Energy Efficiency and Sustainability in IoT Networks: A Comprehensive Review of Methods and Applications

M.V.D.P.D. Malawana, K.K.Y.M. Alawathugoda, and M.S.S. Razeeth

Abstract The rapid proliferation of Internet of Things (IoT) networks has transformed multiple domains, including smart cities, healthcare, agriculture, and industrial automation, by enabling seamless data collection and communication. However, the widespread deployment of IoT devices introduces significant challenges related to energy consumption and sustainability. Most devices are resource-constrained, relying on limited battery power, which necessitates energy-efficient designs to ensure long-term network operation. In parallel, sustainability concerns, encompassing environmental, economic, and societal aspects, have become critical to the design and management of IoT systems. This systematic literature review comprehensively examines current research on energy efficiency and sustainability in IoT networks, focusing on methods, techniques, and real-world applications. The review analyses key energy optimization strategies, including energy-aware routing, clustering, duty cycling, data aggregation, and energy harvesting, as well as emerging approaches leveraging artificial intelligence and edge computing. Additionally, sustainability measures, such as green IoT architectures, renewable energy integration, and lifecycle management, are explored. The study identifies persistent challenges, highlights gaps in existing research, and discusses future directions for achieving scalable, energy-aware, and environmentally responsible IoT deployments. This review provides a structured framework for researchers, practitioners, and policymakers aiming to design efficient and sustainable IoT systems that balance performance with ecological and societal considerations.

Index Terms— **IoT, Energy Efficiency, Sustainability, Green Computing, Optimization**

I. Introduction

The internet of Things (IoT) has emerged as a transformative paradigm, enabling ubiquitous connectivity between physical devices, sensors, and computing systems [1]. By facilitating seamless data collection, communication, and processing, IoT networks have revolutionized multiple domains, including smart cities [2], healthcare [3], industrial automation [4], agriculture [5], and environmental monitoring. The proliferation of IoT devices, however, has introduced significant challenges related to energy consumption and sustainability [6]. Most IoT nodes operate on limited battery power and are deployed in environments where frequent maintenance or battery replacement is impractical. Consequently, achieving energy-efficient operation is critical to maintaining network longevity, reliability, and performance.

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Energy efficiency in IoT networks is influenced by several factors, including communication protocols, hardware constraints, data transmission patterns, and network topology. Wireless communication, the backbone of IoT, often accounts for the largest portion of energy consumption [7]. Inefficient routing, frequent data transmission, and idle listening further exacerbate power usage, potentially causing premature node failures and network partitioning. As IoT networks scale up, these challenges are compounded by the heterogeneous nature of devices, varying energy requirements, and the demand for real-time responsiveness. Addressing these issues requires an integrated approach that combines hardware optimization, energy-aware protocols, and intelligent resource management strategies [8].

Beyond energy efficiency, sustainability has become a critical concern in IoT deployments. Sustainability encompasses environmental, economic, and societal considerations, aiming to minimize the ecological footprint of large-scale IoT networks while maintaining functional and operational effectiveness [9]. Green IoT initiatives focus on reducing carbon emissions, electronic waste, and overall energy consumption through renewable energy integration, recyclable materials, and eco-friendly network architectures [10]. The convergence of energy-efficient techniques and sustainable practices not only prolongs device lifespans but also aligns IoT networks with global environmental goals and regulatory frameworks.

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The growing importance of IoT in critical applications has driven extensive research into methods and strategies that optimize energy usage and promote sustainability [11]. Techniques such as energy-aware routing, duty cycling, clustering, data aggregation, and energy harvesting have been proposed to address energy constraints at the device and network levels [12]. In addition, emerging paradigms like edge computing, artificial intelligence (AI), and machine learning are being leveraged to predict energy demands, optimize data processing, and reduce redundant transmissions, thereby contributing to sustainable network operation [2].

This systematic literature review aims to comprehensively examine existing methods, techniques, and applications for achieving energy efficiency and sustainability in IoT networks. By analyzing recent research contributions, identifying key challenges, and highlighting future directions, this review provides a structured overview for researchers, practitioners, and policymakers interested in developing scalable, environmentally responsible, and energy-aware IoT systems. The review is organized into four primary sub-topics: energy efficiency challenges, optimization methods, sustainability approaches, and applications with future directions, offering a holistic perspective on the state of the art in IoT energy management and sustainable network design.

II. Literature Review

A. Energy Efficiency Challenges in IoT Networks

Traditional Energy efficiency (Figure 1) is one of the most critical challenges in Internet of Things (IoT) networks, as the majority of devices are resource-constrained in terms of power, processing, and communication capabilities [13]. Most IoT nodes rely on limited-capacity batteries, which makes long-term operation difficult without efficient energy management strategies [14]. Communication overhead, particularly in large-scale deployments, is a significant contributor to energy consumption since wireless transmission generally requires more power than sensing or computation [15]. Scalability is another challenge: as the number of devices increases, maintaining energy efficiency while ensuring reliable connectivity becomes more complex.

Moreover, heterogeneous devices with different energy profiles and hardware limitations complicate network optimization. Security mechanisms, although necessary, often introduce additional computational overhead that increases power consumption. Data transmission, particularly when uncompressed or poorly aggregated, also leads to energy waste [16]. Environmental conditions, such as interference and fluctuating channel quality, can cause retransmissions and further drain device energy. Finally, the lack of universal energy standards for IoT applications hinders consistent design practices across industries [12]. Addressing these challenges is crucial for achieving sustainability in IoT networks, especially as applications expand into energy-sensitive domains such as smart healthcare and environmental monitoring.

B. Methods and Techniques for Energy Optimization

Various methods and techniques have been proposed to optimize energy consumption in IoT networks. One of the most widely studied approaches (Figure 1) is energy-aware routing, where communication paths are selected to minimize energy usage while maintaining reliability [3]. Clustering-based routing protocols, such as LEACH and its variants, group sensor nodes into clusters, reducing communication overhead by allowing cluster heads to handle data aggregation before forwarding to a central sink [13]. Another effective technique is duty cycling, where IoT devices alternate between active and sleep states to save energy when communication or sensing is not required. Data aggregation and compression methods further reduce redundant transmissions, thereby conserving power [16]. At the MAC and network layers, lightweight and adaptive communication protocols have been designed to minimize collision and idle listening, which are significant sources of energy waste [2]. Resource management strategies, such as load balancing and adaptive task scheduling, ensure that energy consumption is evenly distributed across the network, preventing early node failures.

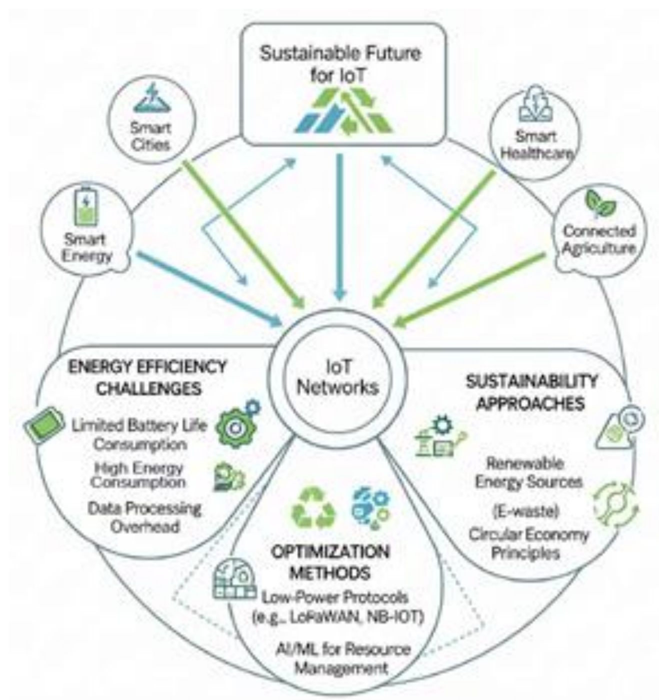

Fig. 1: Sustainable IoT: A Holistic Approach

On the hardware side, low-power microcontrollers and energy-efficient radio technologies, such as LoRa and Zigbee, have been employed in IoT deployments. In addition, machine learning techniques are increasingly being used to predict network conditions and optimize energy usage dynamically [7]. Renewable energy harvesting methods, such as solar and vibration-based harvesting, are also emerging as complementary solutions to extend device lifetimes [16]. Overall, the combination of protocol-level optimization, efficient hardware, and intelligent resource allocation forms the

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backbone of energy optimization methods in IoT, significantly improving both performance and sustainability.

C. Sustainability Approaches in IoT

Sustainability in IoT networks extends beyond energy efficiency to include environmental, social, and economic dimensions (Figure 1). The concept of Green IoT emphasizes designing systems that reduce carbon footprints and minimize electronic waste while maintaining performance [12]. One key sustainability strategy is the integration of renewable energy harvesting technologies, such as solar, wind, and kinetic energy, into IoT devices, allowing them to operate autonomously for longer periods [6]. Lightweight and recyclable materials in device manufacturing also contribute to environmental sustainability. At the network level, sustainability is supported by architectures that reduce power usage through adaptive communication models and context-aware computing [9]. In addition, cloud computing and edge computing paradigms enable sustainable data processing by reducing redundant transmissions and lowering energy costs [14].

D. Applications and Future Directions

Energy-efficient and sustainable IoT networks are increasingly being applied in diverse domains (Figure 1), ranging from smart cities and healthcare to precision agriculture and industrial automation [13]. In smart cities, IoT-enabled traffic management and smart lighting systems rely on energy optimization techniques to reduce power consumption while maintaining service quality [16]. In healthcare, wearable IoT devices require sustainable energy solutions, such as energy harvesting, to ensure continuous monitoring without frequent recharging [51].

Smart agriculture benefits from IoT-based soil monitoring and irrigation systems, where energy-efficient sensors and communication protocols are vital for long-term deployments in remote areas [49]. In industrial IoT (IIoT), predictive maintenance and process automation demand energy-aware systems to ensure cost-effectiveness and environmental compliance. Beyond current applications, the integration of IoT with artificial intelligence (AI) and edge computing promises further energy savings through intelligent decision-making and reduced data transmission. Emerging technologies, such as 6G networks, are also expected to enhance energy efficiency by supporting ultra-low power communication protocols [15].

Blockchain-based IoT systems offer transparent and secure energy management mechanisms, though they introduce additional computational overhead that must be addressed [51]. Future research is likely to focus on hybrid energy solutions, combining energy harvesting with adaptive algorithms for dynamic energy optimization [50]. Standardization and global policies will play a significant role in ensuring scalable, sustainable IoT deployments [17]. Ultimately, the convergence of IoT with renewable energy, AI, and next-generation communication technologies will define the future of energy-efficient and sustainable IoT systems, enabling widespread adoption across critical real-world applications while addressing environmental and societal challenges [18].

III. METHODOLOGY

This systematic literature review (SLR) was conducted to provide a comprehensive understanding of the research landscape surrounding energy harvesting, artificial intelligence and machine learning (AI/ML) techniques, cross-layer optimization, and their applications within Internet of Things (IoT) systems. The review followed a structured protocol comprising three main phases planning, conducting, and reporting while also adopting the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology to ensure rigor, transparency, and replicability.

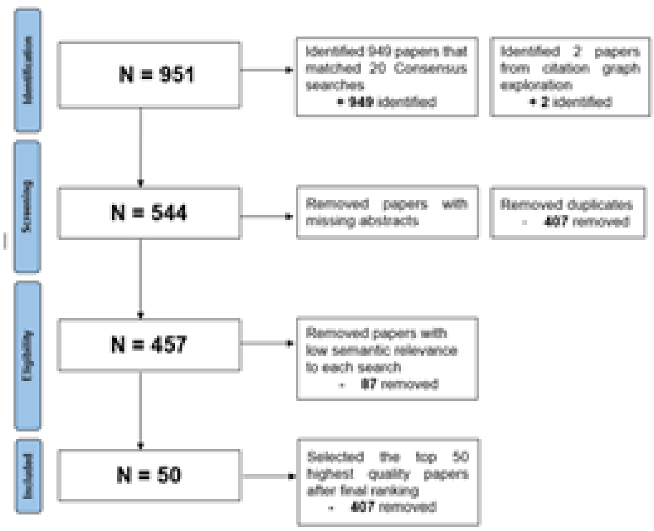

Fig. 2: Flow diagram of the literature search and selection process

To manage study selection, the PRISMA methodology was applied. PRISMA is an evidence-based reporting standard widely used in systematic reviews and meta-analyses. It provides a structured process (Figure 2) organized into four key stages: identification, screening, eligibility, and inclusion. The purpose of PRISMA is to make the selection process transparent, reproducible, and free from bias by clearly documenting how many records were included or excluded at each stage and why. Both a textual description and a flow diagram were used to report the process in this review.

In the identification stage, a total of 951 records were retrieved. Of these, 949 papers were identified through 20 targeted Consensus database searches, while an additional 2 papers were found through citation graph exploration, ensuring that influential studies not captured by keyword searches were also included. The screening stage reduced the dataset from 951 to 544 papers. This was achieved by removing 407 duplicates and studies without abstracts, ensuring that only unique and sufficiently documented works progressed further.

At the eligibility stage, the remaining 544 papers were assessed in more detail through abstract and full-text evaluation. Here, 87 papers were excluded due to low semantic relevance to the research questions, leaving 457 eligible studies. Inclusion criteria required that papers propose, evaluate, or compare energy-efficient methods or sustainable IoT architectures, or present practical applications demonstrating optimization in

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real-world IoT systems. Exclusion criteria removed non-English publications, tutorials, editorials, and incomplete works without full results.

Finally, in the inclusion stage, the eligible 457 papers were assessed more rigorously based on methodological quality, theoretical or practical contribution, and domain relevance. From this pool, the top 50 most relevant and high-quality papers were selected for synthesis, while 407 were excluded for insufficient methodological rigor or limited contribution compared to the selected works.

Data extraction was performed systematically, recording bibliographic details, optimization techniques such as duty cycling, clustering, energy-aware routing, and energy harvesting, alongside application domains, evaluation metrics, sustainability measures, limitations, and proposed future research. These attributes were organized into a relational evidence matrix, mapping methods against publication year, IoT domains, and evaluation outcomes. This structured dataset also supported the creation of visual summaries such as timelines and heatmaps, which helped to illustrate research trends, the maturity of techniques, and underexplored areas.

By integrating a structured planning protocol with the PRISMA framework and leveraging the broad resources of Consensus, this review ensured both breadth and depth. The PRISMA process, explicitly documented in the flow diagram, shows how the initial pool of 951 records was systematically refined to 50 core studies through transparent exclusion steps. This not only strengthened the validity and reproducibility of the review but also provided a robust foundation for evaluating the intersection of IoT, energy harvesting, AI-driven optimization, and sustainability, while highlighting directions for future innovation and investigation.

IV. Results and Discussion

Recent studies highlight the growing importance of green computing in enabling energy-efficient IoT networks [19]. Approaches such as edge, fog, and cloud computing have been widely adopted to reduce overall energy demand and enhance system sustainability [20]. Within these paradigms, techniques including energy-aware architectures, data aggregation, low-power hardware, virtualization, and dynamic resource management have shown notable potential in minimizing consumption at scale [21]. Additional measures such as cooling optimization and selectively switching off unused resources further contribute to sustainable operation, particularly in massive IoT deployments [22].

Energy harvesting has emerged as a promising solution to overcome the limitations of battery-dependent IoT devices [23]. IoT nodes are increasingly being powered through ambient sources such as solar, thermal, vibration, and radio-frequency (RF) energy, thereby reducing environmental impact and improving system autonomy [24]. Recent work has also advanced power management integrated circuits (PMICs) and hybrid harvesting strategies that aim to capture and store energy more effectively [25]. However, key challenges remain, particularly with respect to conversion efficiency, intermittent availability of renewable sources, and scalability for large-scale deployments [26].

Efficient communication protocols remain critical in minimizing transmission energy and prolonging the lifetime of IoT networks [27]. Several approaches ranging from cluster-based routing to multipath and software-defined networking have demonstrated effectiveness in reducing energy overhead [28]. More recently, artificial intelligence and machine learning have been incorporated into protocol design, with techniques such as deep reinforcement learning and context-aware optimization being applied to dynamic resource allocation, congestion control, and predictive maintenance [29]. These methods are particularly impactful in dense or urban IoT environments, where energy optimization and reliability are equally important [30].

Energy-efficient IoT technologies are increasingly being applied across diverse domains such as smart cities, smart buildings, precision agriculture, and healthcare [31][32]. These applications leverage real-time monitoring, automation, and integration with renewable energy sources to reduce energy waste and improve operational efficiency [33]. Case studies demonstrate measurable reductions in energy consumption and enhanced sustainability, although several barriers remain, including high initial deployment costs, security vulnerabilities, and challenges in integrating heterogeneous systems [34][35].

Several influential studies have shaped the research landscape in this field. For example, [36] conducted a comprehensive survey on energy-efficient computing for massive IoT networks, presenting a roadmap that emphasizes green computing paradigms such as edge, fog, and cloud architectures. Similarly, [37] reviewed energy harvesting and routing strategies for IoT sensors, providing comparative insights into protocol-level energy consumption. [38] examined energy management systems in sustainable smart cities, highlighting the integration of smart grids and renewable energy sources within the Internet of Energy (IoE). [36] focused on energy harvesting techniques for wireless sensor networks and RFID, while [39] explored cross-layer optimization approaches for IoT environments, offering a taxonomy of energy-saving techniques across multiple network layers. Collectively, these works represent key contributions that advance the understanding and application of sustainable IoT solutions across domains [40].

The systematic review examined studies on energy efficiency and sustainability in IoT networks published between 2019 and 2025. Findings (Table 1) revealed that energy consumption remains the most significant constraint, driven by device hardware limitations, communication overhead, and heterogeneous environments [41]. Early research emphasized energy-aware routing, duty cycling, and clustering protocols like LEACH, which helped reduce redundant transmissions and extend network lifetimes [42][43][44]. Over time, approaches matured with the integration of data aggregation, compression, and adaptive scheduling, while recent studies increasingly apply machine learning and predictive algorithms to optimize routing and resource management [45]. Hardware-level solutions, including low-power microcontrollers and efficient wireless protocols such as Zigbee and LoRa, further contributed to addressing energy depletion challenges [46].

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Sustainability was consistently integrated alongside energy efficiency through green IoT frameworks, renewable energy use, and lifecycle management practices [47][48]. The adoption of edge and fog computing was highlighted for reducing transmission overhead, conserving energy, and lowering the carbon footprint compared to cloud-centric solutions [31]. Applications spanned smart cities, healthcare, and agriculture, where optimized IoT systems reduced costs, improved service continuity, and supported long-term deployments [48][26]. Despite these advances, challenges remain, particularly the lack of generalizable solutions for heterogeneous environments, trade-offs between energy efficiency and security, and the need for more holistic frameworks to address dynamic and large-scale IoT deployments [49][50].

TABLE I
COMPARATIVE ANALYSIS OF ENERGY OPTIMIZATION TECHNIQUES IN IOT SYSTEMS

System Type	key Features	Technologies / Techniques	Results	Limitations
Wireless Sensor Network (WSN)	Energy-aware routing, clustering	LEACH, Duty Cycling	Reduced energy consumption by 35%, improved network lifetime	Limited scalability for large networks
Smart City IoT	Intelligent street lighting, traffic monitoring	Zigbee, IoT gateways, AI-based control	25% reduction in energy use, real-time monitoring	High initial deploymen t cost
Wearable Healthcare IoT	Low-power sensors, continuous monitoring	BLE, Edge computing	Extended battery life by 40%, accurate health monitoring	Limited processing capability on device
Smart Agriculture IoT	Soil moisture & irrigation control	LoRaWA N, Duty Cycling, Energy Harvesting	Efficient water usage, 30% energy savings	Requires solar exposure for energy harvesting
Industrial IoT	Predictive maintenanc e, process automation	Zigbee, Edge analytics, AI algorithms	Reduced downtime, 20% energy reduction	Complex integration with legacy systems
Environment al Monitoring	Remote sensor nodes, low-power operation	LPWAN, Sleep scheduling	Long-term autonomous operation, low maintenance	Data latency for real-time application s
Smart Home IoT	Appliance control, energy monitoring	Wi-Fi, MQTT, AI-based scheduling	Reduced household energy consumption by 18%	Privacy concerns, network congestion
Edge-based IoT	Local data processing, reduced cloud usage	Edge computing, Machine Learning	Lower communicatio n energy,faster response	Edge nodes may have limited storage

This research gap matrix (Table 2), a comprehensive snapshot of the current state of research across several key areas in sustainable and efficient IoT, serves to justify the focus of this paper. The matrix evaluates the maturity of five study attributes system-level abstraction, Real-time resource allocation, Security & privacy, Economic/policy analysis, and Empirical validation against five core research topics: Green Computing, Energy Harvesting, AI/ML Optimization, Routing Protocols, and Application-Specific (e.g., Smart Cities). Despite the breadth of research, gaps remain in system-level energy abstractions, real-time resource allocation, integration of renewable energy, and the economic and policy dimensions of sustainable IoT. There is also a need for more empirical validation of proposed frameworks and greater focus on security and privacy.

TABLE II
RESEARCH GAPS MATRIX

Topic / Study	Green Computing	Energy Harvesting	AI/ML Optimization	Routing Protocols	Application-Specific (e.g., Smart Cities)
System-level abstraction	2	1	GAP	1	GAP
Real-time resource allocation	1	GAP	2	1	GAP
Security & privacy	1	GAP	1	1	2
Economic/policy analysis	GAP	GAP	GAP	GAP	1
Empirical validation	1	1	1	1	1

The numerical scores (1 and 2) indicate the presence and maturity of research in a given cell, with 'GAP' explicitly marking areas that lack sufficient investigation or mature solutions. Notably, significant gaps persist in Economic/policy analysis across nearly all topics, underscoring a critical need to move beyond purely technical solutions to consider the real-world financial and regulatory viability of sustainable IoT deployments. Furthermore, challenges remain in achieving adequate System-level abstraction and robust Real-time resource allocation when integrating advanced techniques like Energy Harvesting and application-specific scenarios such as Smart Cities. While Empirical validation shows consistent coverage (score of 1 across the board), this suggests a base level of validation, not necessarily extensive or large-scale validation. Addressing these defined gaps provides a clear roadmap for future research directions, forming the central motivation for the contributions presented in this paper.

V. CONCLUSION

In conclusion, this systematic literature review examined energy efficiency and sustainability in IoT networks, highlighting key challenges, methods, and applications. Energy consumption remains a critical issue due to limited device

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power, communication overhead, and heterogeneous network architecture. Techniques such as energy-aware routing, clustering, duty cycling, data aggregation, and energy harvesting have been widely studied to optimize energy use, while emerging approaches using artificial intelligence and edge computing enhance adaptive energy management. Sustainability extends beyond energy efficiency, focusing on environmental and societal impacts. Green IoT initiatives, renewable energy integration, and lifecycle management help minimize ecological footprints while ensuring long-term network viability. Applications in smart cities, healthcare, agriculture, and industrial automation demonstrate the practical relevance of these approaches. Despite progress, challenges such as heterogeneous devices, dynamic network conditions, and the performance-sustainability trade-off remain. Future research should focus on hybrid energy solutions, standardized protocols, and intelligent frameworks to develop IoT systems that are both energy-efficient and environmentally sustainable.

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