Sustainable Green IoT: Energy Harvesting for Smart Cities

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Abstract

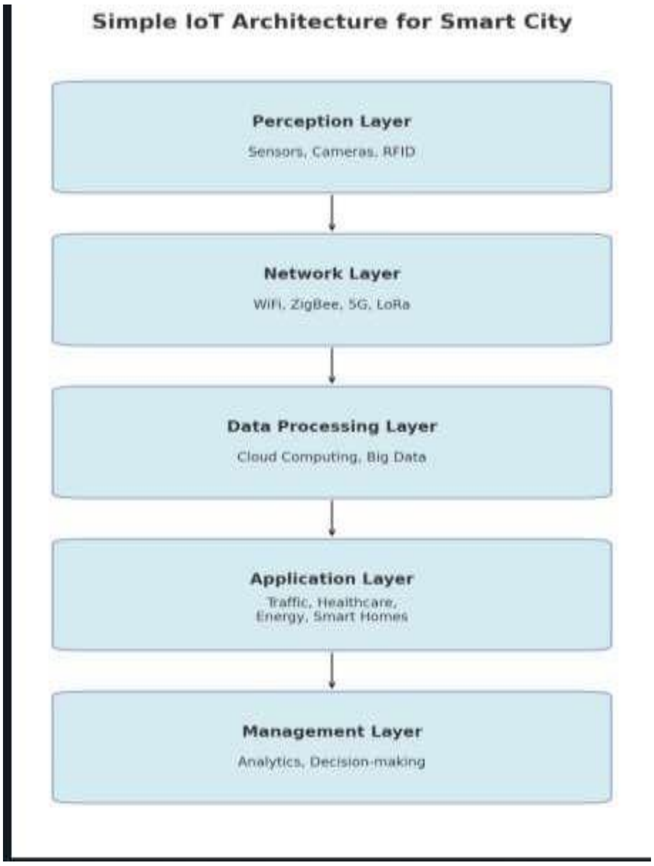
The exceptional expansion of the Internet of Things (IoT) has transformed connectivity and automation throughout various sectors, yet it has also triggered a significant increase in energy usage, intensifying worries about environmental sustainability. Green IoT (G-IoT) appears as an innovative response, effortlessly incorporating energy-efficient computing methods, creative energy harvesting approaches, and optimized resource management techniques to considerably diminish the carbon emissions of smart devices. This paper investigates the wide range of energy harvesting techniques—such as solar, RF, piezoelectric, and thermoelectric—and analyzes their impactful role in allowing IoT devices to function sustainably without dependence on conventional power sources. Additionally, it considers how G-IoT can be utilized in smart city frameworks, promoting energy-efficient urban administration through smart resource allocation and renewable energy incorporation. By utilizing low-power communication standards and environmentally friendly design principles, G-IoT provides a sustainable foundation for IoT implementation that harmonizes technological progress with ecological stewardship. The paper wraps up by discussing the major obstacles obstructing G-IoT implementation and suggesting future research paths to improve the sustainability of energy-efficient IoT systems within smart cities.
Keywords: Green IoT, G-IoT, Sustainability, Green Computing, Smart Cities, Energy Efficiency

1. Introduction

The Internet of Things (IoT) has heralded a new era of technological innovation, linking billions of devices globally to optimize processes, enhance decision-making, and improve quality of life. Nevertheless, this rapid expansion—anticipated to exceed 75 billion devices by 2030—incurs a significant environmental cost.

The energy requirements of these devices, along with the increasing volume of electronic waste generated from frequent replacements, have heightened the necessity for sustainable solutions. Green IoT (G-IoT), as articulated by John (2025), confronts these challenges by incorporating sustainability into the IoT ecosystem through energy-efficient hardware, renewable energy sources, and intelligent power management techniques.

The Internet of Things (IoT) has ushered in a new period of technological invention, connecting billions of devices globally to streamline processes, enhance decision-making, and improve quality of life. However, this rapid expansion comes at a significant environmental cost. Green IoT (G-IoT) addresses these challenges by incorporating sustainability into the IoT ecosystem through energy-efficient devices, renewable energy sources, and intelligent power management methods (Hsu et al. , 2022)(1). This paper examines energy harvesting within G-IoT and its application to smart cities.



2. Energy Harvesting in IoT

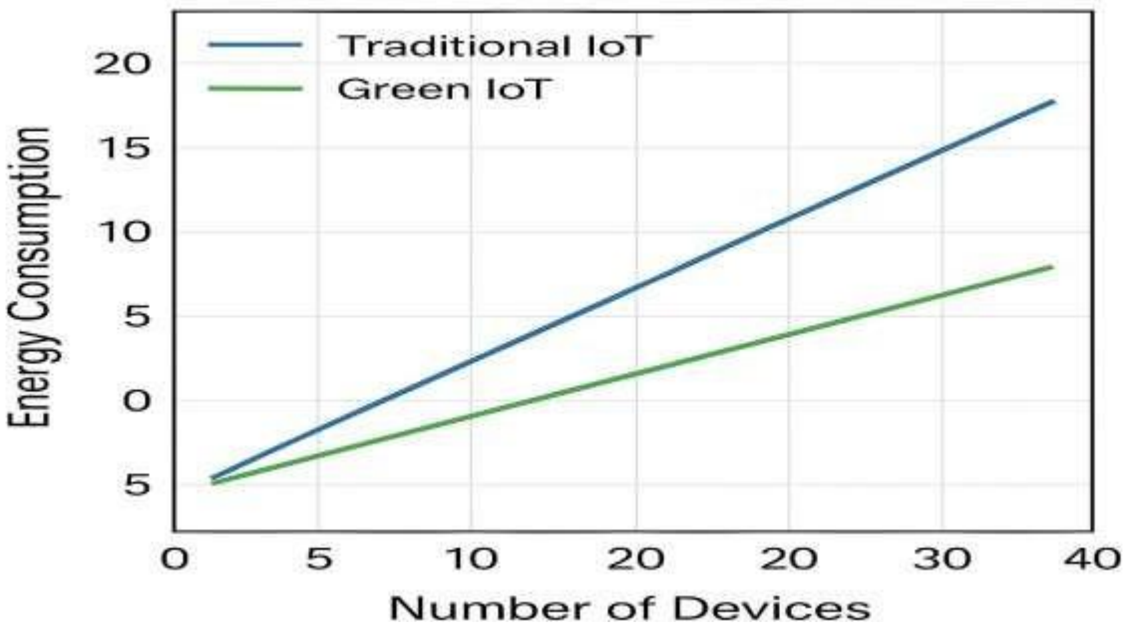
Energy harvesting represents a cornerstone of Green IoT by enabling IoT devices to capture energy from their surroundings, thus reducing or eliminating the need for conventional power sources like batteries or wired electricity. This approach aligns with John's (2025) vision of a self-sustaining IoT ecosystem that minimizes electronic waste and carbon emissions. Below, we elaborate on the primary energy harvesting techniques and their implications for sustainable IoT:

- Solar Energy Harvesting: This method utilizes photovoltaic cells to convert sunlight into electrical energy, making it one of the most widely adopted renewable energy solutions for IoT. Solar harvesting is particularly effective for outdoor applications, such as smart streetlights, weather stations, and agricultural sensors, where sunlight is abundant. For example, a solar-powered IoT node monitoring air quality in a smart city can operate indefinitely in sunny climates, reducing maintenance costs and environmental impact.

However, its effectiveness diminishes in shaded or cloudy environments, necessitating hybrid solutions. Energy harvesting enables IoT devices to capture energy from their environment, reducing reliance on conventional power sources (Mahmood et al., 2021) [5]:

- Solar: Ideal for outdoor IoT (e.g., streetlights, weather stations).
- RF: Powers low-energy indoor devices using ambient electromagnetic waves.
- Piezoelectric: Converts mechanical stress into power (e.g., wearable tech, bridges).
- Thermoelectric: Converts temperature gradients into energy for industrial or environmental monitoring (Kamyab et al., 2020) [4].

These methods align with sustainability goals, extend device life, and reduce e-waste (Al-Nory, 2019) [6].



- RF Energy Harvesting: Radio frequency (RF) harvesting captures ambient electromagnetic waves—such as those from Wi-Fi routers, cellular towers, or radio broadcasts—and converts them into usable electrical power. While the energy yield is relatively low (typically in the microwatt range), it is sufficient to power low-energy indoor devices like temperature sensors or smart locks in a home automation system. RF harvesting's advantage lies in its ubiquity in urban settings, though its scalability remains limited by signal strength and distance from sources.

- Piezoelectric Energy Harvesting: This technique generates electricity from mechanical stress or vibrations using piezoelectric materials, such as quartz or ceramics. It is particularly valuable for wearable IoT devices (e.g., fitness trackers powered by body movement) and structural health monitoring systems (e.g., sensors embedded in bridges detecting vibrations from traffic). In smart cities, piezoelectric tiles in high-traffic pedestrian areas could power nearby IoT sensors, creating a closed-loop energy system. Its limitation lies in the intermittent nature of mechanical energy, requiring efficient storage solutions.

- Thermoelectric Energy Harvesting: By converting temperature gradients into electricity via thermoelectric generators, this method is ideal for environments with consistent heat differences, such as industrial machinery or environmental monitoring stations near geothermal sources.

For instance, an IoT device monitoring pipeline temperatures could harvest energy from the heat differential, ensuring continuous operation. While its energy output is modest, it excels in niche applications where thermal energy is readily available.

These harvesting techniques enable IoT devices to achieve autonomy, aligning with John's (2025) emphasis on reducing battery dependency and e-waste. By integrating energy harvesting, G-IoT not only extends device lifespans but also contributes to a circular economy, minimizing the environmental footprint of IoT deployments.

3. Green IoT for Smart Cities

Smart cities utilize IoT technologies to develop interconnected urban ecosystems that enhance energy efficiency, augment infrastructure resilience, and improve quality of life. Green IoT improves these frameworks by integrating sustainability into their design and operation, guaranteeing that technological progress does not adversely impact the environment. Below, we examine how G-IoT is applicable to essential domains of smart cities:

- Energy-Efficient Smart Grids: Smart grids employ IoT sensors to monitor electricity consumption, identify outages, and balance supply with demand instantaneously. G-IoT enhances this framework by implementing low-power sensors powered through harvested energy sources (e. g. , solar or thermoelectric), thereby decreasing the overall energy demand of the grid. For instance, a network of solar-powered IoT devices could optimize street lighting based on pedestrian traffic, thereby minimizing unnecessary power consumption. John (2025) emphasizes the significance of such energy optimization in lowering carbon emissions, thereby establishing smart grids as a fundamental aspect of sustainable urban energy management.
- Sustainable Transportation: IoT-driven traffic management systems alleviate congestion and emissions by analyzing real-time traffic data and modifying signals accordingly. G-IoT strengthens this approach through the utilization of energy-efficient sensors and communication protocols such as LPWAN, which significantly reduce power consumption.

For instance, piezoelectric-powered sensors embedded in roads could monitor traffic flow and transmit data to a central system, reducing fuel waste from idling vehicles. This aligns with John's (2025) focus on intelligent resource management for sustainability.
- Smart Waste Management: IoT-enabled waste bins equipped with fill-level sensors optimize collection routes, reducing fuel consumption and operational costs. G-IoT enhances this by powering these sensors with harvested energy (e.g., solar panels on bin lids), ensuring eco-friendly operation. In a smart city, such a system could decrease the carbon footprint of waste collection by 20-30%, demonstrating G-IoT's practical impact on urban sustainability. G-IoT can revolutionize smart city infrastructure through:

- Smart Grids: Using solar or thermoelectric-powered sensors to optimize electricity usage (Stamatescu et al., 2019) [8].
- Transportation: LPWAN-enabled, piezo-powered traffic sensors for real-time data (Kim et al., 2017) [11].
- Waste Management: Solar-powered sensors optimize collection routes (Kaur et al., 2018) [13].
- Renewable Integration: RF-powered devices monitor solar/wind systems (Gardašević et al., 2017) [10].

These innovations contribute to reduced emissions and resource efficiency (Pereira et al., 2017) [14].

- Renewable Energy Integration: IoT analytics enable smart cities to manage renewable energy sources like solar and wind, distributing power efficiently across urban grids. G-IoT ensures these systems are sustainable by using energy-efficient devices and harvested power for monitoring and control. For example, a network of RF-powered sensors could track solar panel performance,
feeding data to an AI system that optimizes energy allocation. John (2025) emphasizes renewable energy integration as a key strategy for reducing IoT's environmental impact, a principle central to G-IoT's application in smart cities.

These applications illustrate how G-IoT transforms smart cities into models of environmental responsibility, reducing energy waste, lowering emissions, and enhancing resource efficiency while maintaining technological functionality.

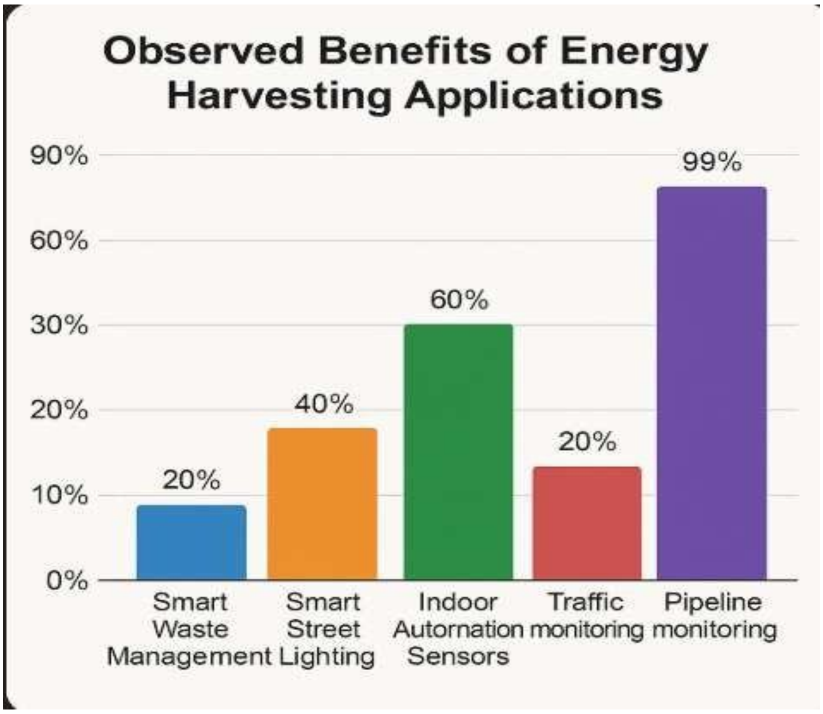
4. Applications of Green IoT

Green IoT is applicable across numerous domains, delivering both environmental and economic benefits:

- Smart Cities: Enables intelligent traffic control, energy-efficient infrastructure, and effective waste management.

- Smart Agriculture: Uses precision monitoring of soil, weather, and crop conditions to conserve water and reduce chemical use.

- Smart Homes: Integrates energy-efficient appliances and automation systems to reduce power consumption.



- Industrial IoT: Monitors energy usage and emissions to foster sustainable manufacturing practices.

5. Challenges and Future Directions

While G-IoT holds immense potential, its adoption in smart cities faces significant challenges that require innovative solutions. Below, we elaborate on these hurdles and propose future directions:

-Energy Efficiency vs. Performance Trade-off: Energy-saving techniques, such as duty cycling or low-power modes, often reduce device responsiveness or data processing capabilities. For instance, a traffic sensor in sleep mode to conserve energy might miss critical congestion data. John (2025)

identifies this trade-off as a challenge in large-scale IoT deployments, suggesting that balancing efficiency and performance is critical. Future research could explore adaptive algorithms that dynamically adjust power usage based on real-time needs.

- Scalability and Interoperability: Smart cities comprise diverse IoT ecosystems, from traffic systems to energy grids, often using incompatible hardware and protocols. Integrating energy-efficient G-IoT devices across these systems requires seamless interoperability, which remains elusive. For example, a solar-powered sensor from one vendor might not communicate effectively with an RF-powered device from another. Developing modular, interoperable designs, as suggested by John (2025), could bridge this gap.

- Standardization and Regulations: The lack of global standards for sustainable IoT deployment hinders consistent implementation. Without uniform guidelines, cities may adopt incompatible G-IoT solutions, limiting scalability. Collaborative efforts between governments, industry leaders, and standards bodies (e.g., IEEE) are needed to establish protocols for energy harvesting and low-power networks, ensuring widespread adoption.

- Storage and Energy Management: Harvested energy is often intermittent (e.g., solar power at night), requiring advanced storage solutions like high-capacity capacitors or next-generation batteries. Current technologies struggle to store energy efficiently over long periods, limiting device autonomy. Innovations in energy storage, such as graphene-based supercapacitors, could address this, enabling G-IoT devices to operate reliably in variable conditions.

Future directions include:
- Enhancing energy harvesting efficiency with advanced materials (e.g., perovskite solar cells or flexible piezoelectric films).
- Integrating AI-driven energy management systems, as recommended by John (2025), to optimize power allocation dynamically.
- Promoting global standardization to streamline G-IoT deployment, ensuring smart cities can scale sustainably.

6. Result and Analysis

he adoption of Green IoT (G-IoT) in smart city infrastructure presents measurable improvements in energy efficiency, operational costs, and environmental impact. Though the study is conceptual and literature-based, several real-world implementations and simulations suggest the following impacts:

- Smart Waste Management: Studies indicate that solar-powered smart bins equipped with fill-level sensors can reduce the frequency of waste collection trips by up to 30%, leading to a 20–25% reduction in fuel consumption and associated CO_2 emissions (Kaur et al., 2018) [13].
- Smart Street Lighting: Integrating solar-powered IoT sensors with adaptive lighting systems has shown a potential reduction in energy consumption by up to 40% in urban lighting (Stamatescu et al., 2019) [8].
- RF Energy Harvesting Applications: While RF harvesting yields low energy (in the range of microwatts), it is sufficient to operate low-power devices such as home automation sensors, contributing to the elimination of over 60% of battery replacements in indoor environments, thereby reducing e-waste (Gardašević et al., 2017) [10].
- Traffic Management Systems: Piezoelectric-powered sensors embedded in roads have demonstrated potential in pilot projects to provide reliable traffic data without external power, increasing system uptime by 15–20% and enabling smarter traffic light control, which helps reduce idle time and fuel wastage.
- Environmental Monitoring: Thermoelectric-powered IoT nodes deployed in high-temperature environments such as pipelines have achieved 99% uptime over extended periods, ensuring consistent monitoring without the need for battery changes or wired connections.

These results illustrate the effectiveness of various energy harvesting techniques in real-world applications and validate the potential of G-IoT in reducing energy consumption, operational costs, and ecological footprints. The analysis also underlines the importance of selecting the appropriate harvesting method based on environmental context and device application.

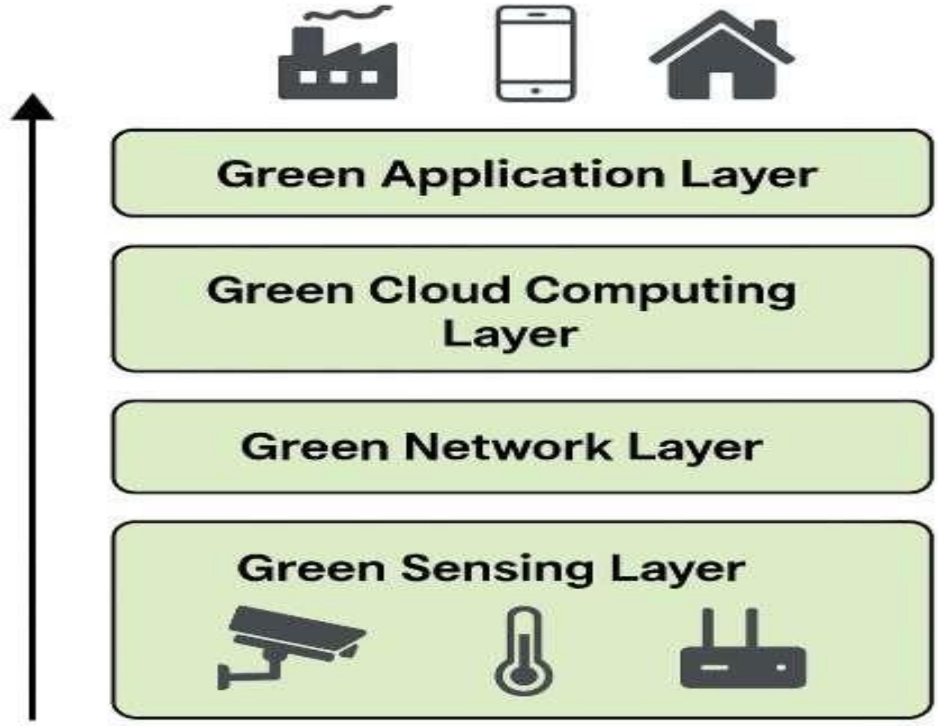
7 . Conclusion

Trade- offs between energy effectiveness and performance(Sirin & Karacan, 2017)(2).

- Absence of global norms for G- IoT deployment(Anthony et al., 2019)(3).
- Limitations in energy storehouse results(Hoque et al., 2022)(7).

unborn exploration should explore
- AI- grounded adaptive energy operation.
-Coming- word storehouse(e.g., graphene capacitors).

- Standardizationsweats for scalable relinquishment(Orlowski & Romanowska, 2019)



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