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Eco-friendly innovation: green energy empowered by IoT

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ABSTRACT

Energy demand is high globally, impacting daily life and promoting sustainable modernization. Goal 9 aims to build an elastic framework for economies, while Goal 15 of the Sustainable Development Goals (SDGs) emphasizes the preservation of terrestrial environment, sustainable woodland management, and biodiversity conservation. The International Energy Agency predicts a significant increase in global renewable capacity, with solar PV being two-third of this growth. Green technology is crucial to combat global warming and Industry 4.0, a digital transformation that aims to create a strong framework for sustainable modernization. The growth of the smart grid is vital, involving energy sources, control techniques, computation, generation, transmission, distribution, and more. Supercapacitors store and deliver energy at high capacity, while green energy transforms fossil fuels into eco-friendly sources using natural resources like hydro, solar, wind, thermal, and biomass. This study explores the efficient use of microprocessors in solar and wind energy, as well as the application of actuators in the green energy sector. Green energy is a sustainable solution to increasing energy needs, reducing dependence on fossil fuels. IoT technologies, including sensors, actuators, microprocessors, and microcontrollers, are used in energy generation, transmission, distribution, and composition.

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1. INTRODUCTION

The agenda of United Nation is to make sure that there is entrance to economical, dependable and contemporary energy service universally till 2030. It also ensures that the improvement in the energy efficiency should be double. The energy demand across the world is very high as it has a crucial role in the routine life of a human being. Goal 9 seeks to build elastic framework, assist sustainable modernization and encourage alteration. Economies having a wide-ranging industrial sector and a well-built structure suffer less destruction and are undergoing speedy recovery. In 2021, worldwide manufacturing spring back from the pandemic, though the recovery remained partial and irregular [1]. Goal 15 of the Sustainable Development Goal (SDG) talks about the preservation, re-establishment, and encouragement of justifiable use of terrestrial environment, sustainable supervision of woodland, combat degradation, land degradation, and loss of biodiversity [2]. The International Energy Agency predicts a significant increase in universal renewable capacity, reaching over 440 GW by 2023, with solar PV capacity accounting for two-thirds of this growth [3]. As there is an increase in the global warming due to the emission of harmful substances, the implementation of green technology is much needed. Industry 4.0 is a digitally transforming innovation which has a significant place in the assistance of organizations and community in working as regards to establish strong framework with sustainable modernization [4]. For the sustainability of the society, we need green energy so that it does not have any negative impact. The main aim of such invention is to ease the work of every individual so that speedy work can be done. The growth of the smart grid is thoroughgoing and is vitally important across the world. It required and demonstrate with multifaceted areas like energy sources, control techniques, computation, generation, transmission, distribution, individuals, functioning, markets, and service provider [5]. Industry 4.0 has achieved the mass production at minimum cost via revolution, cheaper cost, greater reaction to consumer requirements and alternative towards on-demand production [6]. Energy plays a major role in the standard of an individual's life that also impacts the social and economic development [7]. Delivery technologies like supercapacitors store and deliver energy at extremely high amount and offers high conductivity in a short span of time. Electrochemical storage device, sometimes called an ultra-capacitor is the categorization of supercapacitor [8]. Green energy is the transformation of energy basically derived from fossil fuel so that an environment friendly power source is created. In order to generate power, there are many natural resources used like thermal, hydro, solar, wind energy, and biomass. Most importantly, the green energy does not emit any kind of harmful substance which is dangerous for animal or human life.

The key contribution of this study is as follows: i) to explore the effective implementation of various sensors and microprocessor/microcontrollers in green energy sector; ii) this study the role of microprocessors in solar and wind energy; and iii) the explore the applicability of the efficient use of actuators in solar, wind, and hydro energy. The organization of this review article is carefully structured to present a coherent and systematic exploration of IoT-enabled innovations in the green energy sector. Section 2 outlines the methodological framework employed for the review. It details the approach used to identify, select, and analyze relevant academic and technical literature. Section 3 offers an in-depth discussion on the critical role of internet of things (IoT) technologies in enhancing the performance, efficiency, and sustainability of green energy systems. It explores how sensors, microprocessors, and actuators are applied across various renewable energy domains—including solar, wind, and hydro power—to enable intelligent monitoring, real-time data acquisition, system automation, and adaptive control. Section 4 presents the concluding remarks of the article. It synthesizes the key findings from the review and reiterates the importance of IoT in driving innovation within the renewable energy landscape. The structural flow of the article and the interconnection of its sections are visually represented in Figure 1, which serves as a schematic guide for readers navigating the thematic progression of the content.

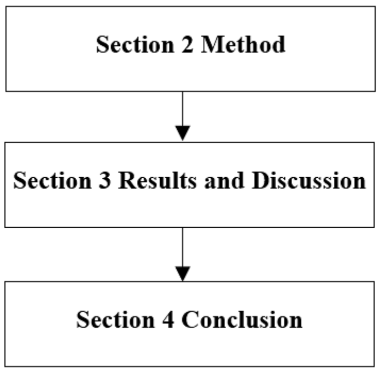

Figure 1. Organization of the article

2. METHOD

This review article adopts a systematic and thematic literature review methodology to explore the integration of sensors, microcontrollers/microprocessors, and actuators in the green energy sector, with a specific focus on solar, wind, and hydro energy applications. The objective is to consolidate, categorize, and critically evaluate the state-of-the-art technological interventions that enhance the efficiency and sustainability of renewable energy systems. To achieve the outlined objectives, a comprehensive literature search was conducted using well-established scientific databases, including IEEE, ScienceDirect, Scopus, Springer, and Google Scholar. Keywords such as "sensors in renewable energy," "microcontrollers in solar energy," "microprocessors in wind systems," and "actuators in hydroelectric systems" were used to filter relevant publications. The inclusion criteria were limited to peer-reviewed journal articles, conference papers, and high-impact technical reports published between 2010 and 2025. The selection was refined to ensure a focus on practical implementations, real-time systems, and efficiency improvements in renewable energy sources. The review was structured into three main thematic areas aligned with the study's objectives: i) implementation of sensors and embedded systems in green energy technologies; ii) role and performance of microcontrollers and microprocessors in solar and wind energy systems; and iii) integration and optimization of actuators in solar tracking, wind turbine control, and hydro gate automation. Each thematic area was analyzed for design architecture, energy efficiency improvements, real-time data acquisition, cost-effectiveness, and adaptability to varying environmental conditions. To ensure a balanced evaluation, both hardware- and software-centric approaches were examined, including control algorithms, embedded programming techniques, wireless communication protocols (e.g., Zigbee, LoRa, Wi-Fi), and power management strategies. Case studies, commercial implementations, and prototype results were synthesized to provide a realistic overview of current capabilities and future trends.

This methodology identifies technological gaps, trends, and improvements in green energy ecosystems, guiding researchers, engineers, and policymakers in selecting and deploying sensor-actuator-microcontroller systems in the evolving landscape of IoT [9]. Sensors, actuators, and vision-based devices contribute to perception surface, significantly influencing economic growth and development. IoT, engineering division, combines millions of small-scale items for collective goals [10]. There are many devices which can work smartly and communicate wirelessly. There is a rich connection of environment to machine as the infrastructure of internet is developed worldwide. It leads to massive amount of data being propagated that is simultaneously converted into useful decision making and actions so that our lives can be simpler and safer [11]. Due to the arrival of various IoT application, the utilization of IoT is also growing rapidly. The analysis of intersection of IoT and green energy innovation is done examining the existing literature from the trusted publishers such as IEEE Xplore, Google Scholar, Springer, ScienceDirect, and others using keyword related to IoT and green energy, such as smart grids, renewable energy, and IoT based energy management. Studies were selected on the basis of its relevancy towards our topic. Data extraction is also done which focuses upon IoT technologies, energy systems, and sustainability outcomes. Quality assessment was made on methodology, data reliability, and impact of the article reviewed while taking a look upon the limitations of our study.

3. RESULT AND DISCUSSION

Internet of things (IoT) helps to resolve the problems by avoidance of procedures and preservation of the security, stability, regularity and environmental accessibility of the power system [12]. Such technologies are designed in such a way that they amalgamate multiple energy sources like hydro, coal, gas, oil, nuclear, wind, solar, geothermal, and marine power so that the presentation shot can be strengthened and the influential and unchanging safety of the power system can be preserved [13]. High complexity is needed for the incorporation of IoT and massive data packaging while uplifting the performance at autonomy levels. There must be an established balance between complexity and performance. There are several types of classification of the energy storage devices like microscopic prevalence management, bulk energy time shifting, frequency stability, and power reliability [14].

3.1. Sensors

For enable the IoT, the sensor is the key. There are distinct types of sensors that exist for developing for various application purposes. Sensors like temperature sensor, light sensor, passive infrared sensors, and proximity sensor. Temperature sensor is the most essential and ordinary element in the environmental framework of temperature. In this sector, the fundamental theory of power production is the procedure for switching mechanical energy into electrical energy, such as mechanical energy is gained from heat energy, e.g., thermal power plants, wind, water flow, and solar power plants. Such energy transformations are acquired by utilizing thermal energy, i.e., temperature. When the temperature changes during normal operations, temperature sensors are used to accelerate the presentation. For example, in order to save energy, timings for switching the ventilation and cooling system are acknowledged by the temperature sensors [15]. Light sensors are utilized to compute luminance (ambient light level) or the illumination of a light. For the application of energy, light sensors are being utilized for various purposes in industrial as well as in household applications. As in the buildings, the main source of energy is related to lighting, it accounts for nearly 15% of total electricity usage [16]. Passive infrared (PIR) sensors are the best sensing model, reporting "detected" when a person is detected within the detection area, with a practical model incorporating time delay [17]. Proximity sensors in wind turbines provide reliable position sensing through blade pitch control, yaw position, rotor and brake position, brake wear monitoring, and rotor speed monitoring [18].

3.2. Actuators

An indispensable constituent of physical system that enables fluctuation by transforming one energy source to another is an actuator. It generally converts electrical, air, or hydraulic energy into mechanical forces [19]. Actuators help to ensure the transformation of renewable sources into beneficial things. Rotary to linear movement is attainable by applying a mechanical communication unit, known as linear motion actuators, that have greater perfection than rotary actuators as they are concise in measurement, and convenient to operate in most of the programs such as solar tracking systems [20]. Linear actuators and rotary actuators track solar energy. Using linear actuator single-axis tracking is attainable where the tracking of the solar panel is confined to daily movement of the sun [21]. As the season changes, the sun also changes its position and the panel cannot change its titled spot [22]. Two actuators, utilized in representation, are also known as a two-axis tracker, where two self-sufficient machines (or actuators) secure movement through an axis: one amounting to the azimuth angle and the other to the altitude [23]. The uniform motion accompanied by a bar operation discusses the ‘roll’ axis that discovers the utilization for the gathering of photovoltaic mechanisms and two dissimilar heliostat-based tracing techniques are considered [24]. The sun’s movement is tracked by rotary actuators or linear actuators at the heliostat mirrors so that maximum sunlight can be reflected by proceeding by rows of horizontal mounted mechanical shutters, so that rotary motion can control and regulate the reflecting beams of the sun according to the required heat [25]. In the residential areas the development of traditional wind turbines is unproductive due to slow wind velocity (<5 m/s). That’s why, in order to capture energy adequately, new geopolitics of transformers are required to handle accordingly in low wind speed system [26]. The use of wave energy is far stronger than other sources for creating electricity, as the energy abstracted from ocean waves is a hydraulic process which results in radiation wave phenomena. The low occurrence of wave undulation, unmethodical wave, and high-force vibrations make it difficult to convert wave kinetic energy to smooth electrical energy [27]. PTO, a device popularly known as power take off helps the linear motion of the rod to change into usable power [28]. There is a major contribution by the hydropower for building clean, low-carbon, safe, and energy-efficient system as it is the most paramount clean and green power source [29]. A micro-pump hydro-energy repository which consist of two reservoirs of 150 m^3 with 100 m height discrepancy, 100 Ah battery bank, and 18 kW solar PV is a small hybrid system project which has been implemented [30]. In order to generate energy, the regulation of the flow of the water through turbine is necessary. Actuators controls the location of the turbine blades so that they can be used efficiently. On the basis of generation of installed electrical capacity the hydropower plants are categorized into large hydro (>10 MW), small hydro (<10 MW), mini hydro (<1 MW), micro hydro (<100 kW), and pico-hydro (<5 kW) whose estimation is that around 10% of universal hydropower is originated from power plants with less than 10 MW of capacity [31].

3.3. Computing platform – uP/uC

ATMega 2560 is connected with sensors and wifi module that effectually presents the value of current, voltage, and power produced by solar panel. NODE-MCU ESP8266 functions as a prime processing factor in this particular system that is advanced by ESP8266. This is a type of microcontroller on single board which could be organized utilizing the NODE IDE. Solar panel (20 W) functions as the main power source of the system. For industrial and domestic purposes, electricity is created by trapping the sunlight, also known as solar energy that uses solar panel to evaluate current, voltage, and temperature. A very vital job is performed by these solar panel for such setups [32]. A comparative analysis of several parameters related to energy transmission and distribution used in different studies is summarized in Table 1.

Table 1. Comparative analysis of different parameters used in energy for its transmission and distribution

Parameters	[33]	[34]	[35]
Sensors	• Temperature and humidity sensors • Light and passive infrared (PIR) sensors • Proximity sensors	• Anaerobic wastewater treatment • Sludge drying moisture - high transmittance, low water sun radiation • Heat pump - energy saving, emission reduction, pollution prevention	-
Actuators	• Pneumatic actuators • Hydraulic actuators • Thermal actuators • Electric actuators	-	-
Microprocessors	-	• Pumps • Aeration	• PV unit (PU) • VAWT unit (VU)
Microcontrollers	-	-	• Hybrid smart control unit (HSCU) • Li-ion battery unit (LBU)

Table 2 illustrates the technological benefits and key features of core IoT components—sensors, actuators, and microprocessors—highlighting their efficiency, power optimization, and compatibility with modern energy systems. As shown in Figure 2, a room is equipped with smart thermostat. As soon as someone enters the room, the temperature sensor in the thermostat detects change in room temperature. A tiny unit called a thermistor, a type of resistor whose electrical resistance varies with temperature helps in the working of the sensor. The temperature of the atmosphere is measured by the sensor. If the room is cooler than the desired temperature set on the thermostat, then the resistance decreases. This change in resistance is then converted into an electrical signal by the sensor. The desired temperature is checked by the sensor. If the measured temperature is higher than the desired temperature, the thermostat will activate the cooling system to lower the room's temperature. This process continues as the sensor continuously monitors the room's temperature, ensuring it remains within the desired range set by the user.

Table 2. Technological benefits

Technology	Benefits	Features
Sensors [36]	• Very cost effective as well as consumes less power. • Performs various tasks like data sensing, computation, data storage and many more.	• The management is done by rechargeable batteries and super-capacitors. • The batteries are for storage classes, which are charged by the internal chemical reactions.
Actuators [37]	• Reduces energetic and peak power requirements.	• Power could be maximized under any circumstances.
Microprocessors [34]	• Feasible to use with modern power electronics.	• Generates a definite torque.
Microcontrollers [32]	• compact micro devices.	• embedded systems and controlled in various electronic gadgets.

In a smart house where the temperature is managed by a centralized system receives input from various sensors placed within the house. When the temperature in a particular room varies from the desired level, the system activates actuators connected to the heating, ventilation, and air conditioning (HVAC) system. When the temperature sensor detects any sort of change, signals are sent to the centralized control system where the instructions are given to the actuators connected to the HVAC to turn on the desired temperature. The actuators here are solely liable for all the controlling of the HAVC system like opening and closing of the ducts, on/off of the compressor, adjustment of speed on the basis of signals that are received from the control system. After setting the desired levels, signals are sent to the actuators by the control system to create comfortable environment as shown in Figure 3.

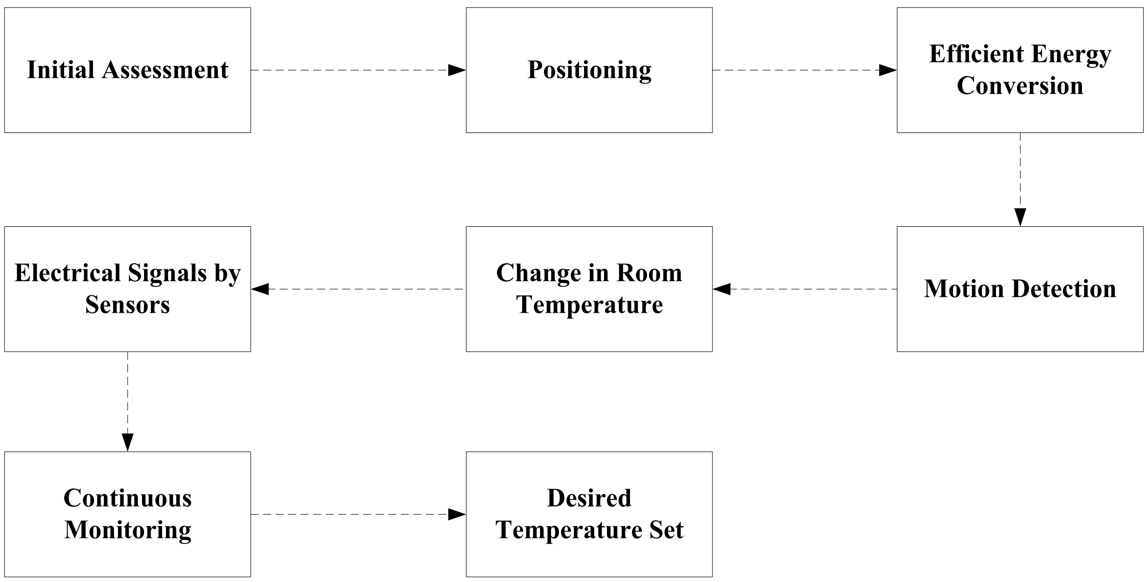

Figure 2. Mechanism of smart thermostat system for a room

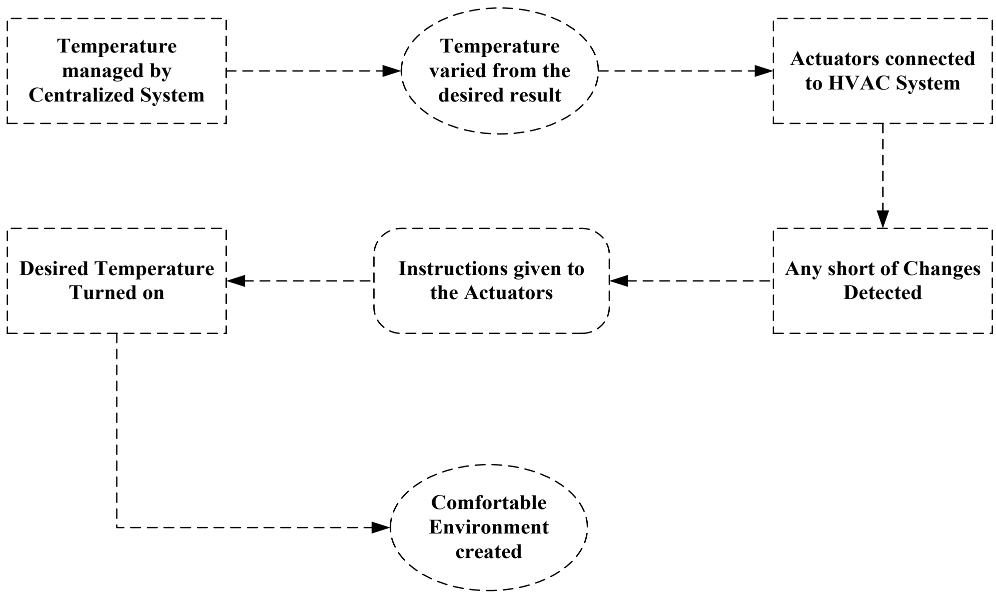

Figure 3. Mechanism of smart thermostat system for whole house

4. CONCLUSION

This review highlights the critical role of IoT technologies—specifically sensors, microcontrollers, microprocessors, and actuators—in advancing the efficiency and intelligence of green energy systems. The integration of microcontrollers and processors in solar and wind energy applications enables real-time monitoring, automated control, fault detection, and performance optimization. Actuators contribute to dynamic adjustments in solar tracking, wind turbine orientation, and hydro flow regulation, improving overall system responsiveness and energy output. The use of sensors ensures accurate environmental data acquisition, enabling predictive maintenance and adaptive energy management. Collectively, these IoT components enhance the reliability, scalability, and automation of renewable energy infrastructures, laying a strong foundation for future development in eco-friendly energy technologies. The integration of IoT technologies into the green energy sector marks a transformative shift in how renewable resources are harnessed, monitored, and optimized. This review has explored the pivotal role of sensors and microprocessor/microcontroller-based systems in enhancing the efficiency, adaptability, and intelligence of green energy solutions. By focusing on the synergy between IoT and renewable energy technologies, this study highlights the potential for sustainable, smart energy systems that not only reduce dependence on fossil fuels but also contribute to a more resilient and eco-friendly future. Continued innovation in this space will be critical in addressing global energy challenges, and the findings of this review encourage further interdisciplinary research and practical deployment of IoT-driven green energy solutions.

IoT intervention in green energy focuses mainly upon integrating renewable resources, enhancing efficiency and reducing environmental impact. Together, these two maximizes the use of clean energy and reduce the carbon footprints across different-different sectors. Some suggestions and recommendations are given below based upon the study done above: i) The development of smart grid system and energy management plans must be studied for the optimization of energy distribution, minimization of losses and management of demands; ii) IoT can be used for smart farming as it can improve the crop management, irrigation and farming activities which are energy efficient; iii) There should be awareness campaigns in respect of the advantages of the green energy and the accessible incentives after adapting technologies of green energy; iv) With the aim of increasing green energy across the country there should be implementation of policies and regulatory bodywork by the government for the encouragement of green energy in the energy sector; v) IoT enabled sensors can be used in solar and wind energy which monitors upon the performance of whole system, improve the energy capture and prediction related to maintenance can be made, and vi) IoT can be used in energy storage systems, as it will optimize the battery storage by balancing demand and supply for renewable energy.

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AUTHOR CONTRIBUTIONS STATEMENT

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Mahim Raj Gupta		✓				✓			✓					

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY

No new data were generated or analyzed; all data are from cited published sources.

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