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INTEGRATING RENEWABLE ENERGY WITH INTERNET OF THINGS (IOT): PATHWAYS TO A SMART GREEN PLANET

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ABSTRACT

The global use of IoT-enabled devices powered by renewable energy can create a smart, efficient, and eco-friendly network. By leveraging data analytics and machine learning, these systems can predict energy consumption, optimize resources, and maintain renewable energy assets proactively. IoT device adoption is rapidly increasing, with a projected 13% growth in 2024, bringing the total to 18.8 billion devices globally. However, there is a critical need for advanced applications of IoT technology, improved sensors implementation, and up-to-date software development to control IoT devices which is essential to fully harness renewable energy and combat global warming, ultimately achieving the vision of a smart green planet. This review examines the operational and technical needs of IoT devices, their integration with various renewable energy sources using Raspberry Pi or Arduino platforms equipped with sensors (such as motion, vibration, flow, and gyroscope), and the application of machine learning in IoT devices to showcase the potential of these technologies in fostering a smart, green world. To further this investigation, the study thoroughly examined the pros and cons of integrating various renewable energy sources to develop smart systems, such as smart grids, smart cities, smart transportation, and smart waste collection. Additionally, this study also examines the challenges faced by smart IoT systems, providing critical analysis and identifying promising directions for future advancements.

KEYWORDS

IoT, Renewable energy, Smart City, Smart transportation, Smart green planet.

1. INTRODUCTION

The Internet is one of the most inevitable parts of modern-day life, which playing a crucial role to build up a smart world by employing the concept-Internet of Things (IoT) (Benhamaid et al., 2022). IoT envisions connecting daily life objects and integrating them to the internet using sensors, transceivers, and protocol stacks. IoT technology aims to connect people to people (P2P), people to machine (P2M), and machine to machine (M2M) through an all-connected, heterogeneous platform for devices and systems through an extensive network consisting of connected systems, sensors, and auto-mobiles antenna (Gulzar & Abbas, 2019). The connected devices gather data and process it through an internet, enabling software to perform assigned tasks. To accomplish those tasks, the sensor is playing a vital role in accumulating the data and converting them to readable signals for designed devices that will be connected to the network of IoT (Al-Fuqaha et al., 2015; Laghari et al., 2022). The application of IoT is very wide including energy sector (Benhamaid et al., 2022), building and construction (Parab & Pandey, 2021c), health (Nižetić et al., 2020), agriculture (Mohammed & Ahmed, 2017), transportation (Zantalis et al., n.d.-b), and environmental monitoring (Bošnjaković et al., 2019; Lieberzeit & Dickert, 2007; E. Sayed et al., 2019) , as classified in Fig.1. In addition, IoT is thoroughly

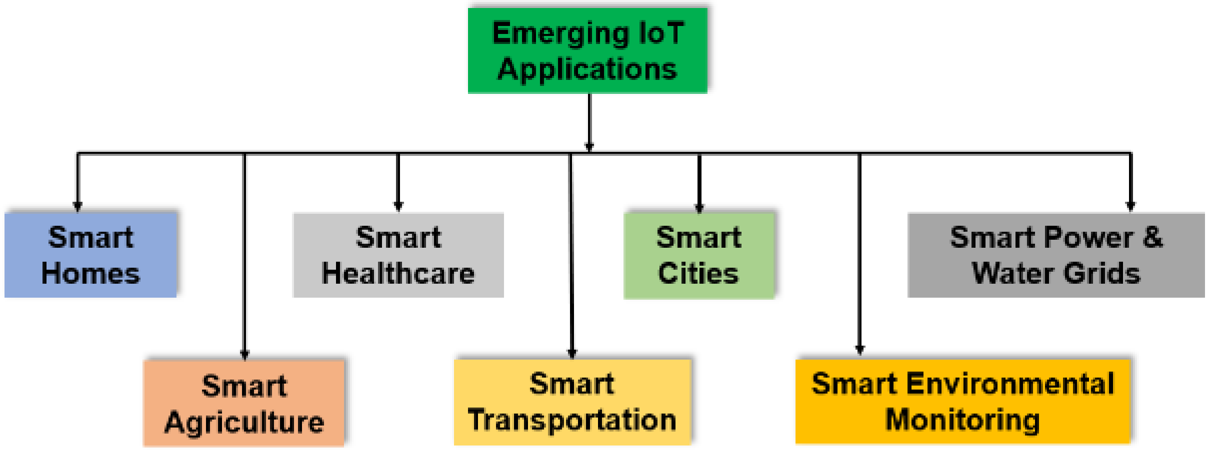

Fig. 1: The extended domain range of the application of IoT which lead us to enter a smart green world.

employed in the predominant system-level design, including aspects like energy efficiency, robustness, scalability, interoperability, and security issues. Therefore, the application of IoT is now practicing from top-notch industrial standard production to everyday objects like pens, clothes, and eye wires (Benhamaid et al., 2022)(Lieberzeit & Dickert, 2007; I. Zhou et al., 2021). Consequently, the world is experiencing ground-breaking growth of IoT devices to enter a smart green world. According to the 2015 Forbes survey , the number of internet-connected objects is likely to be 75.44 billion and the economic growth of the IoT technology will range from \$2.7 to \$6.2 trillion by 2025 (Swamy & Kota, 2020). It is estimated that by 2025, the internet nodes may reside in every single object hence causing the number of devices connected to the internet to rise. According to Cisco, there will be 500 billion devices connected to the internet by the year 2030 (Shafique et al., 2020). This enormous increase in the use of IoT devices in next the few years is boosted up by the emergence of 5G networks and exploitation of other new spectrum frequencies (Benhamaid et al., 2022).

Enabling those wide range of IoT devices applications, a power source must be introduced to the IoT system. The power source is either active current (AC) or direct current (DC). Burning fossil fuel to generate electricity is causing long-term damage to our global environment, and ultimately, the world is looking for a sustainable solution from environmental pollution (Ahmed & Hutton-prager, 2021; Bošnjaković et al., 2019; Environmental, 2000; Manisalidis et al., 2020). Renewable energy sources in this case play a crucial role in implementing the IoT devices in operation to move forward to a smart green world. Renewable energy is playing a vital role in implementing IoT devices in operation since they generate little secondary waste, have little influence on the environment, and can be sustained for the foreseeable future in light of societal, economic, and environmental demands. However, integration of renewable energy to IoT devices is an important task to moving forward to a smart green planet. This process is still challenging due to the specific application of IoT requires different integration system, for instance, renewable energy integration to IoT in agricultural production requires less complex radio frequency identification (RFID) and sensor connection than a smart grid or smart home (Chaudhary et al., 2019; Uribe, 2019). (Balam et al., 2023) claimed that advanced communication and control techniques are used to integrate renewable energy into IoT devices (Balam et al., 2023). This study (Balam et al., 2023) also suggests that the multilevel converters would be a great choice to integrate renewable energy into the IoT devices in a smart grid, smart power plant and smart city. Another study conducted by (Liu et al., 2019) investigated on ambient energy harvesting for green IoT using dual-battery architecture system that faces difficulties for energy storage and distribution to remote area (Liu & Ansari, 2019a). Integration of sensors technology to the IoT devices resolved many issues to develop a smart system. The sensor is the electronic device that is to detect and respond to signal from IoT devices for linking them up virtually in association with an active internet connection (Yang et al., 2023). Sensors are integrated with an RFID tag, which is used to authenticate and identify the users and devices. The tags used in RFID have a unique identification number for each user (Ds et al., n.d.; Khan, 2019). Although many types of sensors are integrated into the system to overcome the above-mentioned issues, the advanced applications of that variety of sensor mechanisms remain in the system to overcome the above-mentioned challenges. Additionally, the advanced applications of a variety of sensor mechanisms remain unclear and need further improvement. The insufficient investigations in the field of renewable energy integration with IoT devices highlight several potential gaps. These include the lack of standardized protocols and interfaces, challenges in ensuring data security and privacy, scalability issues, and the need for improved energy efficiency. Additionally, the high initial costs of IoT devices must be addressed to make this technology more popular and expand its global reach.

This study aims to provide further insight into the potential integration mechanisms of how renewable energy can enable IoT devices to build a smart world. Through numerical modeling of smart cities, smart power plants, smart transportation, smart healthcare, and new sensor applications, we explore how these systems can be efficiently operated. The potential challenges of IoT technology adoption for integration with renewable energy are thoroughly discussed, offering solutions to overcome these obstacles. After a comprehensive investigation, this study reveals recent advances in IoT technology and outlines future directions for the extensive adoption of IoT-enabled devices to transform our world into a smart, green planet. To ensure a seamless flow of information, we aim to break down the work into several sections including the process of integrating renewable energy with IoT devices to build a smart system, discussing how each component operates efficiently with the aid of sensors and advanced machine learning as observed in the literature. To do so, the paper is organized as follows. In section 2 we discussed the pivotal role of sensors in IoT devices and how renewable energy enables IoT devices to operate efficiently and autonomously. Section 3 provides a detailed description of how IoT implemented in the energy sector to control smart grid and powerplants. Section 4 discusses the necessary requirements for using IoT devices to know the integration process of renewable energy to the devices as extensively elucidated in section 5. Section 6 then provides the potential technological challenges of IoT implementation across the world to enter into a smart green planet which inspires to leave some potential future directions in section 7. We demonstrate that all these factors need to be carefully considered to robustly improve the integration process of renewable energy to enable IoT devices, thus building a smart green planet.

2. RENEWABLE ENERGY SOURCES

The most significant source of renewable energy sources is – solar energy (Prasanna Rani et al., 2021), wind energy (Li et al., 2020; Wang & Wang, 2015; Zhang et al., 2023) and hydro-energy (Oliveira et al., 2021; Sakib et al., 2023; E. T. Sayed et al., 2021).

2.1. Solar energy

The process of solar power generation harnesses the energy from sunlight by utilizing the photovoltaic (PV) effect, a phenomenon in which certain materials, like silicon solar cells, generate an electric current when exposed to sunlight (Chitra et al., 2022). A single photovoltaic cell typically produces a modest amount of energy, generating just a few watts. However, by connecting multiple photovoltaic cells into an array, a PV system, commonly known as a solar panel, can significantly boost its energy output by generating 150 to 180 watts per square meter (W/m^2) (Syu et al., 2021). These PV generators are strategically positioned to receive direct sunlight, enabling them to produce direct current (DC) electricity, which is converted into AC in the later stage in a power grid (Kumar et al., 2018). The IoT architecture for PV systems comprises three key Layers: the PV system design environment (Layer 1), gateway linkage (Layer 2), and remote monitoring and control (Layer 3). In the first layer, the PV system's components are interconnected to meet user requirements. These components are linked with the Arduino server, which constitutes the second layer, acting as a gateway between the PV system hardware and the web server as depicted in Fig. 2a. The gateway linkage facilitates connectivity via Ethernet or wireless router modules. The Arduino server, equipped with microcontrollers, monitors, and manages the PV system's hardware components. The third layer, remote monitoring, and control, receives information from the server, delivering it to storage devices for generating periodic reports. Users can access this data in report or visual graph formats using an Android interface, connecting to cloud data through a Wi-Fi network (Kumar et al., 2018; Prasanna Rani et al., 2023) as displayed in Fig. 2a.

2.2. Wind energy

Wind energy is one of the significant sources of renewable energy (Wang & Wang, 2015). Wind is used to generate electricity by converting the kinetic energy of the blowing air into electricity by employing a turbine. The wind applies pressure on the long slender blade of the wind mill to facilitate spinning of blades. The spinning blades then help to activate rotor, and internal shapt of the turbine to spin upto 30-60 revoultuion per minute (rpm) (Li et al., 2020). The turbine is connected to a generator and a controller to generate electricity. The controller is working in a loop in association with the genreator and turbine. Typically, generators require high rpm, which is facilitated by a gearbox to increase the spin rate ~1800 rpm reported elesewhere (Wang & Wang, 2015). Howerver, those gearboxes are expensive and heavy, so it is necessary to overcome those issues by conducting potential research (Li et al., 2020; E. T. Sayed et al., 2021). The produced electricilty by a generator then transferred to the power gird for the larger distribution. This entire process of electricity production using wind energy is displayed in the Fig. 2b.

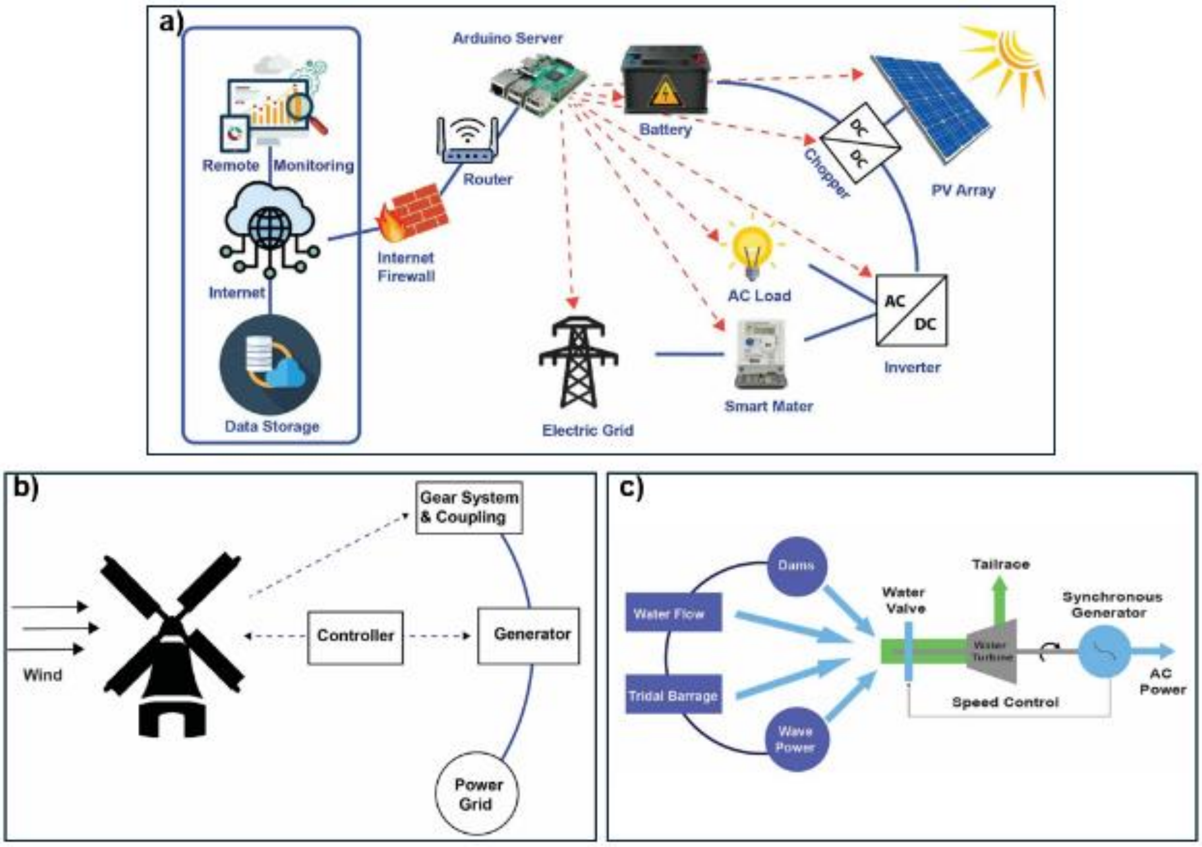

Fig. 2. The different renewable energy sources for electricity production; a) exploitation of solar energy to produce electricity, distribution, and storage system to enable IoT devices (Redrawn from (Kumar et al., 2018) , b) electricity production cycle using wind energy, and c) schematics of AC production process using hydro-energy.

2.3. Hydro-energy

Hydro-energy is another important source of renewable energy, generated using a dam structure to alter the natural flow of a river or other source of water current (E. T. Sayed et al., 2021). The working principle of hydro-energy production relies on the flowing of high-water through a pipe named 'penstock', and then the high flow rate of water employs force to rotate a turbine blade. This spin of the turbine is ultimately used to generate electricity in association with a synchronous generator that works in a loop with a water valve and water turbine to generate electricity. The water flow of the dam flows though a water valve in a designated way of the water flow direction as shown in Fig. 2c towards the water turbine. The turbine is rotating due to the exerted force of the water, the spin of turbine then generates electricity using a synchronous generator as shown in Fig. 2c. The produced electricity afterwards supplied to a power grid in the form AC current to distribute in a particular region.

Table 1: Tabulated summary of how different renewable energy sources can be integrated to enable various IoT devices.

Renewable Energy Source	Integration Method	IoT Device Applications	Benefits
Solar Power	Solar panels and photovoltaic cells	Smart homes, agricultural sensors, wearable devices	Reduced energy costs, sustainability, off-grid capabilities (Goetzberger & Hoffmann, 2005; Guney, 2016; Prasanna Rani et al., 2023; Van Sark & Corona, 2019)
Wind Power	Wind turbines and micro wind generators	Remote monitoring systems, environmental sensors, smart grids	High energy output, low operational costs, renewable (de Falani et al., 2020; Li et al., 2020; E. T. Sayed et al., 2021; Zhang et al., 2023)
Hydropower	Micro-hydro systems and water turbines	Water quality sensors, hydroelectric plant monitoring, smart irrigation	Consistent energy supply, low emissions, reliable (Oliveira et al., 2021; E. T. Sayed et al., 2021)
Biomass	Biomass generators and biogas plants	Agricultural IoT devices, waste management systems, rural electrification	Utilizes waste materials, reduces landfill use, renewable (Ayadi et al., 2020; Oliveira et al., 2021; Panwar et al., 2011; E. T. Sayed et al., 2021)
Geothermal	Geothermal heat pumps and power plants	Building energy management systems, industrial IoT devices, smart thermostats	Stable energy source, low emissions, efficient (Bošnjaković et al., 2019; Duić & Da Graça Carvalho, 2004; Noorollahi et al., 2019)

While the majority of countries continuously rely on imported conventional oil derivatives for energy needs, the storage of petroleum energy is rapidly declining. In this case, renewable energy will be the only sustainable energy source that could help to build a smart green planet, avoiding burning fossil fuels. IoT technology will play a crucial role in bridging the gap between the exploitation of renewable energy and the smart green planet idea (Cheng et al., 2016). Likewise, IoT can increase the adoption of renewables through power consumption monitoring and real-time alerts facilitated by its several components that enable various capabilities such as sensing, identification, actuation, communication, and administration. Sensing, identification , and recognition technologies; hardware, software, and cloud platforms; communication technologies, and networks; software, and algorithms; positioning technologies; data processing solutions; power, and energy storage; and security mechanisms are well-known IoT enabling technologies found in literature (Ayadi et al., 2020; Čolaković & Hadžialić, 2018a; Panwar et al., 2011; Wang & Wang, 2015). Table 1 provides a comprehensive summary of the applications of various renewable energy sources in enabling IoT devices to create smart systems, along with their benefits.

2.4. IoT enabling devices and technologies

2.4.1. Sensors

A sensor is a device that responds to a specified measurement by capturing various physical parameters, such as changes in resistance, capacitance, or impedance, and converting these signals into a human-readable form (Sehrawat & Gill, 2019). Sensors play crucial roles in several fields, including environment , motion and security, pressure and temperature, optical and touch monitoring, and ultrasonic sensing (Chung et al., 2013; IoT Sensors Market Size Worldwide 2025 | Statista.; Sehrawat & Gill, 2019; Yang et al., 2023). This wide range of sensors are integrated into the IoT devices and, making this state-of-the-art technology undoubtedly unique to take us into a smart world. Therefore, the market size of the sensors and IoT devices has increased significantly over the past few years (IoT Sensors Market Size Worldwide 2025 | Statista). According to Statista, the market size of the sensors worldwide would be 42.67 billion US dollar in the year of 2025 as shown in the Fig. 3 (IoT Sensors Market Size Worldwide 2025 | Statista). There are several reasons a significant gain in sensor market is for significant gains in the sector market, such as real-time energy optimization and distribution, improving analytical capabilities, and remote-control systems (IoT Sensors Market Size Worldwide 2025 | Statista, n.d.; Yang et al., 2023). The Statista report also predicted that the number of IoT devices adaptation will be increased to 74 billion worldwide (IoT Sensors Market Size Worldwide 2025 | Statista, n.d.). Fig. 3b illustrates this increasing trend, showing

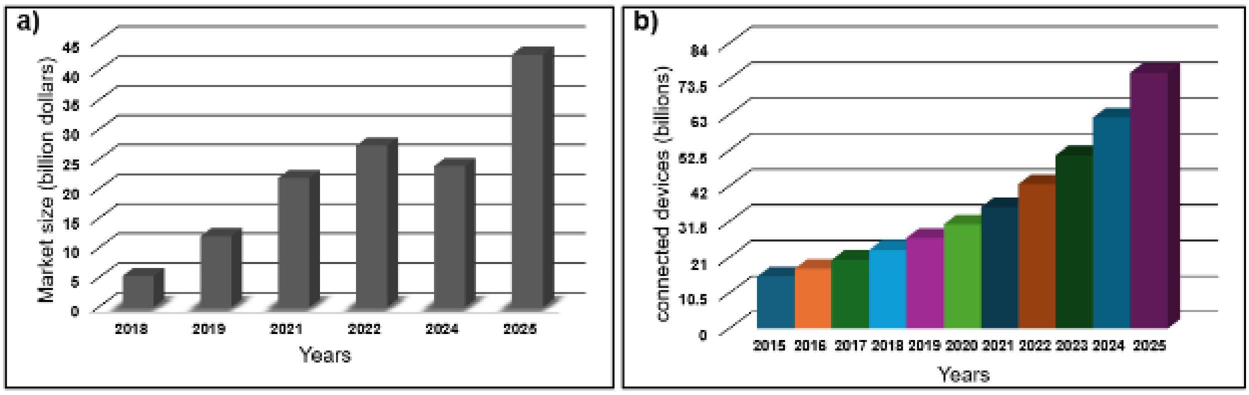

Fig. 3: A graphical representation of - a) IoT sensors market size increment over the past few years and probable market size in the upcoming year; b) the market size of IoT device adaptation over the years from past to future.

that the global adoption rate of IoT devices is expected to increase nearly sevenfold by 2025 compared to 2015. This rapid growth indicates a significant demand for a continuous and reliable electricity supply to ensure the smooth operation of smart systems. Proper utilization and integration of advanced sensors and renewable energy sources with IoT devices could be a crucial step towards creating a smart, green planet.

2.4.2. Smart home

IoT smart home occupancy sensors enable homeowners to monitor activities both inside and outside their homes, enhancing security measures against burglars and vandals. Additionally, these sensors contribute to energy conservation by regulating lighting based on the presence or absence of individuals in specific areas (Sehrawat & Gill, 2019). Various types of IoT smart home occupancy sensors are currently available including motion sensors, open/close sensors, and perimeter sensors (Bedi et al., 2018; Kou et al., 2022; Missaoui et al., 2014). Those sensors allow control of a home (i.e., refrigerators, air conditions, washing machine, thermostat, fire alarm and other electronic gadgets) remotely by employing advanced wireless technology integrated to IoT enable devices as shown in Fig. 4. However, upgraded to smart windows, doors and closets are recent demand to make a home fully automated and smartly controlled. A comprehensive survey conducted by Chettri, and coworkers shows the significant interest to build smart windows and doors that can be operated through internet connectivity, along with the integration of smart sensors and remote-control functionality (Chettri & Bera, 2020).

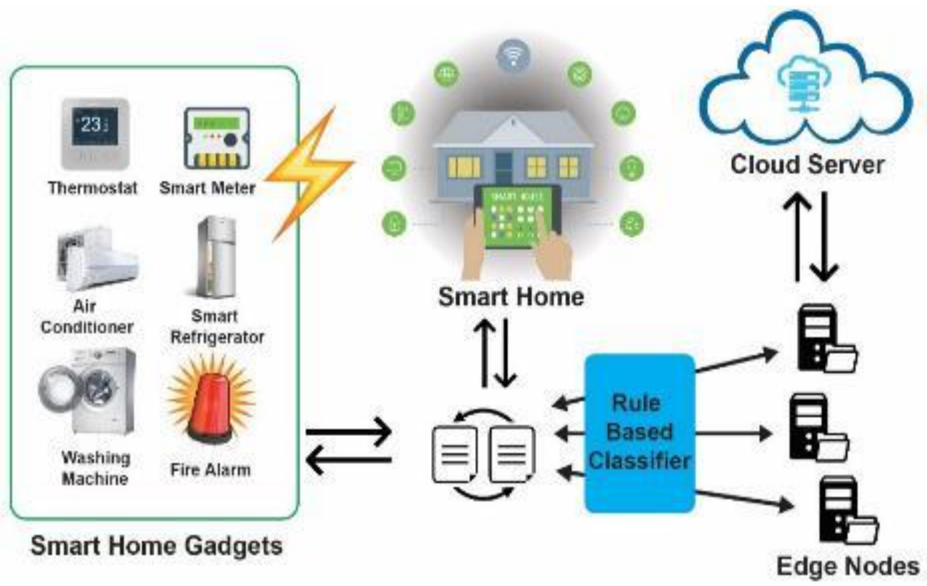

Fig. 4 An illustration of typical smart home controlled by IoT devices integrated to wireless internet and cloud server.

2.4.3. Smart city

A smart city is one that deploys a network of hundreds or thousands of sensors to gather electronic data about its residents and infrastructure, aiming to enhance efficiency and quality of life (Kim et al., 2020) . Several major cities, such as Seoul, New York, Tokyo, Shanghai, Singapore, Amsterdam, and Dubai, have embraced smart projects to enhance urban life (Kim et al., 2020; Kuru & Ansell, 2020). The successful implementation of IoT technology in smart cities requires meticulous planning at every stage of its accomplishments with the support and agreement of governments and citizens. By leveraging the IoT technology, cities can experience improvements across various aspects, including infrastructure, public transportation, traffic congestion reduction, and citizen well-being, fostering greater community engagement (Chitra et al., 2022; Goetzberger & Hoffmann, 2005; Kim et al., 2020). By integrating all city systems, such as transportation, healthcare, and weather monitoring, and enabling ubiquitous internet access for citizens to access databases related to airports, railways, and transportation tracking operating under specified protocols, cities will become smarter through the IoT enabled devices (Kim et al., 2020; Kirmani et al., 2023; Kuru & Ansell, 2020). The next generation smart city is now focusing on building smart transportation systems with autonomous drivers, smart toll roads, smart stadium, smart traffic and smart parking systems (Kim et al., 2020).

2.4.4. Smart weather and climate monitoring technologies

The global environment encompasses various interconnected elements such as the air, ecosystems, water quality, Earth's crust, chemical composition of the atmosphere, outer layer

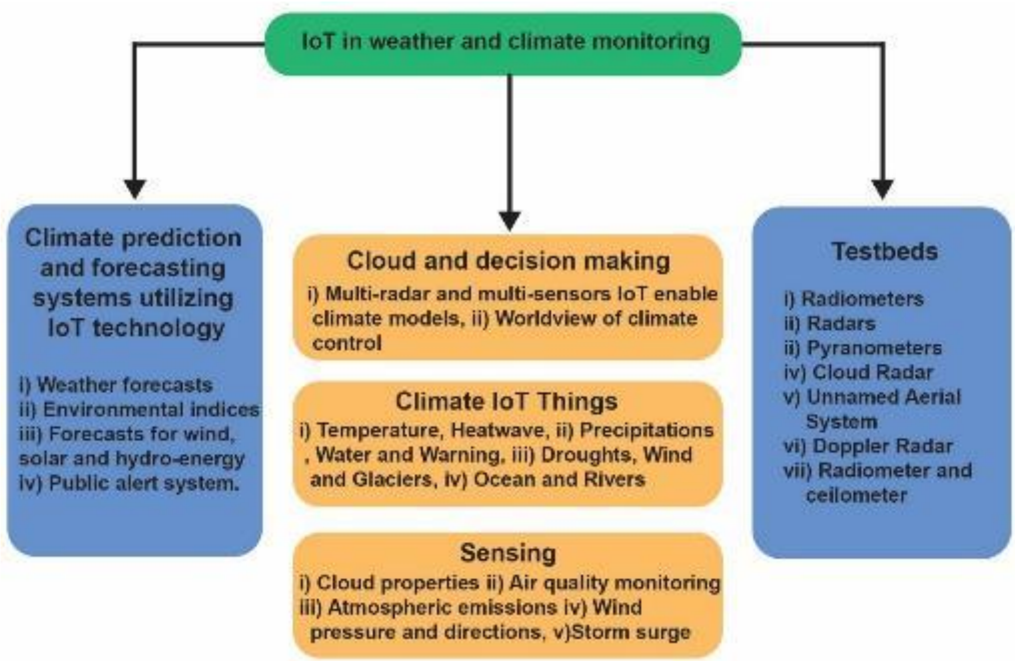

Fig.5. A potential IoT outline for environmental sustainability and climate change architecture.

of the sun, living organisms, and the biological and chemical processes occurring in land and ocean environments (Benhamaid et al., 2022; Liu & Ansari, 2019a; Muslim et al., 2021). State-of-the-art sensor technology combined with IoT enabled devices plays a crucial role in controlling weather and climate systems. Smart weather and climate systems generate automated and accurate signals in advance of natural disasters, allowing for precautionary measures that can save millions of lives worldwide (Mujawar et al., 2019; Ullo & Sinha, 2020). The extensive use of the smart environmental monitoring system extends beyond weather and climate monitoring. These systems are also widely used for monitoring air quality, water pollution, and radiation pollution as reported elsewhere (Ullo & Sinha, 2020). Utilizing environmental sensors, IoT facilitates easier and more efficient monitoring of air quality, radiation levels, water quality, hazardous chemicals, and various other environmental indicators, as illustrated in Fig. 5 (Chaudhary et al., 2019; Shafique et al., 2020; Ullo & Sinha, 2020). Cybersecurity, advanced sensor technology, interoperability and scalability are yet to be integrated to the smart climate monitoring system, which left a significant gap in this field to be filled.

The application of IoT devices in weather and climate monitoring is vast as reported in literature (Kumar et al., 2018; Mujawar et al., 2019; Muslim et al., 2021; Prasanna Rani et al., 2023; Ullo & Sinha, 2020). Notable contributions of IoT devices in this field include cloud monitoring in the atmosphere, tracking emissions, observing the Earth's surface, tracking and monitoring hurricanes, monitoring solar radiations, and conducting observations in the Arctic region (Liu & Ansari, 2019a; Muslim et al., 2021; Sehrawat & Gill, 2019).

2.4.5. Smart transportation technologies

The transportation and logistics sector offers numerous opportunities for the implementation of the IoT (Benhamaid et al., 2022; Chaudhary et al., 2019; Khan, 2019; Kirmani et al., 2023; Misra et al., 2021). These opportunities involve various applications, and requirements within the transportation system (Zantalis et al., n.d.-b, 2019). By utilizing IoT systems, vehicles can be intelligently monitored in terms of their movement, location, operational status, and potential risks. This level of monitoring enables effective management of logistics operations, and the transportation of heavy loads as reported elsewhere (Kumar & Dash, 2017). Additionally, it becomes crucial to monitor the environmental conditions inside vehicles, such as temperature, humidity, and light levels, especially during the transportation of sensitive goods. Furthermore, IoT can automate payment services at tolls and parking areas by integrating vehicle tracking numbers and driver identification (Dubey et al., 2018; Jan et al., 2019). IoT systems also play a significant role in enhancing guidance and navigation control systems across different modes of transportation, including road, air, and water transport. Through centralized control connected via networks, IoT facilitates transportation governance by monitoring various vehicles and assists in managing imports and exports of materials and goods. Additionally, it offers live and integrated services for tracking delivery status and provides location information through GIS mapping (Kumar & Dash, 2017). The recent addition the phone to smart transportation is a digital and remotely controlled traffic system employing a digital remote manager and signal generation by wireless router for enabling data circulation through a smartphone application. The increasing population in urban areas has compelled authorities to optimize the utilization of existing infrastructure, with smart transportation being a crucial component. A smart transportation system offers various services aimed at improving road safety, delivering timely information to drivers and passengers, mitigating traffic congestion, minimizing accidents, and more (Jan et al., 2019; Kumar & Dash, 2017; Zantalis et al., 2019).

3. IOT IN ELECTRICITY PRODUCTION USING RENEWABLE ENERGY

3.1. Smart grid systems

Smart grids (SG) are electricity grids that use information and communication technologies from the points of generation to customers in a smart way, as an integral part of the SG, since they can contribute to the balance, automatically, between generation, consumption, and distribution (Ayadi et al., 2020; Balam et al., 2023). Conventional grids are maintained by a central control panel whereas SG employed a decentralized process for energy flowing in both directions between the service provider and consumer. To maintain the uninterrupted flow of electricity, SG is designed with four subsystems including generation, transmission, distribution and consumption (Kirmani et al., 2023). The main function of the SG is relying on the three types of networks including WAN (wide area network), NAN (neighborhood area network) and HAN (home area network). WAN is used for maintaining control centers, energy distribution, energy sources and generation while HAN is employed to deploy electricity on the consumer side. The NAN is used for gathering information from HAN (Kirmani et al., 2023). Orumwense et. al (2022) also discussed about the communicational infrastructures such as advanced metering infrastructure, customer energy management systems, and supervisory control systems (Orumwense & Abo-Al-Ez, 2022). Those infrastructures improve the function of SG for the generation and distribution of electricity to a wide range of customers through a centralized power system. This SG system provides a virtual link within the grid system between consumers` devices and traditional assets (Kirmani et al., 2023). Fig. 6 displays the wide range of consumers of IoT enabled devices running on electricity, which is generated and controlled by an SG system.

SG has an extensive range of application, including highly efficient for increased power supply, uninterrupted electricity supply, resiliency, and environmentally friendly (Alotaibi et al., 2020; Hameed et al., 2020; Kirmani et al., 2023; Nwaigwe et al., 2019; Ourahou et al., 2020). Another key benefit of SG technology is that real-time, two-way communication permits faster recovery of power service after a blackout. Rotating power outages can cause a damaging domino effect that negatively impacts banking, communications, manufacturing, traffic, and security (Hameed et al., 2020; Pawar & Vittal K, 2019). The system uses digital sensors, smart metering techniques, and intelligent control systems equipped with analytical tools for automating, controlling, and monitoring the bidirectional flow of electricity from power outlet to the plug during the operation (Balam et al., 2023; Kirmani et al., 2023; Pawar & Vittal K, 2019).

Fig.6: Energy distribution through smart grid to enable wide range of IoT devices in different places to create a smart system.

3.2. Smart solar power plant

The proposed system refers to the online display of the power usage of solar energy as renewable energy. This monitoring is done through Raspberry Pi using flask framework. Smart monitoring displays daily usage of renewable energy. This helps the user to analyze energy usage and electricity issues (Deshmukh & Bhuyar, 2019). Fig. 7 shows the instrumentation setup for a smart solar power plant (SSPP) controlled by an IoT enabled device. It is worth to be mentioned that IoT devices control the SSPP in two different ways including solar power plant monitoring and controlling (Deshmukh & Bhuyar, 2019). For solar power plant monitoring instrumental setup as shown in Fig. 7, to remote monitoring of a SSPP. In this setup, IoT devices connected with a Raspberry Pi 3 module via Wi-Fi connection. Raspberry Pi 3 is connected via digital converter to several sensors, including temperature sensor, pressure sensor, current sensor, battery voltage, and solar panel (Deshmukh & Bhuyar, 2019). In the next step of a successful instrumentation setup and build up electrical connections, the IoT platforms employing internet media to connect IoT enabled devices, for instance smart phones, laptops, and computers (Benhamaid et al., 2022; Liu & Ansari, 2019a). On the remote web based IoT platform, user can perform plant monitoring, generation monitoring, historical data analysis, maintenance, and fault detection (Deshmukh & Bhuyar, 2019). The one important caveat of the solar power plant is the thermal losses though the solar collector. Wahid et al. (2016) proposed a method to reduce thermal losses by placing a half-circular vacuum tube in front of the solar collector. This design aims to decrease air velocity near the tube. They used the COMSOL Multiphysics program to monitor and analyze the heat energy flow (Al-Wahid & Al-Shamkhee, 2016). In addition, employing high-temperature coating on absorber surface, maintain optimal panel spacing and orientation, facilitating improved air circulation around solar collectors and using hybrid PV-thermal panels are potential solution for thermal loses from a solar power plant (Rukijkanpanich & Mingmongkol, 2020).

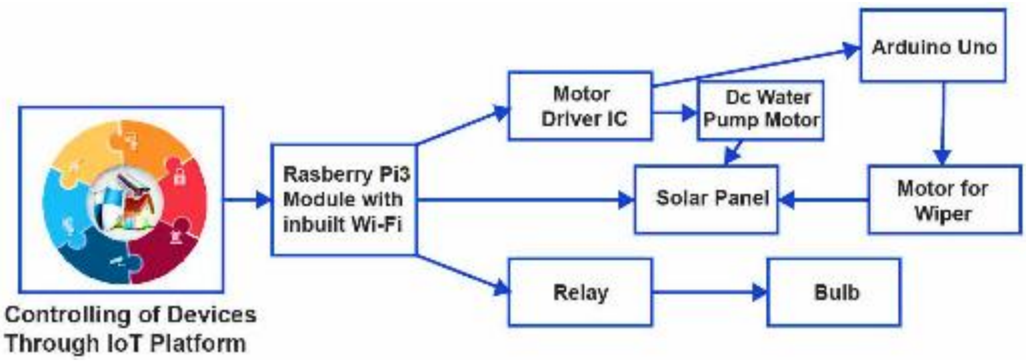

Fig.7. The functional workflow of a proposed smart solar power plant, controlled by an IoT-enabled device, involves several interconnected technical and electrical components. These components work together to create a fully automated solar power plant for generating electricity.

3.3. Smart wind firms

Wind energy is the fastest growing clean energy among the renewable energy sources, and it is also the most promising renewable energy source for large-scale development and commercialization. Despite the limitation of renewable energy sources, wind energy is one of the most sources of clean, sustainable , and abundant sources of energy (F. Zhou et al., 2022). According to research conducted by Zhou et al. (2022) on offshore wind power system, China already has the wind firm with a yearly electricity production rate of 210 million kilowatts (F. Zhou et al., 2022). Not only in China, but also the developed countries including USA, Japan and Russia, the wind firms increase significantly to reduced carbon emission and find a sustainable source of energy (Wang & Wang, 2015). Another study conducted by (Falani et al. , 2020) claimed that the wind energy production is increased with 225% in 2017 from 2001 (de Falani et al., 2020). A simple energy production schematic is shown in Fig. 8 from wind energy to illuminate a smart home controlled by an IoT device. Wind energy production then depends

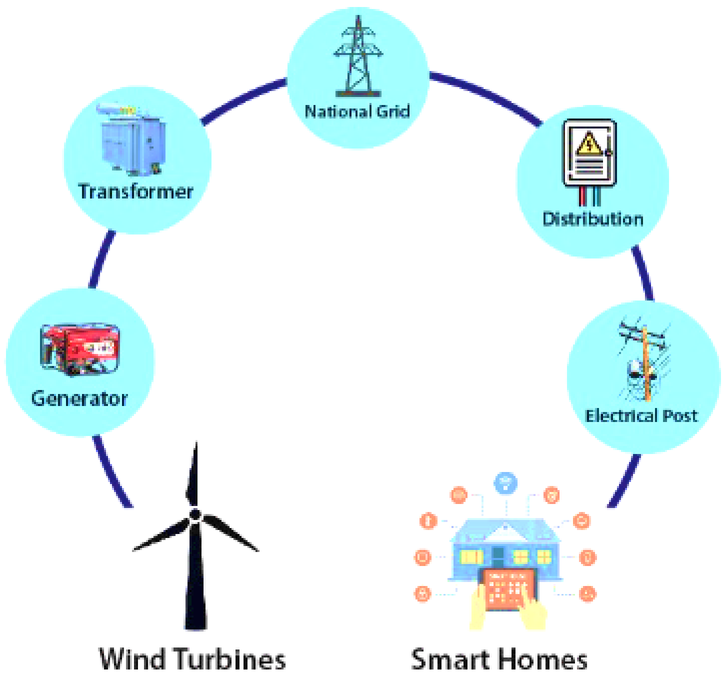

Fig. 8. A complete process of electricity production using wind energy, its broader distribution via smart grid to a IoT enabled smart home.

on the region of the windmill's placements, for instance, on shore wind turbines could generate more energy but are affected more by natural disasters. In contrast, offshore windmills generate a little less energy than onshore but less affected by the natural disaster (de Falani et al., 2020; Li et al., 2020). Compared with onshore units, due to the different environments of offshore units, the design of offshore units will also be different, and so does the focus of operation and maintenance (Wang & Wang, 2015; Zhang et al., 2023). The health of wind turbines is crucial for maximizing electricity production, as malfunctioning turbines can significantly reduce output. (Alyousuf et al., 2023) suggest that integrating a dual-fed induction generator system into the transmission system can enhance wind turbine performance (Alyousuf & Korkmaz, 2023). Therefore, the maintenance of the wind firms is a great challenge and big issues to generate uninterrupted electricity. In a comprehensive review study, (Kou et al., 2022) discussed a wide range of maintenance of the offshore windmills including sea-sky monitoring, sea floor and surface monitoring, and power equipment monitoring of the wind firms (Kou et al., 2022).

Those monitoring processes monitor all sensors functionality and productivity, wind turbine sensors speed, and energy production rate. Those advantages can be achieved with condition-based maintenance technology from smart IoT devices and sensors to drive efficient economic outcomes in offshore and onshore wind. Predictive maintenance technology using IoT is an integrated approach to integrating sensor technology and information networks. Sensors are embedded inside wind power equipment, and these sensors are connected to an information network, and these data are uploaded to predict the health of the components. Data acquisition and cloud-based concepts enable multi-party communication and give maintenance decisions. The cloud-based concept shares data from multiple offshore wind farms between an offshore manufacturer and an offshore wind farm owner or between three parties and an offshore wind farm owner. The cloud-based concept will allow direct feedback to the system based on current wind power equipment health. Like IoT technology applied to other scenarios, IoT technology under maintenance consists of sensor layer, network layer and application layer.

4. TECHNOLOGICAL REQUIREMENTS CHECKLIST FOR IOT ENABLE DEVICES

To implement IoT across the wide range of sectors described in ***Section 3***, several technological requirements must be in place, as listed below:

1. Communication technologies: Communication technologies play a crucial role in gathering and exchanging information concerning the status of IoT devices. There are distinct standards for short-range and long-range communication technologies (Muslim et al., 2021). Short-range options encompass ZigBee, Bluetooth, and ultra-wideband technologies. On the other hand, long-range communication can be achieved through power line communications, optical fiber, wireless cellular networks like 3G and 4G, as well as satellite communications (Garg & Garg, 2018a; Khan, 2019; Muslim et al., 2021).

2. Data fusion techniques: Due to the constrained resources of IoT terminals, including limitations in batteries, memory, and bandwidth, transmitting all information to the destination is impractical (Mohite et al., 2023). Therefore, to enhance the efficiency of information collection, the utilization of data fusion techniques becomes essential. These techniques involve the collection and integration of data for more effective processing (Deshmukh & Bhuyar, 2019; Tan et al., 2019a).
3. Energy harvesting process: As the majority of IoT devices rely on batteries as a primary power source, the process of energy harvesting becomes crucial for IoT applications. This is evident in scenarios such as employing various sensors and cameras to monitor distinct components of an SG (Garg & Garg, 2018b).
4. Reliability: IoT applications operating in diverse environments must meet specific requirements, including reliability, self-organization, and self-healing (Muslim et al., 2021; Prasanna Rani et al., 2023; Woodhead et al., 2018). Consequently, the choice of an appropriate IoT device is essential to address environmental challenges. For instance, in situations where certain devices face energy constraints leading to data transmission issues, it becomes imperative to identify alternative routes to ensure the network's reliability meets the necessary standards (Mohite et al., 2023).
5. Operating in harsh environments: IoT devices deployed on high-voltage transmission lines and in substations are subjected to challenging conditions. Therefore, to prolong the lifespan of their sensors in such environments, it is essential to use sensors that are resistant to high or low temperatures, immune to electromagnetic interference, and waterproof (Kirmani et al., 2023; Sehrawat & Gill, 2019).
6. Security: Security measures should be integrated into every layer of the IoT infrastructure to secure the transmission, storage, and management of data, preventing information leakage and losses while ensuring data protection (Hameed et al., 2020; Woodhead et al., 2018).
7. Sensors: Sensors gauge various quantities such as current, voltage, frequency, temperature, power, light, and other signals, providing raw data for processing, transmission, and analysis (IoT Sensors Market Size Worldwide 2025 | Statista; Liu & Ansari, 2019a; Sehrawat & Gill, 2019).

In the very recent time, nanotechnology has been used to create sophisticated materials that adopt to diverse sensor applications, hence contributing to the growth of the sensor sector (Mohite et al., 2023; Sehrawat & Gill, 2019).

5. INTEGRATION OF RENEWABLE ENERGY IN IOT DEVICES TO BUILD A SMART GREEN PLANET

Over the past ten years, IoT has experienced widespread adoption worldwide, with a projected increase to over 125 billion interconnected devices by 2030 (Benhamaid et al., 2022; Garg & Garg, 2018a; Khan, 2019; Liu & Ansari, 2019a; Mishu et al., 2020; Misra et al., 2021). Typically, reliant on batteries for power, IoT devices face a significant limitation in terms of battery capacity. When these devices communicate with each other, they consume a substantial amount of energy, resulting in limited operational duration (Khan, 2019; Misra et al., 2021). The conventional approach of employing electrochemical batteries to power the extensive network of wireless IoT devices poses various challenges, including high maintenance costs and unavoidable environmental pollution. Consequently, there is a growing focus on energy harvesting, which utilizes renewable sources such as solar, wind, thermal, and vibrational energy to generate electrical power for IoT devices. This approach paves the way for the development of environmentally friendly IoT systems (Sanislav et al., 2021). Given these considerations, the ongoing advancements in energy harvesting technologies are crucial for integrating self-powered autonomous systems into IoT devices.

Energy harvesting (EH) involves gathering energy from various environmental or mechanical sources such as solar, wind, radio frequency, mechanical vibrations, body heat, and foot strikes and converting it into electrical energy that can be utilized (Elahi et al., 2020; Garg & Garg, 2018a; Sudevalayam & Kulkarni, 2011). The essential elements required for a functional energy harvesting system are typically: i) The energy source (Ambient/External energy), ii) The harvesting architecture (Mechanisms required for converting different energies into electrical

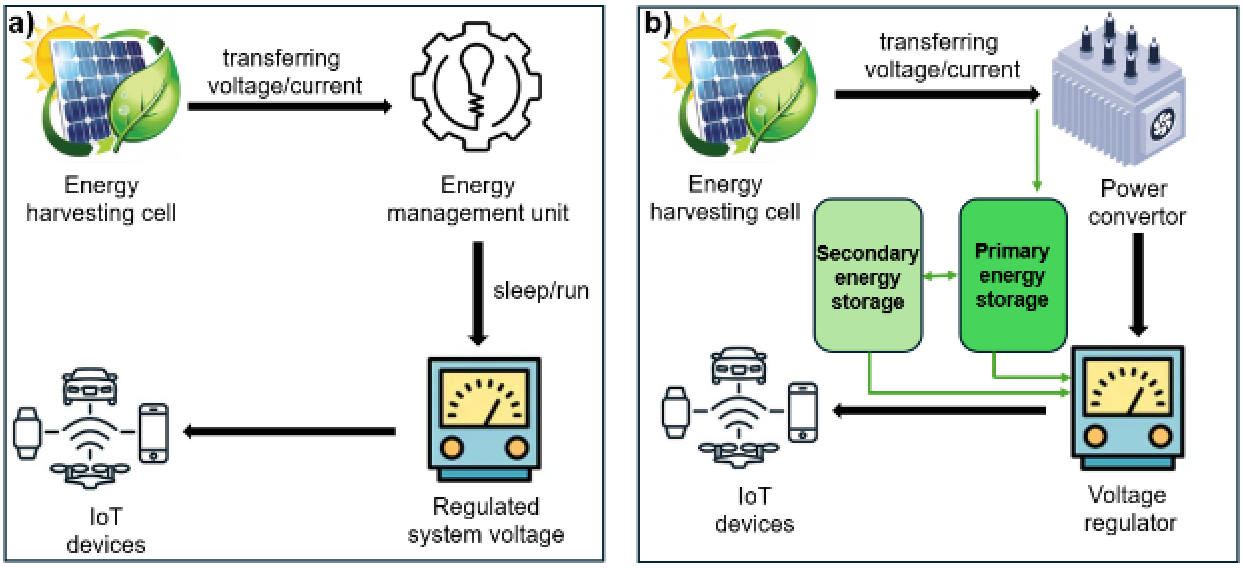

Fig. 9: Two different architectures to harvest clean energy for IoT devices; a) continuously generating energy and consumption, b) energy production, storage and use to enable IoT devices.

energy), iii) The load (The consumer) (Sanislav et al., 2021). The discussion in the reference (Sanislav et al., 2021; Sudevalayam & Kulkarni, 2011) covers a range of energy sources, their specific attributes, harvesting techniques, conversion efficiency, and their role in advancing environmentally friendly IoT systems. The different energy harvesting architectures are- a) Harvest and Use: The process of harvesting and utilizing energy involves the immediate collection and utilization of energy as soon as it is harvested as shown in Fig. 9a; b) Harvest-Store-Use: Energy is collected whenever it is available and then stored for later utilization as illustrated in Fig. 9b. This method ensures that energy is accumulated and preserved for future use (Mishu et al., 2020; Shirvanimoghaddam et al., 2019).

The ambient-based EHIoT can be classified into various subcategories. Among the popular ambient-based EHIoT methods are PV energy, thermal energy, piezoelectric mechanical vibration (MV) energy, pyroelectric energy, triboelectric MV energy, EMI-MV energy, microbial fuel cell (MFC) energy, radio frequency (RF), wind energy (WE), and acoustic energy (AE) (Mishu et al., 2020; Shirvanimoghaddam et al., 2019). Additionally, there are other energy harvesting techniques that involve utilizing small-scale environmental energy sources, such as microwave energy, acoustic energy, and vibration energy, aided by metamaterials (Mishu et al., 2020; Tan et al., 2019b). Furthermore, hybrid energy harvesting approaches, which combine multiple energy sources using hybrid harvesters, as well as single-source harvesters with hybrid mechanisms, have been developed to address the challenges of energy insufficiency and limited practical applications of individual energy harvesters (Costanzo & Venneri, 2020; Tan et al., 2019b). A potential solution to overcome these challenges addressed by (Liu et. al., 2019) (Liu & Ansari, 2019a). Authors proposed a dual-battery green energy harvesting architecture for IoT devices where two cycles of dual batteries are connected by a transceiver Fig. 10 to efficiently store the harvested energy for enabling IoT devices. In their

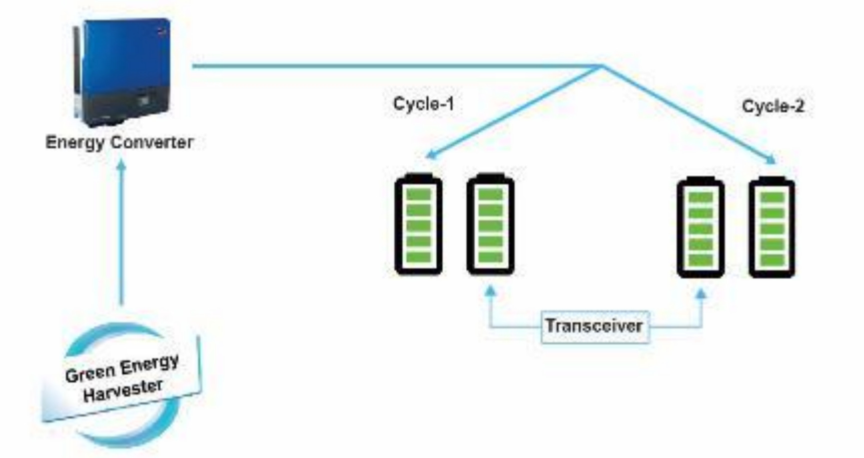

Fig. 10. EH process using a set of direct current battery system in two cycles using a transceiver.

proposal, the authors suggest equipping each IoT device with a dual-battery system, ambient energy harvester, energy converter, transceiver, and two antennas. This setup allows for the utilization of multiple types of ambient energy, with the possibility of integrating multiple ambient energy harvesters into a single IoT device. The harvested energy is converted into direct current (DC) by the energy converter to charge Battery 1, which serves as the storage for the harvested energy. Battery 2, on the other hand, discharges energy from the previous battery cycle to power the device. In the subsequent cycle, the roles are reversed, with Battery 1 discharging and Battery 2 harvesting energy. This arrangement ensures a continuous supply of green power (Liu & Ansari, 2019b).

In general, IoT devices are powered by batteries. As the lifetime of battery is limited thus, there is a strong need of self-powered devices or alternative sources of energy to continuously power the IoT devices. For the same purpose energy harvesting techniques are used nowadays. The energy harvesting sources are used to increase the lifetime and efficiency of the IoT system. The energy sources used for energy harvesting mechanism are either environmental sources like solar, wind, etc. or other energy sources like temperature difference, motion, footfall, breathing, etc. The natural and human environments are abounded with untapped sources of renewable energy, including mechanical energy, acoustic energy, electromagnetic energy, thermal energy, and more (Tan et al., 2019c). Advances in the creation of compact, low-power, portable, and remote devices have given rise to the incorporation of unconventional power sources over the last two decades (Safaei et al., 2019). Research into small-scale energy harvesting methods is highly beneficial for efficiently powering small wireless and mobile electronic devices like smartphones, cameras, chargers, watches, laptops, and more (Selvan & Mohamed Ali, 2016).

6. CHALLENGES OF IOT APPLICATIONS IN SMART SYSTEMS

Though the adoption of IoT enabled devices is increasing significantly worldwide, the following potential challenges need to be addressed to build a smart green planet.

6.1. Sensor energy management

The activation of sensors requires energy which may differ with the type of sensors. Therefore, a minimum range of electricity supply is necessary to maintain a sensors function. However, energy supplies fluctuate on many special occasions, for instance, during natural disasters, power cuts, and unwanted electricity shortage. In order to resolve the sensor issue, (Gaddam et al., 2020) describes several statistical and machine learning techniques to detect faults and anomalies in sensors (Gaddam et al., 2020). This study also describes the potential solutions of sensors problem using machine learning approaches (Gaddam et al., 2020). Additionally, some important protocol is also maintained for managing sensor data and energy consumption optimization as follows-

i. Energy-efficient data processing protocol: This protocol involves encoding data using techniques like Huffman Encoding to decrease energy consumption during data transmission (Idrees & jawad, 2023).

ii. Secure Edge-based energy management protocol: This special type of protocol is designed for electricity distribution in smart grid systems and correlation analysis to predict data forwarding process. This protocol combines ML techniques to enhance energy efficiency and secure data management (Rehman et al., 2022).

iii. Data-driven decision making: Utilizing IoT sensor boards, stakeholders can adopt data-driven decision-making procedures to increase energy efficiency, lower operations costs, and create a more sustainable energy environment (Arshi et al., 2024).

6.2. Energy management

A significant amount of energy is required to operate IoT systems and transmit the large volumes of data generated by IoT devices (Motlagh et al., 2020). Consequently, relying solely on a single battery as the power source for IoT systems is no longer practical. To address this challenge, a hybrid system combining renewable energy sources and batteries can offer sustainable and long-lasting power. However, implementing such a system necessitates new circuit architectures capable of managing multiple power inputs efficiently (Chatterjee et al., 2023). To achieve energy-efficient communication protocols, radio optimization techniques like modulation optimization and cooperative communication, as well as energy-efficient routing techniques such as cluster architectures and multi-path routing, can be employed (Motlagh et al., 2020). Low-power IoT devices can benefit from 6LoWPAN, a protocol that supports their power consumption requirements (Kolhe et al., n.d.). Furthermore, enabling DC-DC power converters into power management units placed between the power sources and IoT devices enables maximum energy efficiency. These converters regulate input voltage to achieve the desired output voltage and employ maximum power point tracking control to ensure that the sources operate at their peak power level (Chatterjee et al., 2023).

6.3. Technological challenges for the IoT

The central idea of the IoT is to establish connections between various objects, regardless of time and location, using the Internet. This necessitates the assignment of unique identities to an enormous number of devices. Therefore, the Internet becomes a significant concern for IoT.

Moreover, the successful implementation of IoT relies heavily on technologies such as Wi-Fi, Cloud Computing, Mobile Computing, Ad hoc Networking, GPS, and others (Čolaković & Hadžialić, 2018b, 2018a; Gupta & Quamara, 2020a, 2020b; M. M. Hossain et al., 2015; Huang et al., 2019). The technological challenges faced by IoT in terms of energy systems encompass several aspects: i) ensuring fault tolerance and efficient device discovery; ii) addressing interoperability and the complexity of software systems; iii) establishing stable power supply solutions; and iv) effectively managing and interpreting the vast volumes of data generated. These factors are crucial for the proper functioning of IoT devices and must be appropriately addressed (Ahmad & Zhang, 2021; K. R. Hossain et al., 2023; M. M. Hossain et al., 2015; Mohammed & Ahmed, 2017).

6.4. Entity-based challenges and security risks of IoT devices

Protection is essential for hardware, software, and data in IoT systems. Hardware devices, including servers and mass data storage devices, are susceptible to physical damage from natural disasters or targeted attacks such as Node Tampering, Malicious Code Injection, Malicious Node Injection, and Sleep Deprivation Attacks (M. M. Hossain et al., 2015; Liu & Ansari, 2019a). On the other hand, software attacks such as Social Engineering, Viruses and Trojans, and Phishing Attacks can compromise device functionality and manipulate data. Additionally, the management of large volumes of data generated by devices, known as Big Data, requires lightweight data handling techniques, which remain an area of ongoing research (Chaudhary et al., 2019; Čolaković & Hadžialić, 2018b; Gupta & Quamara, 2020b). To resolve the security issues of IoT devices user can take some necessary steps including-

i. Regular firmware update: This will enable automatic updates of the operating system that can help maintain security without manual intervention (Cohen, 2023).

ii. Network segmentation and user secure networks: Network segmentation prevent potential attacks from spreading and this isolation helps contain any breacher. Plus, secured and encrypted network gives extra layers of security to the IoT devices.

iii. Implement AI and ML: These technologies can help in predictive threat detection and automated responses to potential vulnerabilities (Owen, 2024).

6.5. Standardization and interoperability

Various vendors introduce devices with different technologies that may not be familiar to everyone. It is crucial to establish a standardized mechanism to ensure interoperability among all physical and sensor devices (Chen et al., 2014). Interoperability is a critical challenge that spans across layers, including physical, device, communication (protocols and spectrum usage), function, and application layers. A comprehensive approach is needed to address and resolve the standardization and interoperability issues of IoT devices and services at multiple layers (Mehta et al., 2018).

6.6. Architectural design and big data processing

When multiple IoT technologies are integrated into a power system, the expectation is that these technologies will facilitate seamless communication irrespective of the complexity of their architectural design, distribution, and mobile characteristics (M. M. Hossain et al., 2015; Liu & Ansari, 2019a). In many instances, this necessitates the use of heterogeneous reference architectures, allowing consumers the flexibility to employ varied end-to-end IoT communication solutions (Mishu et al., 2020). As the scale of an energy system increases, so does the volume of data that requires processing within the system. This poses a significant challenge for IoT-based power systems, which need the capability to process, analyze, and store both current and historical data to make informed future plans. To address this issue, Stojmenovic proposed a localized data processing technique that involves processing local data in conjunction with state information from main servers and neighboring servers (Giordano & Stojmenovic, 2004). Another approach involves the use of a Big Data architecture, where knowledge extraction is performed on the extensive data, and the data is categorized into different levels based on their priority of use (Khan, 2019; Mohite et al., 2023). Following the extraction of valuable insights from big data, the energy system should be able to further classify the information and offer specific services, such as transmitting signals to actuators or sensor systems. For instance, in smart energy systems (SES), data gathered from heat consumption and electricity can be categorized according to customer types (domestic or industrial), with each consumption level further classified into off, standby, and active operation modes. This underscores the introduction of a big data architecture (Adi et al., 2020; Garg & Garg, 2018b; Prasanna Rani et al., 2021).

7. RECENT ADVANCES IN IOT TO ENTER A SMART GREEN PLANET

7.1. Machine learning in IoT

Common IoT devices used in our daily lives include smartphones, home assistants like Google Play, smart vehicles, building automation systems (e.g., smart elevators and temperature control), and unmanned aerial vehicles such as drones for environmental monitoring and leisure activities (Benhamaid et al., 2022; Khan, 2019; Misra et al., 2021; Woodhead et al., 2018). The widespread use of IoT devices extends to back-end cloud storage centers that handle a large volume of generated data (Khan, 2019). This data requires processing techniques like knowledge discovery and machine intelligence to extract meaningful insights (Adi et al., 2020). The data generated from different IoT applications, such as smart healthcare, social media, e-agriculture, e-health, smart grids, and smart vehicles, exhibit heterogeneity based on the specific

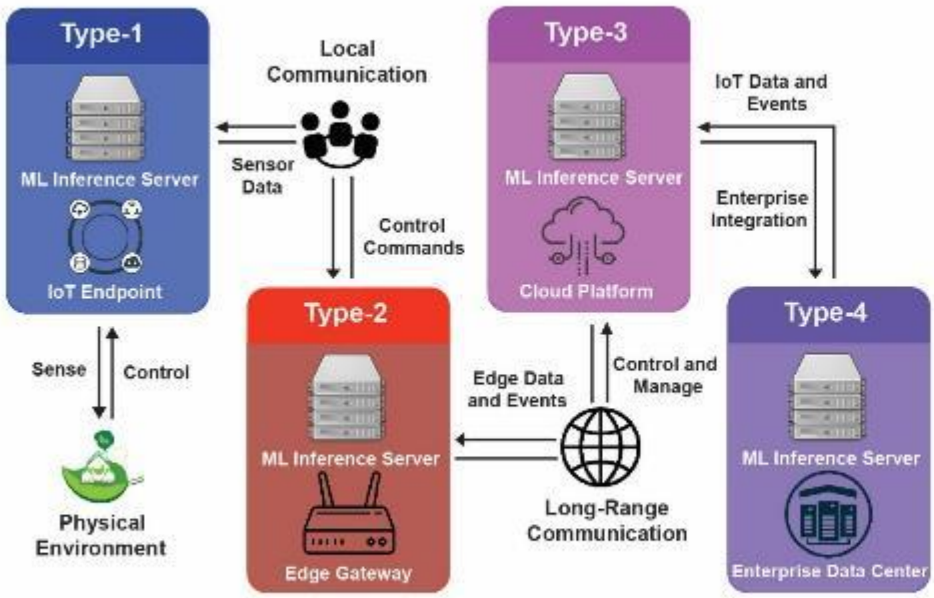

Fig. 11. Four different Machine learning interface server integrated to IoT enable devices for wide range of application including environmental monitoring, local communication, and long-range communication

domain (Zantalis et al., n.d.-b, 2019). IoT devices are designed with custom protocols to accommodate their resource-constrained nature and minimize power usage. Common IoT application-layer protocols include CoAP, MQTT, AMQP, and HTTP (Nafees et al., 2022; Zantalis et al., n.d.-b, 2019). CoAP is lightweight and suited for resource-constrained devices, while HTTP is more resource-intensive and suitable for high-end IoT devices with advanced capabilities. IoT devices generate a significant amount of data, which is processed locally to some extent and then transferred to centralized computing nodes or cloud storage facilities for further analysis (Adi et al., 2020; Nafees et al., 2022). Machine learning (ML) plays a crucial role in automating the analysis of IoT data, as it involves techniques for analyzing data and building models without extensive human intervention (Adi et al., 2020; Nafees et al., 2022). For instance, different ML servers collected data from specific IoT enable devices to analyze and provide meaningful feedback to the users. Fig. 11 displays four major types of ML servers (Type-1 to Type-4) connected to the IoT devices for processing multi-dimensional big data analysis and providing continuous feedback to users according to their desire. Type-1 server collects data from environment and processed them in association with digital sensors to local communities, and Type-2 server controlling that command accordingly with the help of an edge gateway. This processed data typically used for long-range communications, and then the data will be stored in a cloud storage in Type-3 server and Type-4 afterward in a broad spectrum named enterprise data center.

However, human intervention is necessary to analyze the collected data, extract valuable insights, and develop intelligent applications. To address this requirement, the concept of Cognitive IoT (CIoT) emerged, aiming to make IoT devices autonomous and capable of making context-based decisions and learning from collected data (Hussein et al., 2022; Thapa et al., 2022). Thapa et al. (2022) conducted a study to assess the efficiency of CIoT in processing mental healthcare wellbeing data (Thapa et al., 2022). This study yielded significantly positive results, demonstrating the effectiveness of CIoT applications in this field (Thapa et al., 2022). Additionally, by incorporating ML algorithms into IoT infrastructure, significant advancements can be achieved in applications and the overall infrastructure itself (Adi et al., 2020). ML can optimize network performance, mitigate congestion, optimize resource allocation, and facilitate real-time or offline data analysis for informed decision-making (Nafees et al., 2022; Zantalis et al., n.d.-b, 2019). Furthermore, as the number of devices increases, so does the volume of collected data, resulting in the common occurrence of Big data in IoT applications. Conventional databases are insufficient for handling such massive amounts of structured and unstructured data, necessitating specialized infrastructure and techniques. ML algorithms like Ensemble and Artificial Neural Networks offer efficient approaches for processing and analyzing big data, as discussed in the following sections (Zantalis et al., n.d.-a).

7.2. Blockchain in IoT

A blockchain consists of blocks, each containing transaction details, hash values of the current and previous blocks, and a timestamp (Rana et al., 2022; Singh et al., 2020). Decentralized storage, utilized by blockchain, is a method of storing large amounts of data by linking each block to the previous one through smart contract code (Singh et al., 2020). The Interplanetary File System (IPFS) is a decentralized and distributed database that connects different nodes to transfer common files. Blockchain technology leverages IPFS for IoT applications requiring high throughput and utilizes a combination of internet-connected devices, sensor accessories like RFID, and knowledge-oriented data collections.

IoT involves interconnected devices communicating with each other over the internet (Khan, 2019; Misra et al., 2021). However, the substantial volume of data generated by IoT poses challenges related to security vulnerabilities, privacy, and fault tolerance. To address these challenges, researchers propose the use of blockchain technology in IoT. Blockchain-based techniques provide a decentralized and distributed architecture that enhances security, privacy, and fault tolerance (Rana et al., 2022; Singh et al., 2020). However, it should be noted that these techniques may also consume significant energy, incur computational overhead, and introduce delays. By integrating blockchain and IoT, a holistic approach can be achieved, enabling efficient data management and addressing development complexities. The integration of blockchain and IOT finds applications in various fields such as smart homes, smart cities, healthcare, and agriculture. This integration offers a peer-to-peer network for authentication and robustness against attacks.

However, blockchain technology alone does not completely resolve privacy issues in IoT. To overcome this limitation, AI technology is employed through various techniques that focus on controlling personal information, ensuring secrecy and intimacy, and managing information dissemination. By applying artificial algorithms to the data stored in the blockchain, the throughput rate of devices can be analyzed, and attackers can be categorized as either informed or malicious (Singh et al., 2019).

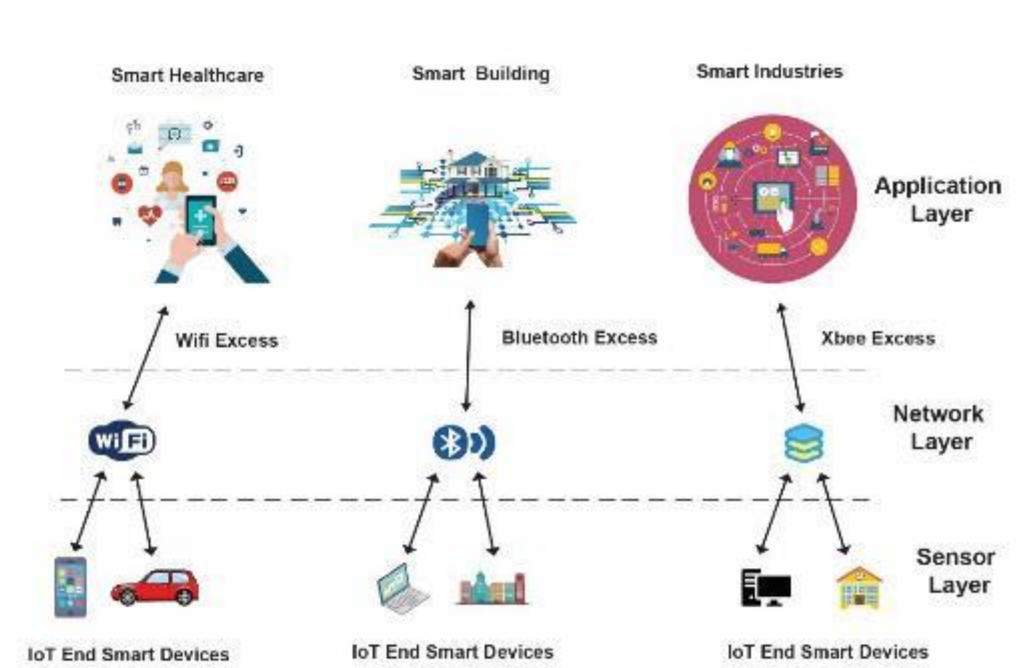

Fig. 12. The blockchain functional diagram with the integration of IoT enable devices, break out the working mechanism in three separate layers; sensors layer directly integrated to the IoT smart devices and connected to the network layer by Wi-Fi or Bluetooth. Network layer then allows enabling IoT devices command in a smart system (smart healthcare, smart building, or industries).

7.3. IoT in e-waste disposal

Electronic waste, commonly known as e-waste, refers to discarded white goods, consumer and business electronics, and IT hardware that has reached the end of its useful life (Chakraborty et al., 2022; Parab & Pandey, 2021a). It encompasses a wide range of electronic products, including household appliances like refrigerators and air conditioners, mobile phones, stereos, computers, and other consumer electronics (Chakraborty et al., 2022; Ramanujam & Napoleon, 2020a). The disposal of e-waste has become a pressing issue, as it poses significant environmental and health risks (Ahmed et al., 2023; Chakraborty et al., 2022). Utilizing IoT technology is demonstrated in the case of an e-waste inverter made from scrap materials, which shows significant success in e-waste management, reported by (Parab and coworker, 2021) (Parab & Pandey, 2021a). This inverter operates using two power sources: the main electric current and solar panels. When sunlight is insufficient to charge the inverter, it automatically switches to the main power supply, thereby conserving energy. The entire inverter is connected to an IoT source, which enables monitoring of its components and measurements of power output, temperature, humidity, voltage, current, and power factor. These parameters can be used to assess the inverter's lifespan and its operational capabilities (Parab & Pandey, 2021a). By combining e-waste, solar energy, and electronic circuits with IoT technology, we can revolutionize the way we think about production. This approach allows us to reduce waste, promote reuse, and enable effective surveillance. It challenges conventional thinking by bridging the gap between renewable and non-renewable resources, encouraging the use of older power supplies alongside newer components. This method fosters cooperation between different resources and challenges established terminology in the production industry (Farjana et al., 2023; Parab & Pandey, 2021b). Farjana et. al. (2023) propped a data-driven decision making process for smart e-waste management system integrated to the IoT enable devices (Farjana et al., 2023).

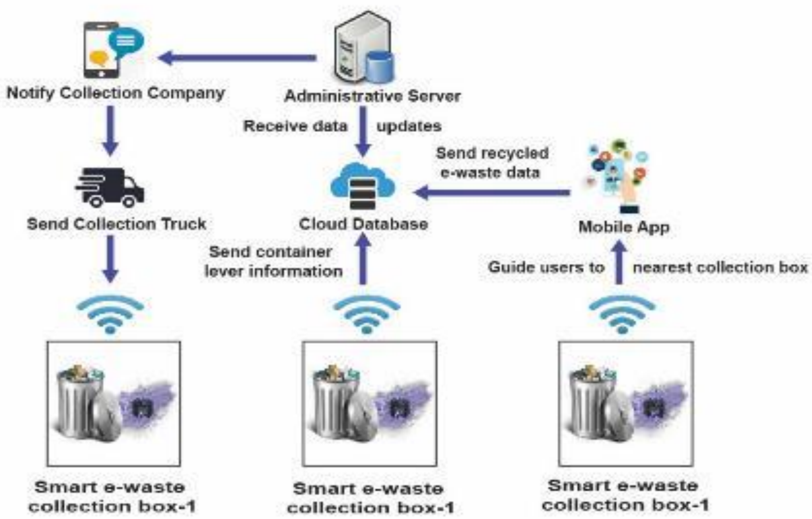

Fig. 13: Flow diagram of smart e-waste collection process using IoT enable devices through administrative server connected to the wireless internet. Redrawn from (Kang et al., 2020).

The working principle Fig. 13 of smart e-waste management heavily relies on signal processing from an IoT-enabled circuit installed in a trash bin. This circuit communicates with a smart device (such as a mobile phone, computer, tablet, or iPad) to notify the waste collection company when it is time to collect the waste (Farjana et al., 2023; Parab & Pandey, 2021a; Ramanujam & Napoleon, 2020a). Fig. 13 displays the signal processing from trash bin to the server and the processed data is stored in a cloud database to distribute users IoT device for the proper management of the e-waste. Tracking e-waste brings several advantages, as better remote monitoring can enhance the accuracy of e-waste data. Recognizing the need for a scientifically based approach to improve information on e-waste streams, there is a growing realization for integrating environmental considerations into IoT standards (Ramanujam & Napoleon, 2020b).

8. GAPS AND FUTURE RECOMMENDATIONS

Environmental pollution from burning fossil fuels is significantly increasing, contributing to global warming and hindering efforts to build a green world. In this context, the production and use of renewable energy offers a beacon of hope, providing pathways to reduce carbon emissions. The application of renewable energy to enable IoT devices is driving revolutionary changes, paving the way for a smart planet where operations are managed remotely through voice commands, hand gestures, and facial recognition. However, integrating renewable energy with IoT devices requires appropriate control measures to ensure a successful transition to a smart green world. Proper integration is essential for accurate data processing and user command control. The successful integration of renewable energy with IoT devices yields several clear benefits, such as:

a. Enhanced energy efficiency, cost savings, and improved resource management;

b. Increased reliability and stability, including grid stability and the resilience of IoT enabled systems

c. Accelerated data-driven decision-making through faster optimization of signals and commands, providing valuable analytics and insights from desired the smart system;

d. Enhanced user experience in controlling smart systems (i.e., homes, industry, transportation, and traffic signal) by managing energy use and enhancing comfort and convenience;

e. Scalability and flexibility due to modular and low cost IoT devices and flexible settings.

However, the integration process of renewable energy to the IoT devices depends on several factors, including architectural design, sensor quality, location of the desired smart system, energy distribution flexibility, and user demand. This study thoroughly discusses the existing integration techniques, technological requirements for IoT devices, and the application of ML, highlighting their advantages, disadvantages, and acceptability. Some renewable energy sources offer high electricity generation rates, and reliability, whereas others may not be available in a specific region of the world. For instance, many countries in South-east Asia lack the wind firms needed to generate electricity. Likewise, some IoT devices require minimal energy, and low-sensitivity sensor to operate, while others are highly sensitive, require precise handling, and have complex circuitry, leading to significantly higher electricity consumption. The recent incorporation of ML in controlling IoT devices has significantly enhanced their performance by cutting down electricity consumption and improving the accuracy of signal processing in response to user command. Furthermore, innovative new technologies are expected to contribute more to successful exploitation of renewable energy, paving the way for a smart green world. Finally, further research is necessary to fully leverage ML and deep learning in IoT devices systems to enhance performance and achieve better outcomes for building a smart system and a smart planet.

9. CONCLUSION

Our research concludes that due to globalization and the massive expansion in the use of electrical devices, millions of IoT devices are being adopted each year. This widespread adoption necessitates appropriate technological advancements to successfully integrate renewable energy with IoT devices, thereby reducing carbon emissions and environmental pollution. Our concern prompted an investigation into potential renewable energy sources, their global availability, and their electricity production capabilities. The findings indicate that solar energy is the most accessible and has the highest output for electricity generation, though other sources also offer viable options with some overlooked drawbacks. We thoroughly examined the role of IoT-compatible sensors and market trends to understand the global demand for IoT adoption in building smart systems (e.g., smart homes, smart cities). The widespread adoption of millions of IoT devices raises the question of how to efficiently integrate renewable energy to power these devices without relying on fossil fuels. Consequently, we explored the technology involved in renewable energy electricity generation and the integration of IoT to upgrade conventional systems to smart systems such as smart grids, smart solar power plants, and smart wind farms. Smart systems offer numerous advantages, including remote operation, reduced system losses, controlled energy consumption, precise energy production with minimal error, and high flexibility. However, maintaining a smart system can be challenging. Ensuring that IoT devices meet specific technological requirements, such as data protection and security, data fusion techniques, communication ranges, and compatible sensors, could streamline this process and enhance efficiency, offering greater control over smart systems. Energy harvesting and storage capacity are crucial for integrating renewable energy with IoT devices to create a smart green world. Energy harvesting cells play a critical role, as any damage to these cells could disrupt the energy supply to IoT devices, leading to system failures. A dual battery green harvesting system could mitigate this issue. Although IoT offers numerous applications for building smart systems, several challenges need addressing to fully leverage this technology. These challenges include sensor energy management, technological and architectural obstacles, big data processing, and interoperability. To address these challenges, machine learning (ML), deep learning, and cloud computing can significantly enhance the integration of renewable energy with IoT devices and improve device efficiency. ML, in particular, can revolutionize IoT by providing greater system control and faster data processing. Exploring hybrid technologies, such as combining ML and deep learning, is essential for enhancing IoT device performance, ultimately transforming our world into a smart, green planet powered by renewable energy.

AUTHOR CONTRIBUTIONS

Mr. Shojib Mia prepared an initial draft and figure panels of this this study. Mr Firoz Ahmed developed the ideas, supervised the work, prepared and polished the manuscript at every stage of writing. Mr Md Imamul Kabir, Ibrahim Khan, Mehedi H. Roni, Anjuman Ara Khatuna, Khadijatul Cobra, and Shahriar Mahmud conducted the initial literature review, proofread the drafts, and assisted in preparing the early draft and figures.

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CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper. All authors have contributed to the work reported, have read and approved the final manuscript, and have agreed to be accountable for all aspects of the work.

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