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APPLIED SOLAR ENERGY

Green internet of things and solar energy

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Abstract

The Internet of Things (IoT) stands out as one of the most captivating technologies of the current decade. Its ability to connect people and things anytime and anywhere has led to its rapid expansion and numerous impactful applications that enhance human life. With billions of connected devices and substantial power and infrastructure requirements, the IoT system can pose a threat to the environment. However, the IoT's vast range of resources and capabilities can also be leveraged to assist in environmental conservation in the evolution of technologies due to massive CO_2 emissions, climate change, and environmental and health issues. In this study, with the two-way integration of IoT and green practices, two distinct concepts for green IoT are presented. Among green practices, energy solutions play a vital role in greening the IoT. In this study, the energy solutions for the IoT system are divided as reducing energy consumption and using green energy sources. Solutions for reducing IoT energy consumption are studied systematically through a five-layer framework to simplify its modular design and implementation. Then, the use of green energy resources is discussed for all components of the IoT ecosystem. Leveraging IoT to make the environment and other technologies green is the other concept of green IoT. IoT technology plays a crucial role in enhancing both energy management systems and the efficient harvesting of renewable energy sources. Switching to solar energy from fossil fuel energy is one of the most fundamental green practices today. In this study, the mutual relationship between solar energy harvesting and the IoT is addressed specifically. Several promising research directions in the realm of green IoT are also highlighted.

Keywords Internet of things · Renewable energy · Solar energy harvesting · Green practices · Layered architecture

Introduction

Climate change and the increase in the Earth's temperature have led to extensive geographical changes in species and have many effects on the environment and weather patterns. These changes have existed in all past periods, but with the increase in human activities in the past decades, the speed of these changes has increased significantly. The elimination of some animal species or extinction and increase in fires, pests, and disease-causing agents are among the results of such changes (Jones et al. 2009). Global warming and climate change are among the most perilous problems the globe has ever encountered. While slowing or stopping them would not be possible with a single action, their environmental harm can be reduced by long-term and regular planning, incremental changes, and contributions across many disciplines (Abd El-Mawla et al. 2019).

Green technology refers to the concept of developing clean technologies to minimize threats to human health and the environment, which helps to reduce the environmental effects of technological activities (Aithal and Aithal 2016). Solar cells are an example of green technology. Through the process of photovoltaics, a solar cell transforms light energy into electrical energy. Solar thermal applications, as another example, utilize solar energy for heating purposes (Kumar et al. 2020). By increasing solar energy usage and decreasing the use of fossil fuels, pollution and environmental harm can be reduced (Kannan and Vakeesan 2016).

The following are the key considerations for the advancement of green technologies (Boye and Arcand 2013; Kannan and Vakeesan 2016; Prabakaran et al. 2022):

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- Reducing energy consumption compared to traditional technologies
- Lowering the use of materials that are harmful to the environment
- Using equipment that can be recycled or discarded without causing environmental damage through waste management
- Lowering air and water pollution while also minimizing the greenhouse effect

The growth of computer and networking technologies has led to the concept of the Internet of Things (IoT), where various things can interact with other systems through the network and Internet, creating a smart environment (Atzori et al. 2010). If everything had an identity and wireless connectivity, computers could handle all aspects of daily life, as objects acquire digital intelligence through integration with IoT technologies (Tuysuz and Trestian 2020) (Da Xu et al. 2014). Today, IoT connects billions of devices, merging the physical and digital worlds and enhancing environment responsiveness and intelligence.

Work and living environments are increasingly being equipped with covert IoT systems and sensors and to improve efficiency and effectiveness (Lee and Lee 2015). IoT is used in many fields. Some of the applications of IoT are smart city, smart agriculture, smart factory, smart home, and the energy sector (Broday and Gameiro da Silva 2023) (Mohanty et al. 2016) (Chen et al. 2017; Hossein Motlagh et al. 2020).

Integration of the IoT and green practices

Taking into consideration the importance of two topics, green technologies and the Internet of Things, in the rest of this article, the issue of the green Internet of things will be examined. Green IoT refers to the integration of the IoT with sustainable and environmentally friendly practices. This includes both making IoT systems green and leveraging IoT to make other technologies green.

The popularity of the IoT has increased over time. The increasing use of IoT devices raises concerns about its potential environmental impact in the short and long term. Research on greening the IoT is absolutely essential as it has tremendous potential to enhance IoT sustainability and guarantee dependable environmental management (Shaikh et al. 2015). The concept of green IoT generally emphasizes producing, designing, utilizing, and disposing of the IoT ecosystem in an environmentally friendly manner to reduce or eliminate any potential environmental damage (Murugesan 2008).

The authors Aithal and Aithal (2016) have discussed methods of making technologies environmentally sustainable to prevent harm to the environment and secure a clean world for future generations. Green information and communication technologies (ICTs) are explored in a study by Zhu et al. (2015), which includes green radio frequency identification, green machine-to-machine, green wireless sensor networks, green cloud computing, and green data centers. Over the past few years, there has been a rise in funding for IoT-related green projects. The authors Shaikh et al. (2015) reviewed the programs and standardization efforts associated with green IoT initiatives.

Energy consumption is a critical IoT issue due to the energy required by devices. The expansion of the IoT will lead to a significant increase in energy consumption by its components, resulting in a major contribution to greenhouse gas emissions and a driver of climate change. According to Abedin et al. (2015), the green IoT core principles aim to conserve natural resources and minimize energy usage during the entire lifecycle of IoT devices.

The use of solutions to reduce energy consumption and increase energy efficiency on the large scale of the IoT leads to a huge saving in energy consumption, which, due to the reduction of fossil energy source usage, causes a reduction in CO_2 production, and global warming, and other environmental damages. Reducing energy consumption also prevents small wireless devices from quickly running out of energy, reducing the need for battery recharging or device deposal and thus decreasing waste generation.

People all over the world are facing significant problems due to climate change. The IoT offers a wide range of resources and capabilities that assist organizations and governments in reducing the negative impact of human activities on the planet (Abd El-Mawla et al. 2019). In this regard, the topic of "green Internet of Things" to lower energy consumption and assist the environment through IoT systems has also been raised in recent years. It has become a new and important research area that plays a key role in improving the efficiency of power generation plants, especially renewable energy sources such as wind and solar energy. In this study, the two mentioned concepts of green IoT are investigated in depth.

Solar energy harvesting is the focus of this study because it is a dominant solution to green technologies. Regarding the two-way relationship between green practices and the IoT, the same relationship exists between solar energy harvesting and the IoT that is analyzed in this article. The first scenario tries to use solar energy to supply the required energy for sensors and other IoT devices. The second scenario uses IoT technology for energy monitoring and management of solar energy harvesting.

Contributions and organization

The existing literature on the convergence of IoT and green technologies predominantly focuses on either greening the

IoT infrastructure or utilizing IoT for environmental sustainability. However, there is a limited understanding of the integration between the IoT and green technologies from an energy solutions perspective.

The contributions of this article are as follows:

- This paper addresses the aforementioned research gap by investigating the integration of IoT and green practices with a specific focus on energy solutions. In this way, two conceptual perceptions of green IoT have been covered.
- A comprehensive five-layer framework for creating a greener IoT is outlined in this work, with an emphasis on energy-efficient strategies and renewable energy sources. The framework is designed to practically guide the implementation and optimization of green IoT systems.
- This study explores the two-way relationship between solar energy harvesting and IoT applications.
- Based on the layered framework and research, future research directions for the integration of IoT and green practices are suggested.

The rest of this paper is organized as follows. In "Greening the IoT" Section 2, the importance of the layered model and its five layers is presented in order to use the layered model for IoT research. Then, the solutions for greening the IoT are described in the five-layer framework. The use of solar energy harvesting to green the IoT has been specially discussed, and its usage in different parts of the IoT system has been investigated. "IoT for greening the environment" section investigates the use of IoT in greening other technologies; then with more emphasis on solar energy harvesting, how the IoT helps in this field is analyzed. We explore future research directions in "Future research direction" section, and finally conclude the article in "Conclusion" section.

Greening the IoT

The uses of the IoT have increased along with its growth and development, and it is predicted that by 2025, there may be 50 billion IoT devices use (Dange and Chatterjee 2019). Energy plays a vital role in the IoT system due to the total high energy consumption of all its components and connected devices and the dependence on a limited energy source for each connected device. As a result, reducing energy consumption is crucial to ensuring the long-term viability of resources and the reliable management of IoT systems (Kaur and Sood 2015).

In this regard, the topic of the Green Internet of Things has come up recently and has evolved into a new and important research area to lower energy consumption and preserve the environment (Abedin et al. 2015). Its energy-saving features throughout the entire life cycle, including design, production, deployment, recycling, and final disposal, are the core elements of the green IoT (Shaikh et al. 2015).

Energy solutions for the IoT system are divided into two categories in this section reducing energy consumption and using green energy sources. To provide a comprehensive exploration of energy reduction solutions within the IoT, this paper first delved into the layered architecture of the IoT. By establishing this foundation, various strategies and approaches for achieving energy efficiency are devised on the basis of layers. A layered design facilitates a modular approach in the transition from IoT to green IoT. Seamless integration of green technologies and components into the IoT system is possible due to the independent development, maintenance, upgrading, or replacement of each layer.

IoT-layered architecture

Vast ecosystem of the Internet of Things necessitates a suitable architecture for its study and design. Layering architecture provides a structured framework for analyzing and implementing energy solutions throughout the system. Researchers do not concur on a single overarching architecture for the IoT (Burhan et al. 2018). Various architectural designs have been presented. A three-layer architecture, including perception, network, and application layers, is a relatively simple architecture introduced at the beginning of the IoT. As the Internet of Things developed, several architectures, often with more layers, were proposed to meet its requirements, and focus on finer IoT aspects (Said and Masud 2013). In this study, the five-layer architecture depicted in Fig. 1 is used for exploring the IoT energy solution (Sethi and Sarangi 2017). The layers are described in the following.

Perception layer: The sensor layer and physical layer are other names for this layer (Burhan et al. 2018; Sethi and Sarangi 2017). To connect the physical and digital worlds and enable real-time data collection and processing, smart wireless devices must be able to automatically sense the environment (Da Xu et al. 2014; Patel et al. 2016). With the help of tags and sensors, sensing and collecting information about the environment are performed in this layer. There are sensors for identifying other objects and numerous types of sensors for sensing physical parameters, such as for water quality, humidity, pressure, motion, position, proximity, temperature, or any other factor (Sehrawat and Gill 2019).

Transport layer: The transport/network layer serves as a conduit for transferring gathered information to the processing layer and vice versa. It also facilitates communication between the components of other layers (Burhan et al. 2018; Da Xu et al. 2014). Smart sensors and devices interconnect using a variety of communication protocols and networks, such as RFID, NFC, 5G, Bluetooth, Zigbee, Wi-Fi, and

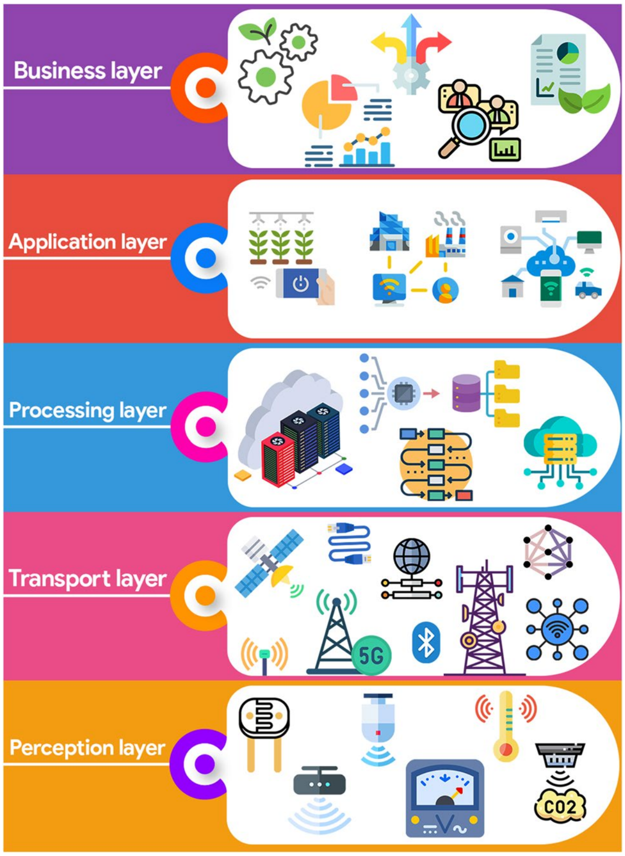

Fig. 1 A five-layer architecture of IoT

low-power wide-area network (LPWAN) (Al-Sarawi et al. 2017).

Processing layer: The processing layer is often referred to as the middleware layer. A large amount of information coming from the transport layer is analyzed, processed, and stored in this layer. It uses a wide range of technologies, including big data processing modules, cloud computing, and databases (Sethi and Sarangi 2017).

Application layer: The application layer serves as an interface for leveraging the processed data to deliver customized functionality and services within the IoT system. It involves the development and deployment of applications that harness the capabilities of the IoT infrastructure. The primary aim of this layer is to utilize processed data intelligently to bring meaningful outcomes that benefit end-users or organizations (Yassein and Shatnawi 2016). The information received from the processing layer is managed, and the necessary reactions are performed depending on the type of IoT application, e.g., smart cities, smart agriculture, smart health, smart home automation, asset tracking, remote monitoring, or industrial automation.

Business layer: The management of the entire IoT system and all IoT applications and services is handled by the activities of this layer. It involves business processes, governance, security considerations, and data management. Depending on the quantity and quality of reliable data received from the lower layer and the effectiveness of the data analysis process, it can provide informative graphs, business models, flow charts, executive reports, etc. (Vashi et al. 2017).

The energy reduction solutions are discussed in the context of the five-layer architecture in the following.

Perception/sensing layer solutions

The perception layer focuses on the collection of data by physical sensors and devices. In this section, the goal is to propose methods for reducing the energy consumption of sensors and devices connected to the IoT.

Utilizing energy-efficient sensors and devices that consume minimal power during operation can conserve energy. Implementing adaptive sensing techniques for the sensors is another method for this purpose. The authors (Srbinovski et al. 2015) suggest a dynamic adaptive sensing technique that can change the sensor sampling rates in wireless sensor networks based on the available energy of the node. By cutting down on unnecessary data collection, this method saves energy, and extends the network's lifespan. Optimizing sensor placement and coverage to minimize energy usage and avoid redundant data collection is also proposed (Castello et al. 2010).

RFID is an electronic device that automatically identifies and tracks tags attached to objects (Juels 2006). Although RFID technology has a significant impact on applications that support a greener society, it also has drawbacks for the environment. Reducing the size of RFID tags and sensors and, consequently, reducing the quantity of nondegradable material needed in their fabrication and lowering energy consumption, are the most simple solutions (Shaikh et al. 2015).

While IoT network nodes are diverse, they typically have limited energy storage. One way to save energy on IoT network nodes is by reducing their wake-up time. To accomplish this objective, sleep scheduling, also known as duty cycling, is employed, which switches network nodes on and off as needed (Zhang et al. 2018). Sleep schedules allow network nodes to be in sleep mode and only wake up to function as needed to save energy (Hossein Motlagh et al. 2020). The majority of wireless node hardware supports multiple modes, such as transmission, idle, and sleep modes. The radio circuitry used for communication remains active during the idle mode, although there is no data transfer. The sleep scheduling mechanism aims to decrease energy consumption during the idle state while keeping the network connected, as the idle state can deplete energy up to tens to thousands of times more than during the sleep state (Carrano et al. 2013).

The design of certain communication protocols, like Bluetooth and ZigBee, takes into account that nodes may sleep for certain periods of time. Moreover, studies have been conducted in the area of network sleep scheduling based on network conditions. The authors (Wang et al. 2016b) proposed using a sleep scheduling mechanism to increase energy efficiency. This method involves putting some nodes into sleep mode during periods of inactivity and waking them up as needed. A deep reinforcement learning-based transmission policy enforcement and multi-hop routing mechanism for quality-of-service aware LoRa IoT networks have been proposed (Muthanna et al. 2022). The proposed method improves reliability and extends the network's lifespan by adaptively adjusting transmission power, transmission rate, and routing according to network conditions.

By duty cycling, energy conservation is achieved at the cost of an end-to-end packet delivery delay. Low-power wake-up radio (WuR) technology has recently been proposed as an alternative to the periodic sleep task. Low-power peripheral radios, called wake-up radios, stay connected to wireless nodes, remain constantly on, and await wake-up calls from transmitters. A wake-up call is a simple message containing the recipient's ID. The primary radio activates in response to a wake-up signal from WuR and gets ready to send or receive data (Khodr et al. 2017). Since 2017, IEEE 802.11 Task Group "ba" has standardized the use of wake-up radios. The functions of WuR PHY and MAC are described in Deng et al. (2019).

The use of directional antennas enhances the efficiency of signal reception and transmission from IoT devices, resulting in less communication interference and higher energy efficiency. Directional antennas present significant challenges when it comes to locating the destination, focusing the antenna, calculating signal power, and measuring distance. The authors Kumari et al. (2018) proposed the use of re-configurable directional antennas as a way to achieve considerable energy savings.

Transport/network layer solutions

The transport layer mainly deals with the data transmission and connectivity aspects of the IoT system. The radio module on IoT devices, which is responsible for transmitting data, uses up a significant portion of the node's energy. There has been a significant focus on optimizing the energy of radio modules by many researchers, and the mechanisms outlined below have been proposed and discussed.

Reducing energy consumption can be achieved by optimizing the modulation and coding schemes in radio modules. Adaptive coding and modulation techniques help IoT systems achieve reliable, effective, and high-capacity communication by continuously assessing channel conditions and adjusting transmission parameters such as bit rate and transmission power accordingly (Anastasi et al. 2009; Lin et al. 2015). Communication power control is recommended to reduce energy consumption. These strategies are designed to decrease signal transmission power while retaining communication quality (Zhu et al. 2015).

Energy conservation can be achieved using communication protocols that are both lightweight and energy-efficient, allowing quick data transmission (Sahoo et al. 2012). This reference compares various IoT communication protocols with regard to energy efficiency. Two popular energy-efficient communication protocols for IoT networks, namely ZigBee and low-power wide-area networks (LPWAN), are the focus of the study (Çorak et al. 2018).

Reducing the amount of data sent is another clear way to save energy. The accuracy of information obtained through IoT systems is dependent on the data collected and processed, which increases energy consumption. As a result, it is essential for IoT systems to achieve an equilibrium between information accuracy and reducing energy consumption due to energy constraints (Kaur and Sood 2015). Different methods can be employed to reduce data without compromising communication quality. The following methods are discussed: aggregation, compression, adaptive sampling, and coding.

The goal of data aggregation techniques is to remove duplicate information from data collected from nearby nodes. In these techniques, valuable data are extracted using aggregation functions (maximum, minimum, average, etc.) before it is sent to the central node. A survey of data aggregation approaches and protocols has been presented to prolong the lifespan of IoT sensor networks (Abbasian Dehkordi et al. 2020).

Another approach to decrease data transmission is to compress it by minimizing the number of bits required to represent each data block. Azar et al. (2019) presented an energy-efficient data reduction strategy for IoT-edge applications using compression algorithms. It has been proven that these compression techniques have a significant impact on energy usage reduction and IoT device lifespan. Spatiotemporal correlations are utilized in adaptive sampling to decrease the number of data samples. Network coding schemes can reduce the number of transmissions by coding multiple data packets within a single transmission.

Solutions that involve network topology, node communication, and routing algorithms can help reduce the overall energy usage in network communication and increase the network's useful life. A key element in the deployment of the IoT is the wireless sensor network (WSN), a network made up of autonomous, spatially distributed sensors that work together to jointly monitor physical or environmental conditions (Zhu et al. 2014). The sensor data in this mesh-architecture network reaches the sink node hop-by-hop. Numerous studies have focused on managing energy and routing in this network. The proposed energy-efficient strategies include cluster structures, multi-path routing, and cooperative communication. These strategies are crucial for maximizing the performance and battery life of IoT devices that rely on WSN (Anastasi et al. 2009; Chen and Lai 2020; Hossein Motlagh et al. 2020).

A significant amount of energy is used when nodes perform routing and forwarding on their own. Anastasi et al. (2009) reviewed hierarchical routing protocols that are more energy-efficient than flat routing protocols. In this method, some sensor nodes act as intermediaries to route to the central node. Hierarchical routing protocols undergo a phase of cluster formation during which the network is partitioned into multiple clusters, each having a designated cluster head. The cluster head is selected based on criteria such as remaining energy, charge ability, or geographic location. The data collected by the sensor nodes are sent to the cluster head, which then compresses and aggregates the data before transmitting it to the sink node. Researchers have proposed changes in cluster structure and node roles to prolong the network's lifespan. Chen and Lai (2020) proposed a scalable solution for managing energy use in IoT networks that enables nodes to operate efficiently under various workloads, improving the sustainability and practicality of IoT systems. Safara et al. (2020) proposed an energy-aware routing protocol for IoT networks that takes into account various factors such as energy levels, signal strength, and network congestion to determine the most efficient communication paths.

Device-to-device (D2D) communication integration can enhance energy efficiency by facilitating nearby devices to exchange data without requiring a centralized network infrastructure. By eliminating the need for frequent connections to distant servers or base stations, it is possible to reduce energy consumption in long-range transmission (Xu et al. 2018).

Energy savings are also possible through advanced communication techniques like MiMo systems and cognitive radios. MiMo systems have the ability to decrease energy usage in various ways. MiMo systems enable efficient utilization of transmit power by simultaneously sending multiple data streams. Diversity gain in MIMO systems reduces the need for retransmissions and ensures reliable communication. By focusing the transmitted energy toward the intended receiver, beamforming techniques can improve the signal-to-noise ratio and reduce interference. By utilizing transmitted power more efficiently, there is an overall reduction in energy consumption (Zhu et al. 2015).

According to Abedin et al. (2015), radio-cognitive methods have the capability to decrease energy consumption by intelligently modifying communication parameters like transmission power and frequency band based on network conditions. Cognitive radio manages the spectrum efficiently but requires continuous radio frequency (RF) spectrum monitoring, causing it to consume more energy. Optimization of cognitive radio performance requires analysis of the trade-offs between effective dynamic spectrum management and efficient spectrum sensing (Shaikh et al. 2015).

Processing/middleware layer solutions

In this section, energy conservation techniques for the processing and storage of data are discussed. Energy consumption can be optimized using low-power CPUs or specialized hardware accelerators in IoT-connected devices for processing tasks (Baliga et al. 2010). However, IoT devices can offload intensive processing tasks to powerful and energy-efficient cloud servers through cloud computing. To make the IoT widely available, storage capacity, cloud computing, and high bandwidth for transmission are necessary to meet the big data requirements of the IoT (Goel and Gautam 2023).

The term "cloud computing" describes both the system hardware and software in the data centers that distribute the applications as services over the Internet (Armbrust et al. 2010). Growing cloud-based applications necessitate the deployment of more resources as well as more energy, which increases environmental problems and CO_2 emissions (Zhu et al. 2015). Hardware and software that consume less energy are the two primary categories of solutions for "green cloud computing." Software solutions offer effective software designs that consume less energy by utilizing resources as efficiently as possible. Services, routers, networking switches, power supplies, backup generators, cooling systems, etc. are all included in data centers (Goel and Gautam 2023). Hardware solutions aim to create devices that use less energy without affecting the quality of their performance (Shaikh et al. 2015).

Optimizing resource allocation, virtualization, and workload consolidation can help reduce energy consumption in green cloud computing. Jararweh et al. (2018) proposed a dynamic resource allocation algorithm considering workload demands for cloud computing environments, with a focus on ensuring efficient energy usage. Ben Alla et al. (2019) developed an energy-conscious task-scheduling algorithm specifically for cloud computing environments. The aim of the algorithm is to optimize the energy efficiency of the cloud system by considering the energy consumption of processing tasks and intelligently allocating resources while ensuring the desired level of performance is maintained. Jayanetti et al. (2022) used machine learning techniques to develop methods that minimize energy consumption by optimizing resource allocation and processing tasks. Cloud providers can reduce operational costs and help the environment by adopting energy-efficient practices and technologies (Baliga et al. 2010).

Another solution could be "edge computing." Distributed processing techniques can resolve different IoT system challenges by distributing computational tasks across multiple edge devices (Yu et al. 2017). The network can be made more effective, and the transfer of large amounts of data to external servers can be reduced by bringing processing and storage facilities closer to the user or "edge" of the network. Shifting computation and communication overhead to nodes with adequate power resources can enhance the overall longevity of the IoT system by extending the lifespan of components with limited power. The authors (Li et al. 2018) argue against conventional centralized architectures and support more distributed and collaborative approaches that incorporate edge devices for data processing and analysis. Data reduction can be considered as an additional strategy for decreasing process load. In this regard, with the help of compression algorithms, an energy-efficient data reduction scheme for IoT-edge applications has been proposed (Azar et al. 2019).

Application layer solutions

The development of applications that harness the capabilities of the IoT infrastructure is performed at the application layer. In this layer, applications that reduce energy-intensive operations and maximize resource efficiency can be developed. Alsaryrah et al. (2018) focused on the development of energy-aware applications specifically designed for the IoT environment. Various techniques and strategies for optimizing energy consumption in IoT systems are discussed in this study. By utilizing energy-aware techniques, IoT applications can effectively enhance their efficiency and sustainability, which can address the surging demand for energy conservation in the rapidly expanding IoT ecosystem.

Applications that control processes and output usually have limited power resources and high computing capabilities because they handle activities like content management and web and directory services (Tahiliani and Dizalwar 2018). Another choice is to incorporate energy-efficient algorithms into IoT applications for control, optimization, and decision-making. In Guiloufi et al. (2023), the authors examined various algorithms that could be used to reduce energy usage and increase efficiency in IoT systems. This paper emphasizes the value of using energy-efficient techniques in various IoT applications and offers details on the advantages of incorporating such methods.

Large-scale energy savings can be achieved based on real-time data from IoT devices. There are various phases involved in formulating policies to achieve energy efficiency, such as monitoring multiple energy consumption scenarios, information management, and user feedback. Users can play an active role in achieving energy conservation goals with the help of IoT applications. Iskandar et al. (2019) examined how energy-aware user interfaces and feedback mechanisms can be integrated into IoT applications to encourage users to make more energy-conscious decisions. For example, with the use of smart metering technology, homeowners may receive real-time feedback on their energy usage, and based on that information, we can provide them with recommendations on how to reduce and control their energy usage (Arshad et al. 2017).

Another crucial solution in the application layer is the development of IoT applications with the aim to decrease environmental harm and pollution that are discussed in "IoT for greening the environment" section.

Business layer solutions

The solutions of this layer involve implementing policies and governance frameworks that prioritize energy efficiency and promote sustainable practices in IoT deployments. The establishment of policies for renewable energy usage, like solar power, can greenly power the IoT system and decrease dependence on traditional power sources in the whole IoT ecosystem (Fadil et al. 2023). Industries can be motivated to reduce their emissions and embrace cleaner technologies through the implementation of carbon pricing mechanisms, such as carbon taxes or emissions trading systems.

Developing energy efficiency policies and standards and performing energy audits and monitoring can result in energy-efficient IoT products and solutions. Arshad et al. (2017) presented a detailed analysis of policies and standards implemented globally to promote energy-efficient IoT devices and underscored the importance of continuous monitoring and optimization efforts.

Education and awareness-raising strategies can be carried out. It is crucial to raise awareness among consumers, manufacturers, and other stakeholders about the environmental impact of IoT expansion. A sustainable and greener IoT can be achieved by educating users about responsible usage of IoT and energy and also demonstrating the advantages of eco-friendly IoT (Aqib and Zaman 2023).

In general, the integration of these solutions throughout the layers of IoT system reduces energy consumption and improves energy efficiency. To customize the mentioned solutions to specific use cases and requirements, it is essential to consider factors such as system size, deployment environment, and operational constraints.

Using solar energy harvesting for the IoT

With the growing awareness of the Earth's depletion of fossil fuels and their detrimental environmental effects from carbon emissions, it is both promising and necessary to employ green (renewable) energy to power IoT components (Liu and Ansari 2019). Diverse environmental energy sources that can be turned into electricity are known as renewable energies. The adoption of renewable energy sources like solar, wind, hydro, and geothermal energy can cut our dependency on fossil fuels and decrease CO_2 emissions (Khan and Imran 2023). The IoT devices can be supplied with the harvested power. One of the most important forms of renewable energy is solar energy. Solar energy harvesting is the most common green energy supply, and its widespread use, low maintenance requirements, and simplicity of installation have made it an excellent choice for IoT (Kazmerski 2016).

According to Wang et al. (2021), solar energy harvesting by photovoltaics has the highest power density of all energy harvesting methods. Utilizing the photovoltaic effect, light that is shone upon semiconducting materials is transformed into electricity. A typical photovoltaic system consists of several solar cells that convert light into electrical energy. When there is enough sunlight, outdoor IoT devices can leverage the photovoltaic effect to harness solar energy and sustain their power requirements. As long as there is adequate indoor lighting, IoT devices situated in buildings can charge on their own. To power IoT devices, Yue et al. (2017) suggested using indoor photovoltaic energy.

Any IoT device in the ecosystem that requires energy to operate can benefit from solar energy. For this purpose, the device should be equipped with a solar panel and a battery to store the harvested energy. However, due to the unidirectional flow of electric current, single-battery IoT devices cannot simultaneously charge and drain a single rechargeable battery while functioning as an IoT device. To address this issue, a dual-battery green energy harvesting design is suggested (Liu and Ansari 2019).

Figure 2 shows the use of solar energy in various components of the IoT ecosystem. These items will be discussed below.

Using solar energy for small IoT devices

Solar energy has emerged as a viable technological option for powering IoT devices. This is primarily because the cost of producing solar panels has decreased significantly over time, while their performance has increased (Simjee and Chou 2008). Solar energy for large-scale applications has been extensively studied. When the goal is to harvest and store this ambient energy on a tiny scale, such as in miniature IoT devices, the difficulty increases since the previously developed solutions (large-scale energy harvesting) no longer function. However, ambient energy use in wireless network nodes, including self-sustaining sensor nodes, has been the subject of several studies (Guo et al. 2014; Wang et al. 2016a). In practice, a sensor node's energy requirements may be met by utilizing a solar panel specifically designed to match the sensor's size (Wang et al. 2016a).

The solar energy harvesting can be a source of power for IoT-enabled outdoor infrastructure, such as streetlights, environmental monitoring stations, and parking meters. The solar panels in these structures gather energy during the day and use it to power IoT devices even during low light or nighttime (Praghash et al. 2021). GPS trackers or asset

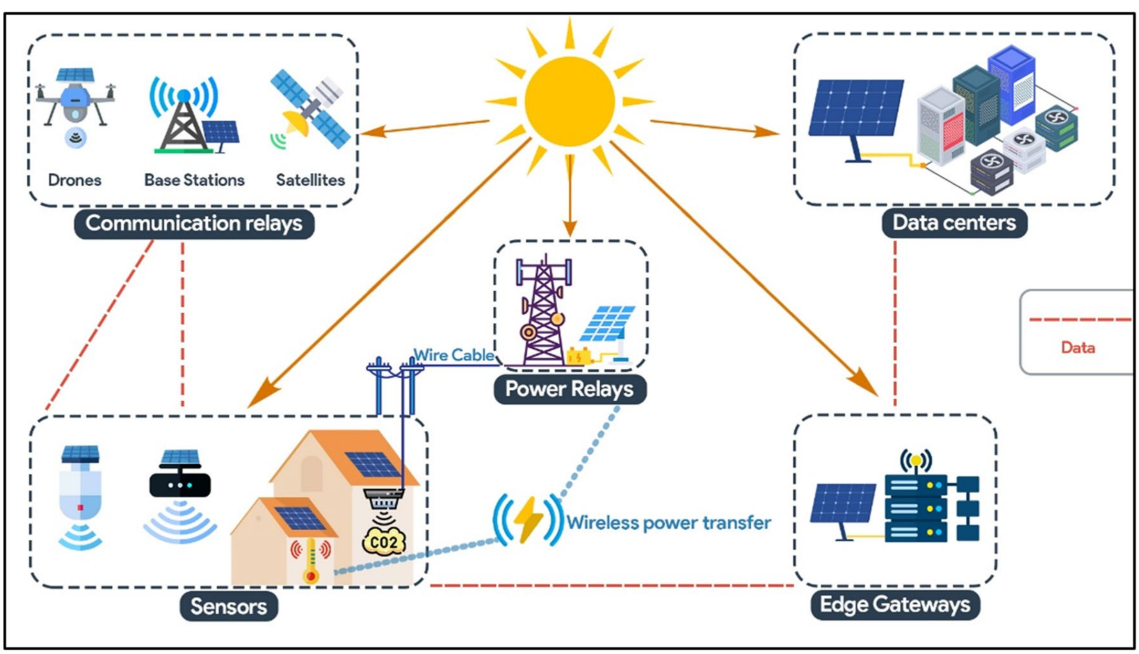

Fig. 2 Solar-powered IoT architecture

tracking systems, which are frequently used in logistics, transportation, or supply chain management, can be powered by solar energy. These devices can operate autonomously for long periods of time using solar energy harnessing, delivering real-time tracking and position information.

For IoT devices without solar panels or adequate access to light, alternative methods can be employed to charge them using solar energy indirectly. The wireless power transfer (WPT) and power relays can be used to still charge them through solar energy, as detailed in the following sections.

Using solar energy for gateways

It is possible to power IoT gateways or edge devices with solar energy as well. They play a crucial role in the IoT ecosystem as intermediaries between IoT sensors and the cloud, collecting and sending data. The utilization of solar energy enables gateways to operate in distant or off-grid areas, thereby lowering their reliance on external power sources for continuous operations (Chinipardaz and Amraee 2022).

Using solar energy for communication relays

For connections between IoT devices and improve network coverage, various communication relays, including base stations, drones, and even satellites, are used. These relays can be equipped with solar panels to harvest solar energy for their functions (Popli et al. 2018). Solar-powered BS, satellites, and drones are shown in Fig. 2.

One specific example for relay satellites is the deployment of many small satellites in LEO orbit that provide lower-latency communication with respect to satellites on other orbits. Thousands of different CubeSat missions have been launched over the past two decades, and many of them play a role in telecommunications and the IoT (Centenaro et al. 2021).

Using solar energy for power relays

In the case where the gathered solar energy is inadequate to power IoT devices, adjacent green base stations can be deployed to wirelessly charge outdoor and indoor IoT devices using wireless power transfer (Chinipardaz and Amraee 2022). The green base stations are equipped with solar panels. Despite the comparatively poor efficiency of wireless charging, BSs can charge nearby IoT devices with radio frequency power transmission for prolonged periods (Liu and Ansari 2019). Three frameworks have been proposed by Chinipardaz and Amraee (2022) that combine wireless power transfer and solar energy harvesting to charge low-consuming IoT devices. The objective is to increase network stability and decrease energy consumption. Two scenarios showing the transfer of harvested solar energy to IoT devices via WPT are shown in Fig. 2.

Since the harvesting of solar energy on Earth is fraught with difficulties, some researchers have proposed harvesting it in space. They claim that capturing solar energy from space without any impediments is a higher priority for investment and is better suited to fulfill future energy needs (Chaudhary and Kumar 2018). For instance, SSPS satellites in GEO orbit produce a great deal more electricity than conventional satellites. Conventional satellites now create just enough electricity to fulfill their operating demands, but SSPS satellites have the potential to generate enough power to meet the Earth's energy needs (Chaudhary and Kumar 2018; Kazmerski 2016).

Using solar energy for data centers

The providers of cloud services and data centers should reduce their use of non-renewable energy sources and replace them with renewable alternatives, such as solar energy to comply with environmental protection standards (Radu 2017). The major cloud providers, such as Apple, Facebook, Google, Amazon, Microsoft, IBM, Salesforce, and others, which have pledged to power their data centers exclusively with renewable energy, are playing a significant part in fulfilling this commitment (Radu 2017).

With solar energy harvesting, IoT components can be made more sustainable, eco-friendly, and independent of traditional power grids. However, the effectiveness and feasibility of solar energy harvesting are determined by factors such as geographical location, available sunlight, the energy requirements of IoT devices, and the capacity of the solar panels used (Chinipardaz and Amraee 2022).

The energy solutions for greening the IoT systems are listed in Fig. 3 in the five-layer architecture. The left column includes energy reduction schemes, and the right column involves solar energy harvesting items.

IoT for greening the environment

To move from traditional fossil fuel-based energy systems, which are one of the main sources of both heat and CO_2 production, to cleaner alternatives, new approaches have been perused in recent years. Utilizing renewable energy sources, energy storage systems, smart grids, and advanced materials can help mitigate climate change, decrease greenhouse gas emissions, enhance energy efficiency, and facilitate the shift toward a more sustainable and green energy industry (Fakhar et al. 2023; Khare 2022).

With its vast array of devices and capabilities, the IoT system can play a crucial role in greening the environment by promoting the efficiency of energy management systems and

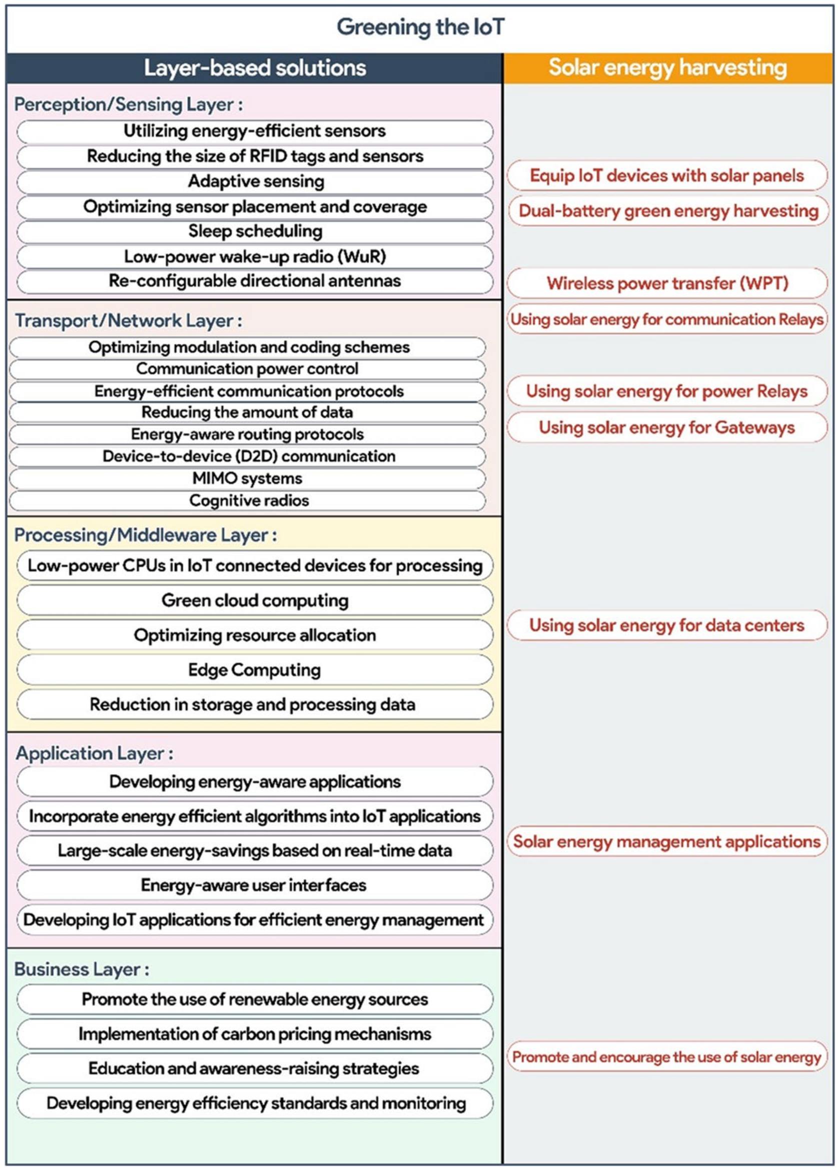

Fig. 3 Five-layer based energy solutions for greening the IoT systems

also for harvesting renewable energy, which are investigated in the following subsection (Abd El-Mawla et al. 2019).

Integrating IoT to smart energy management

To ensure a sustainable future, electricity production should rely on environmental resources like solar and wind that do not generate CO_2. IoT can simplify the integration of renewable energy sources into the electric grid.

A smart grid is an electrical system that integrates digital technology to efficiently monitor, manage, and optimize electricity generation, distribution, and consumption. The use of information and communication technology capabilities, notably IoT, enables smart grids to improve energy production and demand. IoT technology can enable advanced energy management, grid interaction possibilities, and the incorporation of renewable energy. Bidirectional communication between solar energy systems and the power grid is enabled by this integration, allowing for real-time energy usage adjustments, load shedding, and the possibility of selling surplus energy back to the grid. For instance, Cheddadi et al. (2020) offer an IoT solution that can employ an ESP32 microcontroller to perform intelligent and real-time collection and monitoring of power production and environmental conditions of solar systems. This integration leads to a stable grid, energy optimization, and better efficiency in solar energy harvesting.

A microgrid is an electricity distribution network that serves a localized area and is capable of functioning autonomously or in conjunction with the central power grid. This system is often equipped with diverse energy sources, including renewable energy generators like solar panels and wind turbines as well as energy storage systems such as batteries. Integrating IoT technology within a smart microgrid allows for remote monitoring and control of the system's various components, enabling seamless data collection on energy generation, consumption, and storage (Sitharthan et al. 2023).

A smart energy system, on the other hand, refers to a more comprehensive concept that includes not just the electrical grid but also other energy sectors, including heating, cooling, transportation, and overall energy management. A smart energy system is a network of devices and technologies that work together intelligently to optimize energy production, distribution, consumption, and management. It aims to transform conventional energy systems into adaptive, flexible, and responsive networks. IoT technologies are utilized in smart energy systems to monitor, control, and optimize components like renewable energy sources, energy storage devices, grid infrastructure, and end-use devices (Orumwense and Abo-Al-Ez 2023). The authors in Orumwense and Abo-Al-Ez (2023) reviewed the applications and challenges of the adoption of IoT technologies in the energy domain, which has been named the Internet of Energy (IoE). Additionally, the authors in Abd El-Mawla et al. (2019) proposed that the industrial Internet of things (IIoT) could serve as a potential solution for mitigating and adapting to climate change. With the industrial Internet of Things, machines, devices, and sensors in industrial sectors can be linked to enable improved automation, data collection, and analysis. This results in optimized resource usage, actionable insights for decision making, and improved operational efficiency.

Using IoT for solar energy harvesting

Using IoT technologies is a promising way to improve solar energy harvesting. This section investigates the main state-of-the-art methods for how IoT can improve the performance of solar energy harvesting. Solar energy systems can be monitored, optimized, and managed effectively using IoT functionalities. The ways in which IoT can contribute to the advancement of solar energy harvesting are categorized as follows:

Remote monitoring and maintenance

IoT-enabled remote monitoring and maintenance capabilities enable tracking of solar panels' performance, energy generation, and environmental conditions in real time. For instance, it is not possible to remotely manage and observe the operations of a solar power plant using conventional PLC technology. IoT sensors and devices, like solar irradiance or temperature sensors, can collect data on energy generation, panel efficiency, and system health. This data is sent to management programs through the Internet, and is used to detect issues like panel malfunctions, shading, or dirt accumulation, which helps in timely maintenance and maximizes energy output. Using the web portal, users can monitor the status of solar panels from anywhere on the Internet, or the monitoring and settings can be done automatically through machine-to-machine communication without human intervention (Bhau et al. 2023). For example, after analyzing the data, servomotors can be used to control the rotation and configuration of solar panels according to the direction of the sun, thus increasing the effectiveness of power gathering (Karbhari and Nema n.d.).

The system provided in Shakya (2021), based on the generated current and voltage from the solar panels, produces a maintenance alert. In comparison to the solar panel's calibrated values based on various solar radiations, observations from the solar panel systems were made. When there is a significant variation in the amount of power generated by the solar panels, the proposed model alerts the maintenance team. A control unit that can handle some minor maintenance tasks on the connected solar panels can be added to the proposed work to make it more comprehensive.

Detection and evaluation of faults

Identifying faults and abnormalities in solar energy systems is crucial, and the diagnostic capabilities of IoT play a significant role. The analysis of data by IoT-based systems allows for the early detection and resolution of faulty components, wiring problems, or poor connections. This results in better system efficiency, less energy waste, and enhanced energy harvesting performance.

In order to monitor problem detection and solar array management in an intelligent manner, a device and its associated software are presented in Spanias (2017). This system can manage solar farms, carry out problem detection and repair, assist with power optimization in dynamic environments, and decrease inverter transients with the use of IoT.

Predictive maintenance

The IoT can facilitate predictive maintenance by employing machine learning algorithms and predictive analytics. Historical data analysis and pattern recognition in IoT-based systems enable predictive maintenance, and proactive servicing. By taking a proactive approach, system downtime is reduced, continuous energy production is ensured, and overall system performance is enhanced.

The project described in Katyarmal et al. (2018) is based on the adoption of a novel, economically advantageous IoT-based methodology for remote solar plant monitoring and performance assessment. Along with real-time monitoring, this will make it easier to discover plant faults and perform preventive maintenance. Table 1 shows the main

Table 1 Applications of the IoT technology in solar systems

Goals	Year	Application of the IoT	Hardware
Management of rotation and topology of solar panels (Karbhari and Nema n.d.)	2020	Enhancing the power harvesting efficiency	Microcontroller 8051
Power monitoring (Cheddadi et al. 2020)	2020	Intelligent and real-time monitoring	Microcontroller ESP32
Fault detection and solar array management (Spanias 2017)	2017	Control solar farms, identify and fix faults, assist with power optimization in dynamic environments, and reduce inverter transients.	Microcontroller, network radio, relays
Maintenance alert based on the generated current and voltage (Shakya 2021)	2021	Notifies the maintenance team when there is a significant change in the amount of power produced by the solar panels.	Voltage sensor, current sensor, microcontroller
Remotely monitoring a solar plant (Katyarmal et al. 2018)	2018	Remote performance evaluation	ATMEGA 328, INA 219, ESP8266
IoT-based solar energy monitoring system (Bhau et al. 2023)	2023	Displaying the energy consumption of solar power	Raspberry pi, flask framework.
Smart solar energy monitoring systems (Rani et al. 2023)	2023	Cost-effective method for remotely monitoring a solar plant performance	ARDUINO Mega 328
Monitoring of the solar evacuated tube heat pipe (Manivannan et al. 2022)	2022	Energy and environment analysis of a solar system using the IoT	Arduino board, ESP8266

applications as well as their goals and required hardware for IoT technology in solar systems in several recent studies.

The integration of IoT and solar energy harvesting is depicted in Fig. 4. The right side of Fig. 4 includes the overall block design of an IoT solution used to monitor solar plants. These monitoring systems usually have a microcontroller that processes the incoming data from various sensors. Then, it transmits the processed data to the cloud and servers via a wireless channel and gateway. Data exchange is based on client and server requests. A client launches a request, and the server returns a response (Rani et al. 2023).

There are several benefits that can be achieved by leveraging the mutual relationship between IoT and solar energy

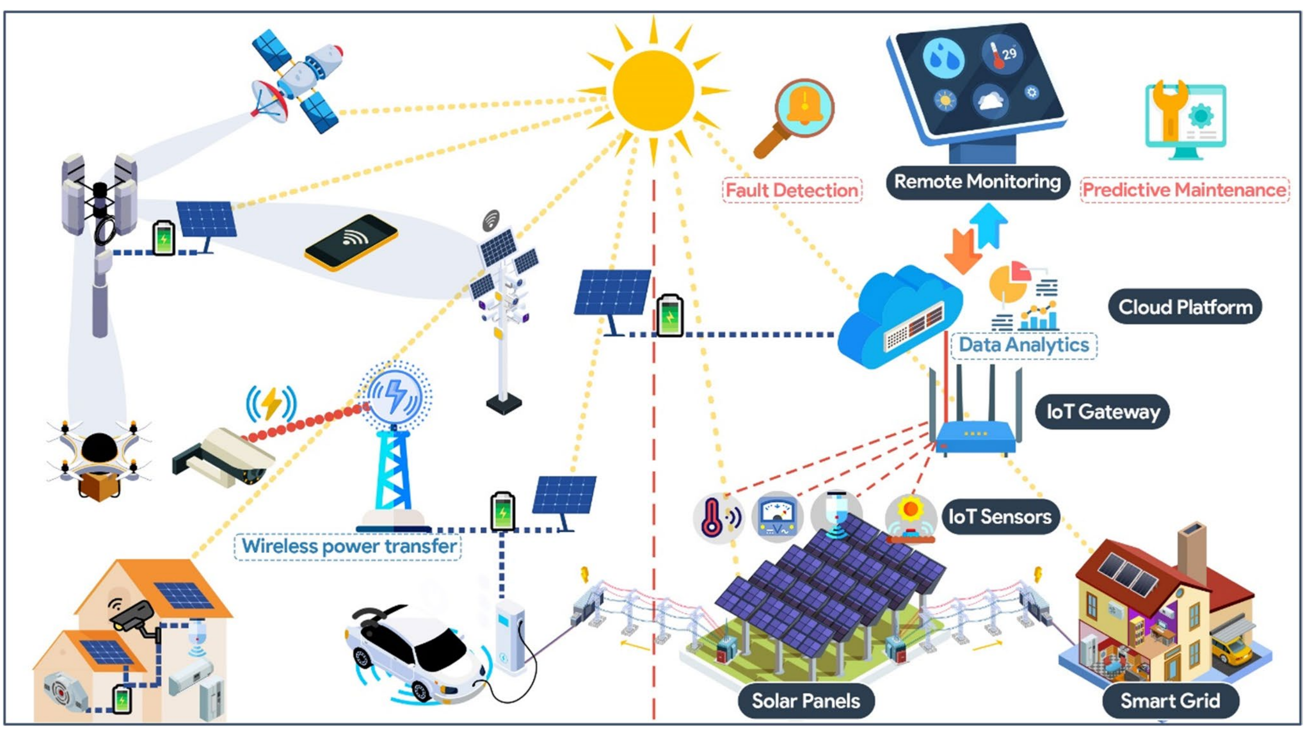

Fig. 4 The integration of IoT and solar energy harvesting

harvesting that have been discussed in this paper. In general, the combination of solar energy harvesting and IoT technologies can enhance the efficiency, reliability, and sustainability of both systems. Solar energy as a power supply for IoT devices decreases their dependance on fossil fuels and minimizes greenhouse gas emissions, making them more sustainable. Solar energy harvesting enables IoT devices to operate off-grid, in remote areas, or in environmentally sensitive locations where traditional power sources may be limited. The sustainability of IoT deployments is promoted through the reduction of their environmental impact and the increase of their resilience. IoT, on the other hand, improves the efficiency and effectiveness of solar energy systems, maximizing performance and minimizing waste. This mutually advantageous relationship supports the broader objective of building sustainable and environmentally friendly systems.

Future research direction

This section outlines multiple research directions in three subsections based on the research conducted. These include research directions for the five-layer IoT architecture, the integration challenges of IoT and solar energy harvesting, and broadening research to other green practices.

Layered-based research directions of green IoT

Examining challenges and ideas in a layered e can help modular IoT development. Each layer can be developed independently by the relevant experts. In the following, potential research directions are introduced for the five-layer architecture.

Perception layer:

- The inclusion of always-on devices in this layer is extremely beneficial.
- The inclusion of always-on devices in this layer is extremely beneficial. These devices can be established through the expertise of researchers and specialists in the domain of hardware and electronics. Through the implementation of energy reduction techniques, coupled with the utilization of solar energy harvesting and WPT, the design of the devices with minimal energy consumption can be achieved.

Transport layer:

- The performance of applications across ~~in~~ different environments can be severely impacted by security vulnerabilities within the IoT ecosystem. To address this, it is recommended that network experts and standardization bodies collaborate in designing and standardizing communication protocols that are energy-efficient and adaptive. In this way, diverse IoT devices must employ adaptive security mechanisms that adjust the security level based on node conditions and resource limitations.

Processing layer:

- Cloud computing energy efficiency can be improved by new machine learning methods that optimize resource allocation, workload scheduling, and proactive decision-making. These new machine learning methods include reinforcement learning, deep learning, transfer learning, and ensemble learning, which can be developed by AI specialists at cloud and service providers such as Google and Microsoft. The application of knowledge gained from one task to another related task is enabled through transfer learning. Transfer learning in cloud computing can be used to exploit the knowledge gained from boosting energy efficiency in one data center and implement it in other data centers. This leads to energy conservation and optimal resource allocation.

Application layer:

- Software developers on IoT platforms can implement user interfaces that promote energy-efficient practices. The device can offer consumers personalized energy-saving tips based on the data it has collected about their usage. These recommendations may include suggestions such as utilizing energy-efficient equipment, making the best use of the heating and cooling systems, or changing how much light is needed.

Business layer:

- Transitioning from the IoT to the green IoT requires modifications across different layers and considerable upfront expenses. Hence, conducting a comprehensive analysis of policies concerning incentives, support, and monitoring for IoT consumers, manufacturers, and other stakeholders is necessary to regulate energy consumption from a short-term, medium-term, and long-term perspective. This study can serve as a valuable resource for managers and government officials in their planning efforts.

To achieve the best green IoT energy solutions, interdisciplinary approaches are required. By utilizing the five-layer architecture, researchers from energy engineering, computer science, environmental science, and business can work together to gain a comprehensive understanding of the complex factors necessary for achieving energy efficiency in IoT systems.

Maximizing the benefits of the integration of IoT and solar energy harvesting

Although IoT and solar energy harvesting offer benefits through their mutual relationship, challenges must be addressed to maximize these benefits. Addressing these challenges requires careful and innovative studies.

Solar energy production is affected by weather and fluctuates throughout the day. The unreliable and dynamic nature of solar power can be problematic for IoT components that require a consistent source of energy. A green solution that includes the use of several forms of renewable energy and the integration of energy storage systems to ensure continuous power supply during periods of low solar irradiation can provide certainty for decision makers.

Although IoT can optimize solar energy harvesting systems, it is crucial to ensure that IoT devices are energy-efficient. Proper management of the energy needs of IoT components like sensors, actuators, and communication equipment is crucial to prevent energy inefficiencies and maintain the energy balance of the system.

Designing an IoT solution for the management of solar power plants, which on the one hand contributes to the energy efficiency of solar panels and on the other hand provides the energy of its components by solar energy harvesting from the facilities of the same panels, is a combined and optimal solution for this problem. This mutual solution requires careful planning, design, and implementation.

The integration of IoT with other green practices

The main emphasis of this article is on energy solutions, while green practices can be explored in other areas as well. Figure 5 shows the four main aspects of green practices that this research can be expand to. One such area is waste management that can be investigated in light of this mutual relationship. There are various methods to make IoT waste management eco-friendly, including optimizing energy usage to reduce waste generation, adopting sustainable materials, implementing recycling programs, and using eco-friendly disposal methods. Conversely, the integration of IoT technology into waste management systems can enhance waste collection and recycling procedures and minimize the impact of waste disposal on the environment. Developing smart waste bins, tracking and monitoring waste flows, and optimizing collection routes are some examples of ways to do so.

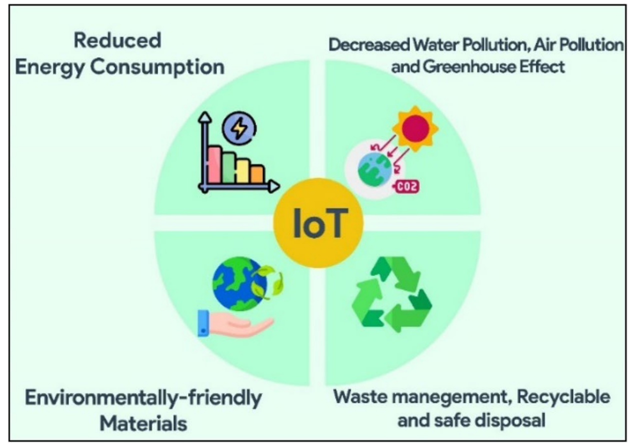

Fig. 5 Four major aspects of green practices for the extension of this research

Conclusion

This study addresses a crucial research gap by investigating the integration of IoT and green practices from an energy solutions perspective. By examining both modes of combining these two domains, both concepts of green IoT have been clarified. Solutions for greening the IoT by implementing green principles in IoT systems, as well as using the IoT to promote sustainable and environmentally friendly practices, have been investigated, all through the lens of energy solutions.

The study article specifically focused on solar energy harvesting as an efficient and rapidly growing energy solution. It has been shown that the combination of solar energy harvesting and IoT technologies can enhance the efficiency, reliability, and sustainability of both systems. The ultimate aim of this mutually beneficial relationship is to construct sustainable and eco-friendly systems. Future research directions based the two-way relationship between solar energy harvesting and the IoT are discussed. The findings pave the way for future research that can further optimize energy-efficient IoT systems and harness the full potential of renewable energy sources.

An appropriate five-layer architecture for an IoT system was considered in this article. Studying energy solutions within the framework of the five-layer architecture is useful because each layer has a distinct target audience. Therefore, by adapting this framework, a comprehensive coverage of the solutions was investigated, determining the responsibilities of individuals and organizations at various levels. Several future research directions for green IoT were also expressed in the form of the layered framework. An overview of other aspects of green practices to study their potential integration with IoT is also offered provided for the future extension of this research. By implementing such strategies, we can effectively reduce energy usage, greenhouse gas emissions, and resource wastage, leading to a more balanced and sustainable relationship between technology and the environment.

Author contribution All authors contributed to the conception and design of the study. Maryam Chinipardaz prepared the sections "Greening the IoT" and "Using solar energy harvesting for IoT." Ali Khoramfar investigated the "IoT-layered architecture" section and prepared the figures. Maryam Chinipardaz and Ali Khoramfar also prepared the original draft paper. Somaieh Amraee investigated the section "Using IoT for solar energy harvesting" and reviewed and edited the paper. All authors have read and approved the final version of the manuscript.

Declarations

Ethics approval The authors declare that all the ethical rules specified in the submission guidelines have been followed for this study.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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