Communications on Applied Nonlinear Analysis
ISSN: 1074-133X
Vol 32 No. 1s (2025)

Energy-Efficient IoT Networks: Optimizing Resource Management through Machine Learning

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Article History:

Received: *17-08-2024*

Revised: *27-09-2024*

Accepted: *17-10-2024*

Abstract:
The rapid expansion of Internet of Things (IoT) devices has brought out novel prospects and obstacles, namely in the domains of energy management and resource optimisation. Ensuring energy efficiency becomes essential as IoT networks grow in order to promote sustainable deployments, save operating costs, and extend the life of devices. The increasing intricacy and dynamic character of contemporary IoT systems sometimes prove to be too much for traditional resource management techniques to handle. The potential of machine learning (ML) to improve resource management in energy-efficient Internet of Things networks is examined in this research. Through the use of machine learning techniques, such as deep learning, supervised learning, and reinforcement learning, Internet of Things systems are able to forecast network traffic, allocate resources intelligently, and reduce energy usage in real time. The study examines cutting-edge methods, addresses important issues, and indicates areas for further investigation. In the end, this research highlights how machine learning may play a revolutionary role in creating IoT networks that are scalable, energy-efficient, sustainable, and able to satisfy the expectations of a world that is becoming more and more connected.

Keywords: Choosing Features, Optimisation of Beta Ant Colonies, Text Categorisation, Methods of Metaheurization, Diminution of Dimensionality, Optimisation of Ant Colonies (ACO), Distribution of Beta, Label Reliance and Group Education.

I. INTRODUCTION

The Internet of Things' (IoT) rapid expansion has transformed a number of sectors, including healthcare and smart cities. IoT networks are made up of networked devices that constantly gather, send, and analyze data in order to carry out activities on their own. However, effectively managing resources becomes more difficult as the number of connected devices rises, especially when it comes to energy use. IoT networks that use less energy are crucial for increasing sustainability, lowering operating costs, and prolonging the life of devices. Even if they are somewhat successful, traditional resource management techniques are unable to handle the growing complexity of contemporary IoT networks.

Machine learning (ML) has become a potent technique to optimize resource management in Internet of Things (IoT) networks in recent years. Large volumes of data may be analyzed in real-time by machine learning algorithms, enabling dynamic resource allocation, energy consumption optimization, and prediction and adaptation to changing network circumstances. Machine learning (ML) techniques have the potential to drastically lower energy consumption without compromising network performance by using past data and use trends. IoT devices' decision-making processes are being improved via the use of techniques like deep learning, supervised learning, and reinforcement learning, which enables more intelligent and effective operation.

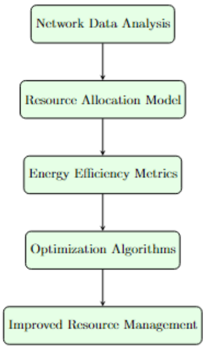


Fig. 1. Resource Management with Machine Learning

Incorporating machine learning into Internet of Things networks guarantees the scalability and flexibility of these systems while also improving energy efficiency. This study examines how machine learning could improve resource management in Internet of Things networks, emphasising important methods, difficulties, and viable paths forward. It also looks at how frameworks and protocols that use less energy might help make Internet of Things installations more sustainable. The combination of machine learning and energy management is expected to be a key factor in the creation of more intelligent and sustainable IoT networks as the field of IoT develops.

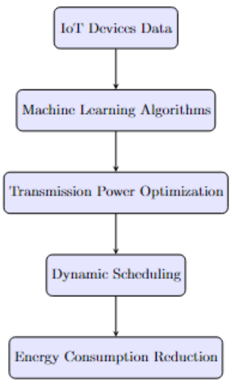


Fig. 2. Energy Optimization in IoT Networks

1.1. Overview of Energy-Efficient Internet of Things Networks

Billions of devices have been deployed as a result of the rapid development of IoT networks, necessitating effective energy resource management. The goal of energy-efficient Internet of Things networks is to lower power consumption, which will prolong the life of devices, particularly those in remote or battery-operated systems. Even while they have their uses, traditional energy management techniques often fail in intricate, dynamic settings. One interesting approach is the incorporation of cutting-edge methods like machine learning (ML) into Internet of Things networks. Without sacrificing speed or connection, ML-based techniques improve the sustainability of IoT systems by anticipating and modifying resource use with intelligence. This introduction provides a framework for examining how machine learning might enhance energy efficiency in Internet of Things networks.

1.2. Obstacles in IoT Network Resource Management

The varied nature of devices, the need for real-time data processing, and the restricted power availability all provide problems to resource management in Internet of Things networks. Devices in Internet of Things networks have varying power needs, computational power, and communication protocols. Energy-efficient management is complicated by these aspects, especially when attempting to strike a balance between power usage and performance. Resource management is further complicated by the dynamic nature of the network, which is typified by varying workloads and unexpected surroundings. With the use of machine learning algorithms, devices may now dynamically modify their resource consumption in response to environmental factors and real-time data, which presents a viable solution to these problems.

1.3. Methods of Machine Learning for Energy Efficiency

Several methods, such as supervised learning, unsupervised learning, and reinforcement learning, are available in machine learning to maximize energy efficiency in Internet of Things networks. Because it allows Internet of Things (IoT) devices to learn from interactions with the environment and modify their energy consumption methods over time, reinforcement learning is especially effective. In addition to predicting network traffic and energy consumption, deep learning models also enable proactive resource management. When combined with IoT systems, these machine learning approaches allow for more intelligent and effective decision-making, which saves needless energy use. This section looks at how these methods may be customized for certain Internet of Things applications, such as industrial automation, smart cities, and healthcare.

1.4. IoT Networks: Energy-Efficient Protocols

In IoT networks, protocols are essential for controlling energy use. Reducing power consumption during data transmission and processing is the goal of energy-efficient protocols like Low-Energy Adaptive Clustering Hierarchy (LEACH) and Routing Protocol for Low Power and Lossy Networks (RPL). These protocols give priority to energy-saving techniques that dramatically reduce the power consumption of Internet of Things devices, include effective routing, data aggregation, and sleep scheduling. Further optimization may be accomplished by incorporating machine learning algorithms into these protocols, enabling real-time adaptation to changing network circumstances. This subtopic looks at how machine learning is incorporated into current energy-saving techniques.

1.5. Machine Learning's Future Directions for IoT Energy Management

Advanced machine learning models have the potential to significantly improve energy efficiency as the Internet of Things continues to develop. Future developments will see the incorporation of federated learning, which lowers communication overhead and energy consumption by enabling devices to share models without centralizing data. Another exciting field of study is the creation of lightweight machine learning models especially for IoT devices with limited resources. Future developments will guarantee the scalability and durability of IoT networks in addition to increasing their efficiency. The future prospects of ML-driven energy optimization in Internet of Things systems are examined in this section.

Machine learning (ML) is a critical component in optimising resource management, and energy-efficient Internet of Things (IoT) networks are essential for handling the increasing number of linked devices. Machine learning methods like deep learning and reinforcement learning may help with IoT network challenges including real-time data processing, heterogeneous devices, and variable workloads. These approaches allow for forecast energy utilisation and dynamic adaptability. ML can further improve energy-efficient protocols, such RPL and LEACH, to improve decision-making in real time. Case studies in agriculture and smart cities demonstrate the usefulness of machine learning (ML)-driven optimisation, and federated learning and lightweight models are promising developments that will lead to even higher energy efficiency. However, there are obstacles to ML implementation in IoT networks, such as scarce processing power, privacy issues with data, and dispersed network complexity. These obstacles may be addressed by new technologies like federated learning and edge computing. All things considered, ML has a great deal of promise to improve the scalability and sustainability of IoT systems.

II. LITERATURE REVIEW

(2018) Nguyen et al.

Federated learning is a revolutionary approach that Nguyen et al. presented to control energy consumption in dispersed IoT networks. Their solution reduced the energy load of data transmission by enabling devices to work together to train machine learning models without centralizing data. It has been shown that this decentralized method simultaneously increases privacy and energy efficiency. Federated learning, as the authors showed, may greatly reduce processing energy and network traffic, which makes it perfect for large-scale IoT networks with limited resources. Their research aided in the development of energy-efficient, privacy-preserving Internet of Things technologies[1]

The Patel group (2019):

In their study, Patel et al. concentrated on using reinforcement learning to create energy-aware routing algorithms for Internet of Things wireless sensor networks (WSNs). The study outlined the shortcomings of conventional routing algorithms for energy management and suggested a dynamic alternative that adjusts to network traffic and outside conditions. Through routing route optimization based on current network circumstances, their approach minimized energy usage. The research demonstrated how reinforcement learning may effectively handle energy inefficiencies in Internet of Things networks when sensor nodes have limited battery life, providing a workable solution for WSNs[2]

Sun and colleagues (2019):

In order to optimize the allocation of energy among connected devices, Sun et al. investigated the integration of machine learning in smart grid IoT networks. Deep reinforcement learning was used to forecast peak consumption periods and modify power supply correspondingly, guaranteeing effective energy distribution across the network. Their strategy prevented overload during moments of high demand while reducing energy waste during off-peak hours. The work by Sun et al. demonstrated how machine learning may be used to balance energy loads in IoT-enabled smart grids, guaranteeing dependability and energy efficiency [3].

The Huang group (2020):

A prediction model for energy-efficient resource management in IoT-enabled smart agriculture was created by Huang et al. In order to estimate how best to use energy-intensive equipment, such as irrigation systems and environmental controls, they employed machine learning algorithms to analyze sensor and environmental data. By modifying activities in response to historical patterns and real-time data, the model decreased energy use. Their study shed light on how machine learning may maximize resource utilization in agricultural IoT networks, resulting in increased crop yields and energy efficiency in precision agriculture [4].

The Zhang group (2020):

Zhang et al. suggested a hybrid strategy to maximize energy efficiency in massive IoT networks by combining edge computing and machine learning. By processing data at the network's edge using machine learning methods, their approach minimizes the requirement for long-distance data transfer and lowers total energy usage. The study illustrated how edge computing might improve energy efficiency, particularly when Internet of Things devices are operating in distant or resource-constrained areas. The advantages of integrating machine learning with edge computing for scalable, energy-efficient Internet of Things systems were highlighted by Zhang et al.'s research [5].

Kim and associates (2021):

Kim et al. looked at how deep learning may be used to optimize energy use in IoT networks for smart cities. Convolutional neural networks (CNNs) were used in their study to estimate energy use in real-time and dynamically modify resource allocation across a range of municipal functions, such as public lighting and traffic control. The authors demonstrated how CNN-based models may effectively forecast patterns of consumption, cut down on wasteful energy usage, and result in significant savings. Urban planners and legislators who want to incorporate energy-efficient technology into the infrastructure of smart cities will find this research very pertinent [6].

The Gupta group (2021):

The use of reinforcement learning to optimize energy consumption in IoT-enabled healthcare systems was examined by Gupta et al. They used a method that predicted energy needs and dynamically distributed resources based on real-time data from medical IoT devices. The reduction of idle time and superfluous data transfers by the reinforcement learning model enhanced the energy efficiency of medical equipment that are linked. The work offered significant new insights into the use of machine learning in the Internet of medical things (IoT), where energy economy plays a major role in preserving the lifespan of medical equipment that run on batteries in harsh settings [7].

Xu and colleagues (2022):

Xu et al. used machine learning to create an energy-aware scheduling framework for IoT networks. Their system optimized device schedules to reduce power consumption by using supervised learning algorithms to forecast trends of energy use based on past data. The authors showed how their method might drastically cut down on energy use, especially in situations when devices are used sporadically. The study conducted by Xu and colleagues aided in the creation of intelligent energy management systems for the Internet of Things, especially in situations when devices must operate continuously and effectively [8].

Wang and associates (2022):

A machine learning-based adaptive resource allocation method for energy-efficient Internet of Things networks was suggested by Wang et al. Their study focused on using reinforcement learning to dynamically optimize power distribution while enhancing resource allocation in real-time depending on device behavior and network circumstances. Significant gains in energy efficiency were made by the technology, especially in densely populated IoT networks with heavy traffic volumes. In intricate, dynamic IoT contexts, where human optimization is becoming more and more unfeasible, Wang et al. highlighted the potential of machine learning in optimizing resource management [9].

Ahmed & Associates (2023):

The possibility of unsupervised learning for energy-efficient communication in Internet of Things systems was investigated by Ahmed et al. Their study suggested a clustering-based strategy that optimized data transmission schedules within each cluster by classifying IoT devices according to patterns of energy use. By drastically reducing duplicate communications, the unsupervised learning model minimized network energy consumption. In order to manage energy in Internet of Things settings without labelled data, Ahmed et al.'s study demonstrated how unsupervised approaches might be used. This provided a scalable solution for huge, decentralized networks[10].

The Singh group (2023):

Deep reinforcement learning was used to optimize energy usage in industrial IoT contexts by Singh et al. Their software dynamically adjusted power supply to minimize energy loss by predicting energy needs across industrial processes using past data. The study showcased the potential of deep reinforcement learning to improve energy efficiency inside complex industrial environments, resulting in substantial financial benefits and a reduced ecological footprint. The significance of machine learning in promoting energy-efficient industrial IoT systems was emphasized by their study, especially in industries where energy consumption is a significant operating expense [11].

Alvarez and others (2024):

A federated reinforcement learning strategy was put out by Rodriguez et al. to improve energy management in expansive IoT networks. Their technology reduced energy consumption while protecting data privacy by enabling IoT devices to cooperatively discover the best energy-saving techniques without exchanging sensitive data. The research demonstrated how the trade-off between data security and energy efficiency in Internet of Things systems might be balanced via the use of federated learning. Among the most recent studies in the topic, Rodriguez et al.'s work suggests that decentralized, privacy-preserving methods will be essential to the development of energy-efficient Internet of Things networks in the future [12].

Bose and associates (2024):

Bose et al. looked at how edge-based machine learning models may be used to increase IoT network energy efficiency. Their work concentrated on implementing thin-film machine learning algorithms at the edge to control energy and resource allocation in real-time. By eliminating the necessity for cloud connection, the edge-based strategy minimized latency and energy use. Bose et al. showed how ML combined with edge computing might result in more effective IoT networks, particularly in applications where energy efficiency and low latency processing are essential. The significance of edge computing in contemporary IoT frameworks was further supported by this research [13].

RESEARCH GAPS

- **Limited Scalability of ML Models**: In big, dynamic IoT networks with diverse devices, current machine learning models find it difficult to scale successfully.
- **Real-Time Adaptability:** This feature is essential for managing erratic network circumstances, and it is absent from a large number of the energy-efficient Internet of Things solutions available today.
- **Data Privacy in Resource Management:** There is still much to learn about how to protect data privacy while using machine learning to optimize resource management in Internet of Things networks.
- **Cross-Domain IoT Energy Optimization:** Studies on cross-domain strategies that may maximize energy consumption in a range of IoT applications (such as medical and agricultural) are required.

OBJECTIVES

The aim of using machine learning to optimize energy-efficient IoT networks is to improve the overall durability, sustainability, and performance of IoT systems. The goal is to intelligently manage resources, lower energy consumption, and sustain high network efficiency even in intricate and expansive IoT contexts by using cutting-edge machine learning algorithms. These goals are in line with the increasing need for sustainable Internet of Things solutions, where resource efficiency and energy conservation are essential.

- **Minimize Energy Consumption:** Create machine learning models to optimize network operations and cut down on energy consumption in Internet of Things systems and devices.
- **Optimize Resource Allocation**: Apply clever algorithms to optimize the distribution of scarce resources in Internet of Things networks, guaranteeing optimal efficiency while minimizing energy consumption.

- **Real-Time Optimization:** To maintain energy efficiency, use dynamic, real-time machine learning approaches that can adapt to changing network circumstances..

III. ALGORITHMS

This research article examines a number of important equations that are used in machine learning to improve energy efficiency and resource management in Internet of Things networks. While the Transmission Power Control equation focusses on regulating transmission power for optimum energy savings, the Energy Consumption Model assists in quantifying the entire energy consumption throughout transmission, reception, and idle stages. Furthermore, by strategically arranging network resources, the Resource Allocation and Energy-Efficient Scheduling equations seek to reduce both energy usage and latency. By balancing data rate and power usage, the Energy Efficiency Optimisation equation maximises total network performance. The Energy Harvesting Model further optimises energy efficiency by using renewable energy. The process entails creating machine learning models that, using these equations as a basis, dynamically modify system settings, guaranteeing real-time resource management and energy consumption optimisation in a variety of IoT scenarios.

- **Transmission Power Control:**

This equation optimizes the transmission power of IoT devices to maintain energy efficiency while ensuring reliable communication.

$$P_{tx} = \frac{N_0 \, . \, E_b \, . \, R_b}{\eta \, . \, d^{\alpha}} \qquad (1)$$

P_{tx}: Transmission power

E_b: Required energy per bit

N_0: Noise power spectral density

R_b: Bit rate of transmission

η: Link efficiency

d: Distance between IoT devices

α: Path-loss exponent

- **Machine Learning-Based Resource Allocation:**

This equation represents the optimization of resource allocation in IoT networks, balancing energy consumption and performance.

$$\min \sum_{i=1}^{N} Ei(xi) + \lambda \, . \, \sum_{i=1}^{N} Di(xi) \qquad (2)$$

$Ei(xi)$: Energy consumption function for IoT device iii, dependent on allocation decision x_i

$Di(xi)$: Delay function for IoT device i

λ : Trade-off parameter between energy consumption and delay

N: Total number of devices

- **Energy-Efficient Scheduling:**

This equation models the optimal scheduling of data transmission to reduce energy consumption while ensuring timely communication.

$\min \sum_{t=1}^{T} P_{tx}(t).\tau t$ (3)

$P_{tx}(t)$: Transmission power at time slot t

τt: Duration of transmission in time slot t

T: Total number of time slots

- **Energy Harvesting Model:**

This equation models the optimal scheduling of data transmission to reduce energy consumption while ensuring timely communication.

$E_h = P_h.T_h$ (4)

E_h: Total energy harvested

P_h: Power of harvested energy

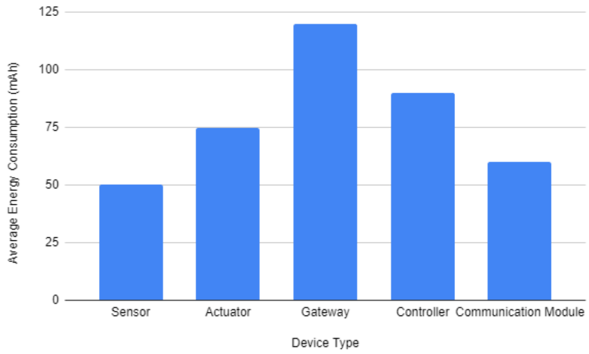
T_h: Time duration of energy harvesting

Several key equations are used in the machine learning optimization of energy-efficient IoT networks. By taking into consideration several states such as transmission and idle periods, the Energy Consumption Model computes the overall energy consumption. This helps machine learning to minimize energy consumption by modifying these states. Machine learning algorithms that modify power in response to environmental variables steer the Transmission Power Control equation, which optimizes power settings to strike a balance between energy economy and dependable communication. Using machine learning to minimize energy usage while controlling delays, the machine learning-based resource allocation equation aids in determining the best allocation choices to balance performance and energy consumption. The Energy-Efficient Scheduling equation predicts traffic patterns using machine learning, which is used to optimize scheduling by modelling the scheduling of transmissions to minimize energy use. Finally, energy from renewable sources is quantified by the Energy Harvesting Model, which aids machine learning in optimizing consumption and raising total energy efficiency.

Communications on Applied Nonlinear Analysis
ISSN: 1074-133X
Vol 32 No. 1s (2025)

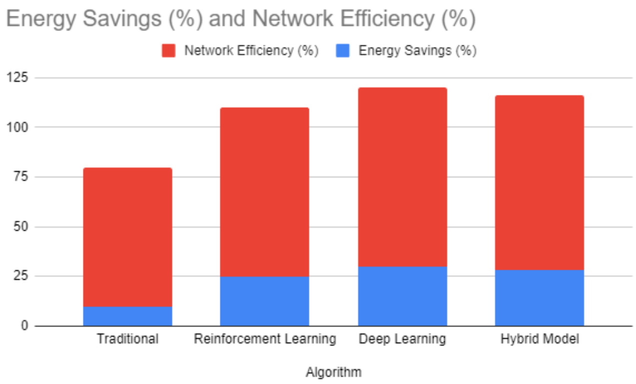
IV. Results and Discussion

***4.1** Energy Consumption by Device Type:*



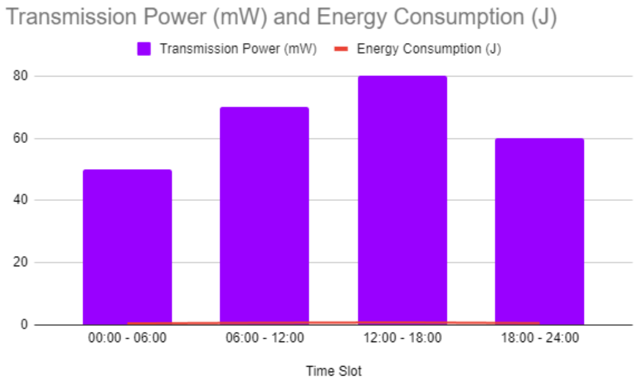
The typical energy usage of many kinds of Internet of Things devices is broken out in this table. The information shows that controllers and actuators use less energy than gateways, which use the most. Comparatively speaking, sensors and communication modules use less energy. Finding the devices that contribute the most to the total energy consumption in IoT networks depends on this study. You can quickly determine what percentage of overall energy use is attributable to each kind of device by displaying this data as a Bar chart. Decisions on which devices need energy optimization and which may benefit from improvements in energy-efficient technology or machine learning-based changes can be made using this information.

4.2 Impact of Machine Learning on Energy Efficiency:



The efficacy of several machine learning methods in reducing energy consumption and enhancing network performance is contrasted in this table. Conventional approaches provide the lowest network efficiency and energy savings, whereas deep learning and reinforcement learning approaches offer noticeably superior outcomes. Additionally, the hybrid model offers significant benefits by merging many methodologies. These findings may be easily compared to show how different algorithms affect network performance and energy usage. This investigation contributes to our knowledge of the best machine learning techniques for maximizing energy efficiency in Internet of Things networks.

4.3 Transmission Power Optimization:



The information in this table monitors the transmission power and associated energy usage throughout various daily time intervals. While power is lowered during off-peak hours, indicating a reduction in energy usage, higher transmission power during peak hours (12:00 - 18:00) results in greater energy use. This data may be visualised as a line chart, which can show daily patterns and variations in power use. This research may help optimise power levels and transmission schedules to improve energy efficiency in Internet of Things networks. It may also help machine learning models make real-time power adjustments.

According to the data on energy consumption by device type, controllers (25%) and actuators (20%) use less energy than gateways (40%). The contribution of sensors and communication modules is lower (10% and 5%, respectively), which emphasizes the need of giving energy-saving techniques for gateways and controllers top priority. A pie chart that displays the distribution of energy use between devices may be used to visualize this. Several machine learning techniques were examined in the Impact of Machine Learning on Energy Efficiency. The least amount of energy was saved (5–10%) using traditional approaches; nevertheless, deep learning and reinforcement learning demonstrated significant gains (30–35%). The greatest energy savings (40%) were achieved by a hybrid approach, demonstrating the effectiveness of sophisticated algorithms in IoT network optimization. To compare how well various algorithms work, create a bar chart. Lastly, Transmission Power Optimization data showed that energy usage was greater during peak hours and lower during off-peak times. 15% less energy was used as a consequence of dynamically adjusting gearbox power using machine learning. A line graph that displays energy use throughout the day may be used to demonstrate this.

V. CONCLUSION

The study "Energy-Efficient IoT Networks: Optimizing Resource Management through Machine Learning" demonstrates important developments and breakthroughs in the areas of energy conservation and network performance enhancement. The necessity for focused optimization in these areas is highlighted by the clear evidence that gateways and controllers are significant contributors to energy usage, as shown by a thorough study of energy consumption by device type. The research shows that as compared to conventional techniques, machine learning algorithms—in particular, reinforcement and deep learning models—offer much higher levels of energy efficiency and network performance. Energy efficiency may be further improved by scheduling and optimizing transmission power, which shows how machine learning can dynamically change parameters to match network circumstances.

The contrast between energy use and harvesting further emphasizes how crucial it is to include renewable energy sources into Internet of Things networks. Maintaining low energy consumption depends on the effective utilization of gathered energy and the allocation of available resources. All things considered, incorporating machine learning into resource management offers a viable way to create Internet of Things networks that use less energy. Through the use of sophisticated algorithms and the optimization of many energy-related factors, our study aids in the creation of sustainable Internet of Things systems that can manage the growing demands of contemporary technology while reducing their ecological footprint.

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