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Greening the Internet of Things: A Comprehensive Review of Sustainable IoT Solutions from An Educational Perspective

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ABSTRACT

Green IoT, or the use of Internet of Things (IoT) technologies to promote sustainability and reduce environmental impact, has gained increasing attention in recent years . TThe purpose of this paper is to increase awareness about the environmental effect of IoT and to share insights and ideas for making IoT more sustainable and contributing to a more environmentally friendly future. The paper discusses the benefits and challenges of using solar, wind, and other renewable energy sources in IoT applications, as well as the use of sensors, data analytics, and machine learning to optimize resource usage and monitor environmental conditions . The key findings of this paper indicate that Green IoT has the potential to play a significant role in addressing environmental challenges , such as climate change and resource depletion . However , there are still many challenges that need to be addressed, including the high cost of renewable energy sources and the complexity of managing large-scale IoT networks . Overall , this paper emphasizes the importance of Green IoT and the need for further research to develop more efficient and sustainable IoT solutions.

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1. INTRODUCTION

The Internet of Things (IoT) is an emerging technology that links actual items to the Internet, allowing them to share data and communicate with one another. Smart homes and wearable gadgets, as well as industrial production and transportation systems, are all using IoT devices (Dian *et al*., 2020). With the expanding quantity of IoT devices and their use, there is growing worry about their environmental effect. The manufacture, usage, and disposal of these gadgets can all contribute to greenhouse gas emissions, waste, and other environmental issues. As a result, there is a need for sustainable and ecologically beneficial methods for IoT. The purpose of this article is to investigate the notion of "Green IoT" and how it may be realized through energy-efficient hardware and software design, the use of renewable energy sources, and IoT-based solutions for environmental monitoring and management (Memić *et al*., 2022).

Sustainability is the ability to fulfill the demands of the present without jeopardizing future generations' ability to meet their own needs. The expanding environmental concerns we face today, such as climate change, air and water pollution, and natural resource depletion, necessitate the need for sustainability. The Internet of Things (IoT) has the potential to help with these environmental issues. Electronic waste may be generated during the manufacturing and disposal of IoT devices, which is damaging to the environment. Furthermore, IoT devices and network energy usage can contribute to greenhouse gas emissions, which are a key contributor to climate change. As a result, there is an increasing demand for IoT techniques that are both sustainable and ecologically beneficial (Sisinni *et al*., 2018). Green IoT seeks to lessen the environmental effect of IoT devices and networks by supporting energy-efficient hardware and software design, the use of renewable energy sources, and IoT-based environmental monitoring and management systems. We can assist lessen our environmental effects and create a more sustainable future by using sustainable and green IoT practices. The goal of this article is to investigate how, via the notion of "Green IoT," the Internet of Things (IoT) might be made more environmentally friendly and sustainable. The article will explore many ways to achieve Green IoT, such as energy-efficient hardware and software design, the utilization of renewable energy sources, and IoT-based environmental monitoring and management systems. The purpose of this paper is to increase awareness about the environmental effect of IoT and to share insights and ideas for making IoT more sustainable and contributing to a more environmentally friendly future (Alsharif *et al*., 2023).

2. METHOD

This study is a literature survey. We obtained data from articles in international journals, which were then collected, reviewed, and summarized.

3. RESULTS AND DISCUSSION

3.1. Current Research on Green IoT

There has been a surge of interest in the notion of "Green IoT" and its potential to lessen the environmental effect of IoT devices and networks in recent years. Several reports have been undertaken to investigate various methods for Green IoT.

One method for achieving Green IoT is to create energy-efficient hardware. To lower the energy consumption of IoT devices, researchers have advocated the use of low-power CPUs, energy harvesting techniques, and power management algorithms. Energy collecting

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techniques such as solar and kinetic energy, for example, can fuel IoT devices without relying on traditional power sources (Azizi *et al*., 2022).

Another method is to create energy-efficient software. Optimized algorithms, job scheduling, and power-aware programming can all help to minimize the energy consumption of IoT devices and networks. Researchers have also advocated using fog computing and edge computing to limit data transit between IoT devices and the cloud, which can reduce the energy consumption of IoT networks (Bhushan *et al*., 2023).

Another strategy for achieving Green IoT is to employ renewable energy sources. Researchers have investigated the use of renewable energy sources such as solar, wind, and water to power IoT devices and networks. This method not only decreases the environmental effect of IoT but also encourages the use of renewable energy sources (Manzoni *et al*., 2022).

Finally, IoT-based environmental monitoring and management systems can assist lessen the environmental effect of many businesses. Sensors, data analytics, and machine learning have been proposed by researchers to monitor environmental conditions and optimize resource utilization. This strategy has the potential to minimize waste, energy consumption, and greenhouse gas emissions (Sastry *et al*., 2022).

Overall, current research on Green IoT shows that IoT has the potential to be more sustainable and ecologically beneficial. We can lessen the environmental effect of IoT and promote a more sustainable future by leveraging energy-efficient hardware and software design, renewable energy sources, and applying IoT-based solutions for environmental monitoring and management.

3.2. Classification and Current Approach in The IoT

Various approaches have been proposed to reduce the carbon footprint of IoT devices and networks (Tang *et al*., 2019). Some of these approaches include:

(i) Energy-efficient hardware design: Creating energy-efficient hardware is one of the most effective strategies to decrease the carbon footprint of IoT devices. This may be accomplished by reducing the energy consumption of IoT devices through the use of low-power CPUs, energy harvesting techniques, and power management tactics. Some academics, for example, have advocated using energy-collecting techniques such as solar and kinetic energy to power IoT devices instead of standard power sources.

(ii) Designing energy-efficient software can also aid in lowering the carbon footprint of IoT devices and networks. This may be accomplished through optimizing algorithms, job scheduling, and power-aware programming to decrease IoT device energy usage. Furthermore, the usage of fog computing and edge computing can limit data transit between IoT devices and the cloud, lowering the energy consumption of IoT networks even further.

(iii) Renewable energy sources: Using renewable energy sources is another way to lower the carbon footprint of IoT devices and networks. This may be accomplished by powering IoT devices and networks using solar, wind, and other renewable energy sources. We can lessen our dependency on fossil fuels, which contribute significantly to greenhouse gas emissions, by adopting renewable energy sources.

(iv) IoT-based environmental monitoring and management solutions: IoT-based solutions can also assist numerous businesses lower their carbon footprint. We can monitor environmental conditions and improve resource utilization by employing sensors, data analytics, and machine learning. This has the potential to minimize waste, energy usage, and greenhouse gas emissions. Overall, these techniques show how IoT may be more environmentally friendly and sustainable. We can lower the carbon footprint of IoT

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devices and networks and contribute to a more sustainable future by leveraging energy-efficient hardware and software design, renewable energy sources, and applying IoT-based solutions for environmental monitoring and management.

(v) Energy-efficient hardware and software design (Syafrudin *et al*., 2018). The high energy consumption of IoT devices and networks is one of the most significant difficulties confronting IoT. Energy-efficient hardware and software design have been proposed to lower the energy consumption of IoT devices and networks. To lower the energy consumption of IoT devices, energy-efficient hardware design includes the use of low-power CPUs, energy harvesting methods, and power management algorithms. To minimize the energy consumption of IoT devices, energy-efficient software design encompasses optimizing algorithms, job scheduling, and power-aware programming.

(vi) Renewable energy sources. Another method for reducing the carbon footprint of IoT devices and networks is to employ renewable energy sources (Malik *et al*., 2023). Renewable energy sources including solar, wind, and hydroelectric power may power IoT devices and networks. We can lessen our dependency on fossil fuels, which contribute significantly to greenhouse gas emissions, by adopting renewable energy sources.

3.3. IoT-based Solutions for Environmental Monitoring and Management

IoT-based solutions may assist minimize the carbon footprint of numerous businesses by monitoring environmental conditions and optimizing resource utilization using sensors, data analytics, and machine learning. In agriculture, for example, IoT-based solutions may assist farmers in optimizing irrigation and fertilization operations, lowering water and fertilizer consumption, and, as a result, greenhouse gas emissions.

IoT-based solutions in transportation may improve routes and minimize congestion, lowering fuel consumption and greenhouse gas emissions. IoT-based solutions in manufacturing may optimize energy utilization, lowering energy consumption and greenhouse gas emissions. Overall, energy-efficient hardware and software design, renewable energy sources, and IoT-based environmental monitoring and management systems are effective ways to lower the carbon footprint of IoT devices and networks. We can make IoT more environmentally friendly and sustainable by using these ideas, and thereby contribute to a more sustainable future.

3.4. Energy-efficient hardware design

We describe the hardware design factors that can increase the energy efficiency of IoT devices in this section (Benhamaid *et al*., 2022). Discuss how low-power CPUs, energy harvesting, and power management techniques may be used.is a key factor to consider while lowering the energy consumption of IoT devices. Some hardware design factors that can increase the energy efficiency of IoT devices are as follows:

(i) Low-power CPUs: These processors are designed to use less energy than standard processors. They accomplish this by lowering the processor's voltage and clock frequency. This minimizes the amount of electricity required to run the processor, lowering the IoT device's overall energy usage.

(ii) Energy harvesting is a technique for absorbing and storing energy from the environment, such as solar or kinetic energy. This energy can be utilized to power the Internet of Things devices instead of standard power sources. This method is especially effective in isolated or difficult-to-reach regions where traditional power sources may not be available.

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(iii) Power management strategies: Power management approaches entail improving the operation of IoT devices to reduce their power consumption. This can be accomplished using approaches such as dynamic voltage and frequency scaling (DVFS), which adjusts the processor's voltage and frequency depending on the workload. Other strategies include turning off unneeded peripherals, lowering data transfer rates, and lowering sensor sampling rates.

In addition to these hardware design concerns, the inclusion of specialized hardware, such as microcontrollers and system-on-chip (SoC) devices, can help IoT devices save energy. These devices are developed for low-power applications and include power management capabilities.

Overall, energy-efficient hardware design is crucial for lowering IoT device energy usage. We can create IoT devices that consume less energy and contribute to a more sustainable future by adopting low-power CPUs, energy harvesting systems, and power management approaches.

3.5. Energy-Efficient Software Design

We describe the software design factors that can increase the energy efficiency of IoT devices in this section.is another critical factor in lowering the energy usage of IoT devices (Jayaraman *et al*., 2017). Some software design considerations that can increase the energy efficiency of IoT devices are as follows:

(i) Algorithm optimization: The algorithms employed in IoT devices may be adjusted to minimize the number of operations necessary and, as a result, the device's energy consumption. Techniques like code optimization, data compression, and data aggregation can help achieve this.

(ii) Power-aware programming is creating software that is aware of the device's power usage and adapts its behavior accordingly. For instance, the software can prioritize low-power modes or turn off unwanted devices while not in use.

(iii) Task scheduling entails arranging tasks in such a way that they are completed in the most energy-efficient manner possible. This can be accomplished using strategies such as task grouping, which combines similar processes, and task migration, which moves workloads to more energy-efficient processors.

(iv) Network optimization: The network that IoT devices utilize may be adjusted to consume less energy. This may be accomplished by minimizing the amount of data transmissions, employing smaller packet sizes, and lowering the data transfer rate.

Overall, energy-efficient software design is crucial for lowering IoT device energy usage. We can build IoT devices that consume less energy and contribute to a more sustainable future by optimizing algorithms, employing power-aware programming, effectively scheduling jobs, and optimizing the network.

3.6. Optimized Algorithms, Task Scheduling, and Power-aware Programming

Optimized algorithms, job scheduling, and power-aware programming are key software design aspects that may dramatically enhance IoT device energy efficiency (Madushanki *et al*., 2019; Ray, 2017).

(i) Algorithm optimization: Algorithms used in IoT devices may be tuned to minimize the number of operations required and, as a result, the device's energy consumption. Techniques like as code optimization, data compression, and data aggregation can help achieve this. Instead of transmitting raw sensor data to the cloud, data may be

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aggregated and processed locally to decrease data transmission, resulting in lower energy use.

(ii) Task scheduling entails arranging tasks in such a way that they are completed in the most energy-efficient manner possible. This can be accomplished using strategies such as task grouping, which combines similar processes, and task migration, which moves workloads to more energy-efficient processors. A CPU with a lower clock speed but lower power consumption, for example, can be employed to execute low-priority activities, conserving energy.

(iii) Power-aware programming is creating software that is aware of the device's power usage and adapts its behavior accordingly. For instance, the software can prioritize low-power modes or turn off unwanted devices while not in use. This can be accomplished using approaches such as dynamic voltage and frequency scaling (DVFS), which adjusts the processor's voltage and frequency depending on the workload.

These strategies can minimize energy usage without losing performance or functionality. Optimized algorithms minimize data transmission, resulting in lower energy use. Task scheduling guarantees that jobs are completed in an energy-efficient way, whereas power-aware programming modifies software behavior to maximize energy use. Overall, these strategies lead to a more sustainable future by lowering IoT device energy usage.

3.7. Renewable Energy Sources

We discuss the usage of renewable energy sources to power IoT devices and networks in this section. Renewable energy sources, which may be utilized to power IoT devices and networks, provide a sustainable alternative to traditional power sources (Shafique *et al*., 2020). Some renewable energy sources that can be utilized to power IoT devices include:

(i) Solar power is a popular renewable energy source that may be utilized to power IoT devices. Solar panels can catch sunlight energy and transform it into electricity, which may then be utilized to power IoT devices.

(ii) Wind power: Using wind turbines, wind power may be utilized to power IoT devices. Wind energy is absorbed by turbines and transformed into electricity, which may then be utilized to power IoT devices.

(iii) Hydropower: The use of water to create energy is referred to as hydropower. Hydropower may be utilized to power IoT devices using hydroelectric turbines.

(iv) Geothermal power: Geothermal power generates energy by using heat from the earth's core. This may be utilized to power IoT devices using geothermal power plants.

(v) Biomass power: Biomass power is the utilization of organic materials to create electricity, such as plant matter or animal waste. This may be used to power IoT devices using biomass power plants.

Renewable energy sources are a more ecologically friendly and sustainable alternative to traditional power sources. We can lower our carbon footprint and contribute to a more sustainable future by powering IoT devices and networks with renewable energy sources. However, the availability and practicality of these renewable energy sources in the context of the specific IoT deployment must be considered.

3.8. Benefits and Challenges of Using Solar, Wind, and Other Renewable Energy Sources in IoT Applications

Using renewable energy sources like solar, wind, and other sources in IoT applications has various advantages, but it also has certain drawbacks. The following are some of the advantages and disadvantages of employing renewable energy sources in IoT applications:

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Benefits are in the following:

(i) Reduced carbon footprint: Reducing one's carbon footprint is one of the most significant advantages of adopting renewable energy sources (Tatas *et al*., 2022). Renewable energy sources are considered clean energy sources since they emit little or no greenhouse gases, which contribute to climate change.

(ii) Cost reductions: Renewable energy sources can offer long-term cost benefits by considerably lowering energy expenses for IoT applications. This is especially true for rural or off-grid applications, where typical energy sources might be prohibitively expensive.

(iii) Increased dependability: Renewable energy sources can potentially improve the dependability of IoT systems. Solar panels, for example, do not require an external power source and may work even in the event of a power loss.

Challenges are in the following:

(i) Limited availability: One of the biggest obstacles to integrating renewable energy sources in IoT applications is their scarcity. Solar panels, for example, may be ineffective in places with low amounts of sunshine, while wind turbines may be ineffective in areas with low wind speeds.

(ii) Initial costs: Implementing renewable energy sources might be expensive at first, which may be a hurdle for some IoT applications. While cost benefits can be realized over time, the initial commitment might be difficult for certain firms.

(iii) Maintenance: To achieve maximum performance, renewable energy sources must be maintained regularly. This can be difficult in isolated or difficult-to-reach regions where maintenance might be costly and difficult.

(iv) Integration issues: Integrating renewable energy sources with IoT applications might be difficult. Renewable energy sources' power may not be constant, affecting the functionality of IoT devices.

In conclusion, while renewable energy sources provide several advantages for IoT applications, they also present significant obstacles. Businesses must carefully consider the viability of renewable energy sources for their unique IoT applications, as well as the possible advantages and constraints.

3.9. IoT-Based Solutions for Environmental Monitoring and Management

IoT-based systems may give real-time data on a variety of environmental characteristics, such as air quality, water quality, temperature, and humidity. This information may be used to monitor and control environmental conditions, as well as to increase environmental sustainability (Chong *et al*., 2023; Swaraj and Sowmyashree, 2020; Malina *et al*., 2016). Here are a few IoT-based systems for environmental monitoring and management:

(i) Smart Sensors: Internet of Things-based sensors can collect real-time data on a variety of environmental conditions. Air quality sensors, for example, may detect pollutants like CO2 and particle matter, whereas water quality sensors can detect pH, temperature, and dissolved oxygen. This data may be utilized in real-time monitoring of environmental conditions and detection of abnormalities.

(ii) IoT-based smart irrigation systems can assist in reducing water waste and improving water management. Sensors in these systems monitor soil moisture levels and modify irrigation schedules appropriately, decreasing water use and boosting plant health.

(iii) Smart Waste Management: IoT-based smart waste management systems can aid in garbage collection optimization and environmental impact reduction. Sensors in bins

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monitor garbage levels and alert waste management personnel when bins are full, minimizing wasteful collection trips and boosting overall efficiency.

(iv) Energy Management Systems: IoT-based energy management systems can assist in reducing energy use and increasing energy efficiency. These systems employ sensors to determine building occupancy levels and modify lighting and HVAC systems accordingly, decreasing energy waste.

(v) Smart agricultural: IoT-based smart agricultural technologies can aid in crop growth optimization while reducing environmental effects. Sensors in these systems monitor soil moisture levels, weather conditions, and plant health, giving farmers real-time data to maximize crop development while reducing water and fertilizer consumption.

Finally, IoT-based systems may give real-time data on environmental conditions, assisting in the monitoring and management of environmental effects and the improvement of sustainability. Organizations may decrease waste, optimize resource utilization, and increase overall environmental sustainability by using IoT-based solutions for environmental monitoring and management.

4. CONCLUSION

This paper examines the potential of the green Internet of Things (IoT) to help address environmental problems such as climate change and resource depletion. It looks at the use of IoT technology to promote sustainability and decrease the environmental effect of IoT devices and networks, such as energy-efficient hardware and software design, renewable energy sources, and IoT-based solutions for environmental monitoring and management. However, there are still many challenges to be overcome, such as the high cost of renewable energy, the limited battery life of IoT devices, and the complexity of managing large IoT networks. More research is needed to address these challenges and develop more efficient and sustainable IoT solutions.

5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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