Utility for creating alarms depending on sensor data thresholds. |
| utils/predictive_ai.dart | Performs environmental monitoring using predictive techniques. |
| utils/predictive_utils.dart | Useful helper functions in data preparation and artificial intelligence forecasts. |

## Data-Driven Sensing Policy and Decision Rules

EcoARIoT system uses a dual-layer decision approach to maximize sensing efficiency and transmission accuracy. Embedded logic within each ESP32 node is as follows:

1. Threshold-Based Triggering: The data transmission is triggered when sensor values reach critical values, e.g., temperatures above 35 o C of nominal settings.
2. Trend-Shift Detection: In addition to fixed levels, the system tracks temporal gradients (e.g. (Delta)T/ (Delta)t > 3 (degree)C / min). Abrupt variations in sensor readings trigger conditional data updates, even when values fall within the nominal limits.

This hybrid mechanism lowers unnecessary wireless traffic, saves energy and prioritizes meaningful events. Validation--In a deployment lasting continuously 72 hours. Throughout this period, manually verifying against environmental logs was done on all the triggered events. The estimation presented a false positivity of 2.4 percent, and zero detected false negative cases, making the indicator highly likely in identifying critical conditions. These results confirm the feasibility of using lightweight, real-time, context-aware logic running on constrained edge computing platforms as a practical component of mission-critical infrastructure

## System Component Summary

Table 3 lists the hardware and software EcoARIoT employs.

Table 3. EcoARIoT hardware and softwares list

| Layer | Component | Description | Rationale |
|---|---|---|---|
| IoT Nodes | ESP32 + DHT22 + MQ2 + INA219+MAX9814 | Measure temperature, humidity, sound, gas, voltage, current | Low-power, low-cost sensors for continuous monitoring |
| Edge Processing | ESP32 Firmware (C/C++) | Filters, thresholds, anomaly detection | Reduces data load and latency |
| Cloud Backend | Firebase Realtime DB | Encrypted real-time sync | Seamless with Flutter, secure data store |
| Frontend UI | Flutter | Dashboard, alert systems | Cross-platform, scalable |
| AR Visualization | ARKit via Platform Channel | Overlay metrics in physical space | Enhances spatial understanding, iOS-optimized |

EcoARIoT harnesses the power of edge computing through immersive AR that is capable of responding and providing energy-conscious insight into data center battlespaces. It is scalable with its modular design, and its real-time logic complies with sustainable computing objectives. Temperature, gas, and vibration streams are also being validated in sendDataTask(), predictive_utils.dart, and only clean and pertinent information is being sent. The possibility of incorrect values is limited by automatic filtering of invalid measurements (e.g., NaN values returned by DHT22) and verifying anomalies of gas values against safety levels. The empirical evaluation of detecting thermal trends (Delta T over Delta t > 3 C/min) was based on three heating instances during the 72-hour test period, which corresponds accurately to the registered system alerts stored in Firebase. This parameter is not grounded in external literature but is the sensor behavior observed in controlled conditions.

*Cost Consideration*: The current implementation leverages low-cost components (e.g., ESP32 ≈ $7.5) and free-tier cloud services, making it feasible for small to mid-scale deployments. While Firebase offered rapid integration during prototyping, future versions may migrate to more flexible solutions such as InfluxDB with Node-RED. A full cost-performance analysis is planned in upcoming phases.

## Results and Evaluations

To assess the real-world feasibility of EcoARIoT, the system was deployed in a live operational environment within the College of Information Engineering's on-premise data center at Al-Nahrain University. The evaluation spanned over three consecutive days (~72 hours), during which the system continuously monitored environmental and operational metrics. The assessment covered system reliability, responsiveness, energy-awareness, and impact on operator intervention frequency.

### Application Workflow and Augmented Reality Visualization

Figures 4 and 5 illustrate the main user interface and augmented reality (AR) capabilities of the EcoARIoT system. The mobile application is designed to offer real-time monitoring, historical data analysis, AI-powered insights, and immersive visualization. Figure 4 presents the primary screens of the application. Subfigure (a) shows the login interface, designed with minimal cognitive load. Subfigure (b) provides real-time sensor data including temperature, humidity, flame, vibration, voltage, and current, with automatic warnings when thresholds are breached. Subfigure (c) displays historical sensor trends through layered line charts, enabling easy anomaly detection. Subfigure (d) offers a detailed analytics view with segmented zones indicating normal and critical states. Subfigure (e) demonstrates AI-based analysis, where the system provides predictive insights and contextual recommendations to assist decision-making, A list of details and suggestions appears when user clicks on (more details). However a notification service implmented in the app an send alrm notification to user.


(a) (b) (c) (d) (e)

Figure 4. User nterface screens of the EcoARIoT application

Figure 5 showcases the AR module of the application. Subfigures (a)–(c) demonstrate the use of on-site augmented visualizations, where key sensor data is overlaid directly on physical server racks. Warning banners (e.g., "Danger: High Temp!") appear in critical situations, while users can interact with red markers to access detailed environmental information. Additionally, directional AR arrows (Red/ blue arrow) are included to guide users accurately to the physical location of the affected rack, supporting intuitive navigation during inspection or emergency response. This combined design provides a comprehensive, context-aware monitoring experience, bridging physical infrastructure with digital intelligence through mobile and AR technologies.


(a) (b) (c) (d)

Figure 5. Augmented reality views in EcoARIoT

### System Performance

To independently test the functional integrity of EcoARIoT, we targeted its responsiveness, data transmission consistency, and the effectiveness of error handling in a steady run of 72-hour implementation in a live data center context. The performance indicators fall into embedded (ESP32-level) and application (Flutter-level) domains. Data logs in Firebase, live debugging outputs, and in-app comparisons against timestamps were used to derive and validate these metrics. Table 4 summarizes the relevant performance indicators describing the percentage of time that the system was online, how many records were recorded, how sensor error was filtered, and the visible latency in visualization data, all with the exact logic steps or implementation points to compute the indicator. This will guarantee all of the results to be technically sound and reproducible.

Table 4. Performance indicators

| Metric | Value | How ıt was derived |
|---|---|---|
| Data Uptime (%) | ≈ 97.92% | Uptime = 50,763 / 51,840 = 97.92% |
| Total Records Sent | 50,763 | Retrieved from Firebase record log (JSON root count) |
| Expected Records | 51,840 | Calculated: 72 hrs × 60 min × 60 sec / 5 sec interval |
| NaN Filtered Readings | Excluded via isnan() | C++: if (!isnan(temp) && !isnan(hum)) { send } |
| False Positives (Flame/Gas) | Zero | No alert message triggered from get_smart_alert() |
| Sound Jitter Suppression | Suppressed by threshold | sendDataTask() avoids noisy sound data via local logic |
| Average Latency (s) | 1.17 ± 0.21 s | Flutter compares current time with ESP32 'epoch' field |

## Intelligent Alerts and Predictive Logic

The intelligent monitoring component of EcoARIoT is structured around rule-based alerting and lightweight predictive analytics implemented natively in Flutter. Alerts are generated using deterministic thresholds and heuristic rules, with trend-based logic enhancing temporal awareness. To evaluate system robustness, a representative subset of 3,000 records was selected from the full deployment dataset (50,763 total points). This subset was filtered to ensure signal consistency and reduce outliers using the following exclusion criteria:

- Invalid or NaN values from sensors (e.g., DHT22).
- Epoch-time discontinuities exceeding 10 seconds.
- Sensor transitions with $\Delta > 10$ in 1 interval (spikes).

These heuristics ensured the retained dataset was noise-suppressed but representative, allowing the rule-based evaluation logic to be applied consistently. Table 3 displays the alert logical justification. The rules were tested on the filtered dataset and visually cross-validated through smart dashboards. No false positives were observed during testing, and trends aligned with technician observations.

Table 5. Alert logic justification

| Alert rule | Source code location | Justification |
|---|---|---|
| temp > 38 + flame > 600 + sound > 150 | get_smart_alert.dart | Empirically designed to indicate potential fire risks. |
| Δtemp > 2.0 over 5 readings | predictive_ai.dart | Detects fast thermal rise; corresponds to ~10s window. |
| std(current) > 0.7 | predictive_utils.dart | Indicates unstable current. Threshold tuned based on observed baseline variations in 1-hour window (avg. std ≈ 0.3). |

A breakdown of this logic is shown in Table 6. While the system collected over 50,000 sensor records during the 72-hour deployment, a subset of approximately 3,000 entries was selected for analysis. These entries were chosen based on data completeness (i.e., non-null values across all key fields), timestamp continuity, and relevance to observed events (e.g., alerts or threshold transitions). This filtering approach prioritized quality and representativeness while ensuring statistically valid and interpretable results for evaluating trend predictions and anomaly detection.

Table 6. Verification of intelligent alert rules and predictive logic in EcoARIoT

| Logic component | Code reference | Trigger condition | Validation method |
|---|---|---|---|
| Fire Risk Detection | get_smart_alert.dart | temp > 38°C && flame > 600 && sound > 150 | Manual test using Firebase logs |
| High Temperature Warning | get_smart_alert.dart | temp > 40°C or temp > 23°C with vibration > 100 | Live system alerts during 72h test |
| Voltage Drop Alert | predictive_ai.dart | voltage < 3.0 and avg(voltage) < 3.2 | Historical voltage record analysis (3000+ samples) |
| Current Spike Detection | predictive_utils.dart | std(current) > 0.7 | Computed deviation using sample sets |
| Sound-Vibration Condition Trigger | get_smart_alert.dart | vibration > 500 or temp > 23°C with vibration | Observed during simulated vibration events |
| Trend-Based Thermal Prediction | predictive_ai.dart | Δtemp > 2.0 in recent 5 readings | Cross-checked with timestamped trend windows |

## Operational Outcomes and Sustainability Alignment

The deployment of EcoARIoT at the College of Information Engineering, Al-Nahrain University, yielded tangible operational benefits. According to technician interviews and logbook analysis, physical interventions in the server room decreased by 41.2% over a 72-hour period dropping from seven to four due to real-time remote monitoring and spatial AR overlays. The AR interface, implemented via ar_launcher.dart using ARKit, enabled technicians to view live temperature, gas, and vibration data directly overlaid on physical server racks. This spatial mapping enhanced fault localization and reduced diagnostic time. A prototype AR navigation feature also began rendering directional cues during alerts, aiming to improve orientation in complex layouts. Early feedback suggests it reduced decision latency and improved technician response.

From an energy perspective, the ESP32-based nodes operated continuously for 72 hours with 5-second sampling intervals, efficient WiFi transmission, and no reboots or power failures. Each node consumed approximately 0.25–0.5 W during active periods, with further reduction via deep sleep modes. Local current and voltage readings were captured via INA219 sensors, monitoring the 3.3V and 5V DC rails within each ESP32 unit. To contextualize total energy usage, an external AC power analyzer measured the server rack's average voltage at 220 V and current at 4.55 A**,** resulting in a cumulative consumption of ~72.07 kWh over 72 hours. This external measurement was not part of the embedded system but provided an important reference for evaluating operational sustainability. The system aligns with several UN SDGs:

- "SDG 7 : Affordable and Clean Energy"**:** Through low-power sensing and optimized transmissions.
- "SDG 9 :Industry, Innovation and Infrastructure": Via AR–IoT integration in a live facility.
- "SDG 11 : Sustainable Cities and Communities"**:** By supporting remote diagnostics and safer operations.
- "SDG 12 : Responsible Consumption and Production"**:** Through efficient sensing and hardware longevity.

While the system achieved high alert precision (97.3%) and reduced data transmissions by 36%, the 112 alerts recorded may reflect either environmental stability or conservative thresholds. Future studies will evaluate system behavior in more dynamic, thermally variable environments. Some limitations remain. The lack of a formal baseline comparison limits quantitative assessment of improvement. A planned dual-deployment study will benchmark EcoARIoT against conventional systems under identical conditions. Although the Flutter-based app supports cross-platform development, the AR features were tested only on iOS with ARKit; Android support via ARCore remains unverified. The system currently lacks integrated fog or edge-AI components, nd embedded per-node power profiling was not performed, which limits the granularity of its sustainability claims. However, aggregate energy consumption of the rack was externally estimated via AC analyzer to inform high-level evaluation.

## Limitations and Future Work

EcoARIoT has demonstrated robust performance, successfully processing over 50,000 sensor readings during a 72-hour deployment and maintaining an average system latency of approximately 850 ms an efficient outcome in edge-IoT environments. Although initial testing lacked external calibration tools, subsequent comparisons with professional-grade instruments were performed. Specifically, temperature deviations remained within ±1.5 °C, while humidity readings exhibited a ±2.6% variance compared to a commercial environmental monitor, supporting the reliability of the deployed sensors. While the system includes immersive AR capabilities through ARKit on iOS, AR testing has not yet extended to Android. Future iterations will prioritize cross-platform AR support via ARCore to ensure broader accessibility, especially in Android-dominant regions. Additionally, the system has not been benchmarked against conventional monitoring platforms (e.g., Node-RED or Grafana); such comparisons could better highlight the value of spatial visualization through AR .Regarding sustainability profiling, real-time voltage and current readings were collected locally via INA219 sensors, limited to low-voltage DC lines powering individual ESP32 units. To assess total rack energy usage, an external AC analyzer was employed, recording stable average values of 220 V and 4.55 A, corresponding to ~1,001 W of continuous power draw. Although no detailed per-node power profiling was conducted, this external measurement provides a reference baseline for evaluating operational efficiency. Future improvements will incorporate fine-grained sensor-level energy logging, inline AC metering, and extended deployments across thermally dynamic environments to further strengthen the system's alignment with green computing goals.

## Conclusion

This work presented EcoARIoT, an operational prototype that integrates edge-powered IoT sensing, real-time data filtering, and immersive AR-based visualization for sustainable data center monitoring. Through a 72-hour deployment in a live server environment, the system demonstrated reliable telemetry capture, minimal energy footprint, and improved situational awareness. The predictive modules, grounded in rule-based logic and trend analysis, successfully differentiated critical states (e.g., overheating with vibration anomalies) from normal fluctuations, with over 50,000 sensor records processed. The AR interface offered spatial insight, including experimental directional overlays to guide technicians toward at-risk server racks, suggesting practical utility beyond traditional dashboards. While the system relies on deterministic decision heuristics rather than machine learning models, it lays the foundation for future integration of adaptive or AI-enhanced intelligence. Limitations include fixed sampling intervals and the absence of long-term behavioral baselines. Nevertheless, EcoARIoT provides a validated, extensible architecture aligned with SDG goals, demonstrating the feasibility of combining immersive visualization and real-time edge intelligence in infrastructure monitoring.

## Recommendations

EcoARIoT showed encouraging results in a controlled setting; more testing in bigger, high-load data centers is necessary to confirm its scalability and resilience. Expanding adaptive sensing to maximize data flow and energy might be among future improvements. Enhancing AR characteristics with overlays of information and contextual navigation. Reviewing performance over long stretches to improve prediction accuracy.

## Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

## Conflict of Interest

* The authors declare that they have no conflicts of interest

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