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IoT Based Design and Implementation of a Smart Home Energy Management System Using a Turbo-Wheel Micro Turbine

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KEYWORDS

Turbine, Arduino UNO micro controller, regulated power supply, Liquid Crystal Display, embedded systems.

ABSTRACT

The escalating global energy crisis and the imperative for sustainable energy solutions have necessitated innovative approaches to residential power generation and management. This research presents the design and implementation of an Internet of Things (IoT)-enabled smart home energy management system integrating a turbo-wheel micro turbine as the primary power generation source. The proposed system employs an ESP-32 microcontroller as the central processing unit, interfacing with multiple sensors including DHT11 for temperature and humidity monitoring, and Light Dependent Resistor (LDR) for ambient light detection. The system features both automatic and manual operational modes, enabling adaptive energy management based on environmental conditions and user preferences. Real-time data visualization is achieved through an LCD display, while intelligent control mechanisms regulate connected loads including fans and LED lighting systems. The turbo-wheel micro turbine converts kinetic energy into electrical energy, which is stored in battery banks for continuous power availability. The IoT integration facilitates remote monitoring, data logging, and system optimization through cloud connectivity

I. INTRODUCTION

The contemporary world faces an unprecedented energy challenge characterized by rapidly depleting fossil fuel reserves, escalating environmental concerns, and exponentially growing energy demands driven by population growth and technological advancement. According to recent estimates, global energy consumption is projected to increase by nearly 50% by 2050, placing immense pressure on existing energy infrastructure and natural resources. This alarming trajectory has catalyzed intensive research into alternative energy generation methods, efficient energy management systems, and sustainable technological solutions that can mitigate the environmental impact while meeting the ever-increasing energy requirements of modern civilization. Within this context, residential energy consumption represents a significant portion of total global energy usage, accounting for approximately 20-40% in developed nations and showing similar trends in developing economies. Traditional homes operate as passive energy consumers, drawing power from centralized grid systems with minimal consideration for efficiency, optimization, or sustainability. The absence of intelligent monitoring and control mechanisms results in substantial energy wastage through inefficient appliance usage, poor load management, and lack of real-time consumption awareness. Furthermore, the increasing frequency of power outages, grid failures, and energy supply disruptions has highlighted the vulnerability of centralized power distribution systems and the critical need for decentralized, resilient energy solutions at the household level.

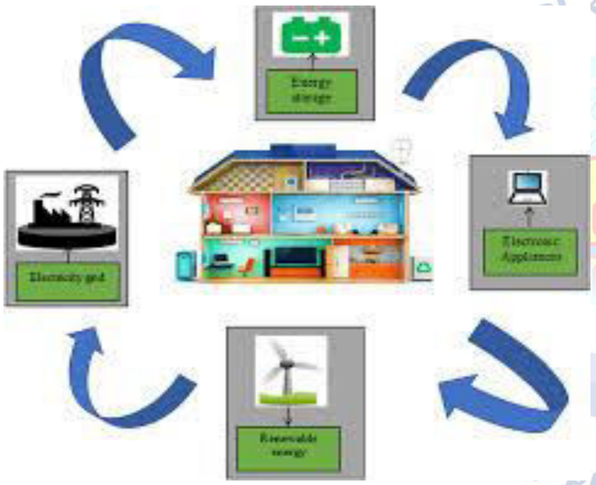

Fig 1: Home automation

Microgeneration technologies, particularly micro turbines, have emerged as promising solutions for distributed power generation in residential and small-scale commercial applications. Unlike large-scale centralized power plants, microgeneration systems enable on-site energy production, reducing transmission losses, enhancing energy security, and providing backup power during grid failures. Turbo-wheel micro turbines, specifically, offer several advantages including compact design, relatively low maintenance requirements, silent operation, and the ability to harness various energy sources such as wind, water flow, or even waste heat. These characteristics make them particularly suitable for integration into smart home energy systems where space constraints, noise considerations, and operational simplicity are paramount concerns. Environmental monitoring and responsive control constitute critical components of intelligent energy management. Sensors such as the DHT11, which measures temperature and humidity, and Light Dependent Resistors (LDR), which detect ambient light levels, provide essential environmental data that enables context-aware automation.

The proposed system architecture positions the turbo-wheel micro turbine as the primary energy generation component, converting mechanical energy into electrical power that charges battery banks for storage. The ESP-32 microcontroller serves as the central intelligence unit, processing sensor inputs, executing control algorithms, managing communication protocols, and interfacing with output devices. The DHT11 sensor continuously monitors indoor climate conditions, enabling temperature and humidity-based automation. The LDR sensor detects ambient light levels, facilitating intelligent lighting control and energy optimization. An AUTO/MANUAL mode selector provides users with flexibility to choose between autonomous system operation and direct manual control, accommodating different user preferences and scenarios

2. LITERATURE SURVEY

[2] Kumar and Singh (2019) explored micro-turbine integration in residential environments, focusing on decentralized power generation. Their study analyzed operational efficiency, thermal performance, and emission characteristics of small-scale turbines. They conducted performance testing under variable load conditions to determine optimal efficiency ranges. Economic feasibility assessments were performed considering installation cost, fuel consumption, and maintenance expenses. Their findings showed that micro-turbines could provide consistent supplementary power for residential loads. Under optimal operating conditions, the payback period was estimated between 5–7 years. The study also compared grid-tied and standalone configurations. Reliability testing confirmed stable operation during grid fluctuations. Environmental impact analysis revealed lower emissions compared to conventional diesel generators. The authors suggested hybrid integration with solar PV systems for enhanced performance. Their research contributed to distributed energy resource planning.

[3]Patel and Deshmukh (2020) developed an ESP-32 based home automation system integrating environmental monitoring and appliance control. Their design leveraged the ESP-32's dual-core processor and built-in Wi-Fi/Bluetooth capabilities. Multiple sensors including temperature, humidity, and light intensity sensors were interfaced simultaneously. The system demonstrated stable wireless communication with cloud platforms for real-time updates. Power consumption of the microcontroller was optimized using deep sleep modes. The authors implemented MQTT protocol for efficient IoT communication. Performance testing confirmed reliable actuator control with minimal latency. Cost analysis showed the system was affordable compared to commercial alternatives. The study validated ESP-32's capability in handling multi-threaded IoT tasks. Security features such as encrypted data transfer were included. Their implementation demonstrated scalability for larger home automation networks.

3. PROPOSED SYSTEM

The proposed system presents an integrated IoT-based smart home energy management solution that synergistically combines turbo-wheel microgeneration, intelligent sensor networks, energy storage, and adaptive load control within a unified architecture. At the core of the system, an ESP-32 microcontroller orchestrates all sensing, processing, communication, and control functions, leveraging its powerful dual-core processor and built-in wireless connectivity. The turbo-wheel micro turbine serves as the primary distributed generation source, converting kinetic energy into electrical power that charges battery banks for continuous availability and grid independence. A comprehensive sensor suite including DHT11 temperature-humidity sensors and LDR light sensors provides real-time environmental awareness, enabling context-driven automation and energy optimization. The system features innovative AUTO/MANUAL operational modes, allowing seamless transitions between autonomous intelligent control and direct user intervention based on preferences and scenarios. Output devices including LCD displays, variable-speed fans, and LED lighting systems demonstrate intelligent load management with potential for expansion to additional appliances and systems. IoT integration through Wi-Fi connectivity enables remote monitoring, cloud-based data analytics, mobile application control, and integration with broader smart home ecosystems. The energy storage subsystem with intelligent charge management ensures power availability during generation gaps and peak demand periods while maximizing battery lifespan. Real-time data visualization through the LCD interface enhances user engagement and energy awareness, displaying generation metrics, consumption patterns, environmental parameters, and system status. The modular, scalable architecture facilitates cost-effective implementation and future expansion, making the solution accessible for widespread residential adoption while addressing sustainability, efficiency, and energy independence objectives comprehensively.

3.1 Block Diagram:

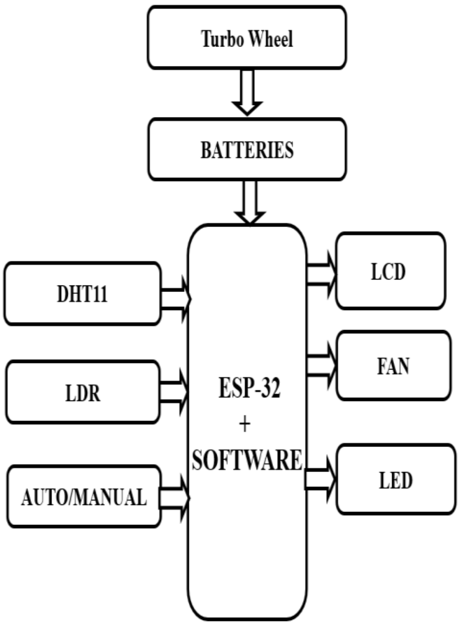

Fig: Block Diagram

3.2 Block Diagram Explanation:

The system architecture depicted in the block diagram illustrates a hierarchical energy flow and control structure centered around the ESP-32 microcontroller as the intelligent processing hub. The turbo-wheel micro turbine occupies the topmost position in the hierarchy, representing the primary energy generation source that converts mechanical rotational energy into electrical power through electromagnetic induction principles. The generated alternating current from the turbine passes through rectification and voltage regulation circuitry before charging the battery bank, which serves as the energy storage and power stabilization component ensuring continuous operation regardless of instantaneous generation fluctuations. The battery system provides regulated DC power to the ESP-32 microcontroller and all connected peripheral devices, creating a self-sustaining energy ecosystem independent of grid infrastructure.

On the input side, three critical sensor and control elements interface with the ESP-32: the DHT11 digital temperature and humidity sensor communicates via a single-wire protocol to provide climate data for environmental monitoring and thermal comfort optimization; the LDR (Light Dependent Resistor) analog sensor detects ambient illumination levels through resistance variation, enabling automatic lighting control and daylight harvesting strategies; and the AUTO/MANUAL mode selector switch allows users to toggle between autonomous algorithmic control and direct manual operation, providing operational flexibility and user empowerment. These input devices continuously feed environmental and user preference data to the ESP-32, which processes this information using, embedded algorithms to make intelligent control

3.3 Flow Chart

The flow chart through an integrated flow of energy generation, monitoring, control, and optimization. The process begins with the turbo-wheel micro turbine generating electrical power from available energy sources such as airflow or fluid movement. The generated power is conditioned using rectifiers and voltage regulators before being distributed to household loads and battery storage systems. Sensors continuously monitor parameters such as voltage, current, power consumption, turbine speed, and battery state of charge. These real-time data values are transmitted to a microcontroller (such as ESP32) which processes the information and sends it to a cloud server via IoT connectivity.

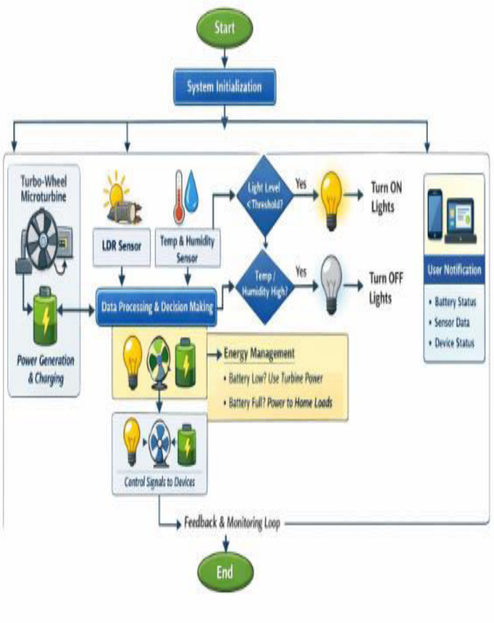

Fig 3: Flow Chart

4. RESULTS AND DISCUSSION

The IoT-based smart home energy system effectively generates supplementary power using a micro turbine while enabling real-time monitoring and control through a smart dashboard. It improves energy efficiency by optimizing appliance usage, reducing electricity consumption, and supporting sustainable smart home applications.

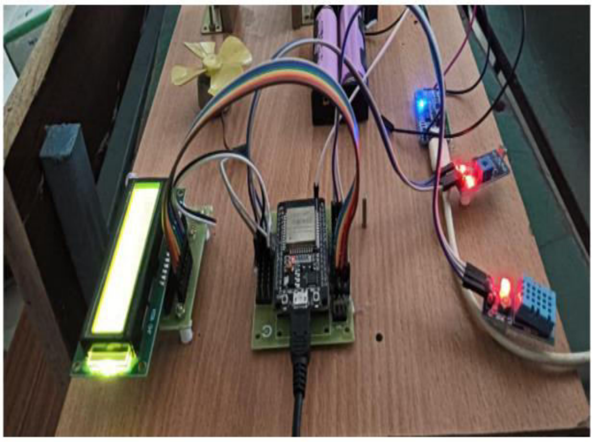

Fig 4: Hardware Implementation

Figure shows a turbo-wheel micro turbine to generate power from airflow. A DHT11 and LDR sensor enable automatic control of lights and fans based on temperature and light. Bluetooth allows manual control via mobile, while an LCD displays real-time data and system status.

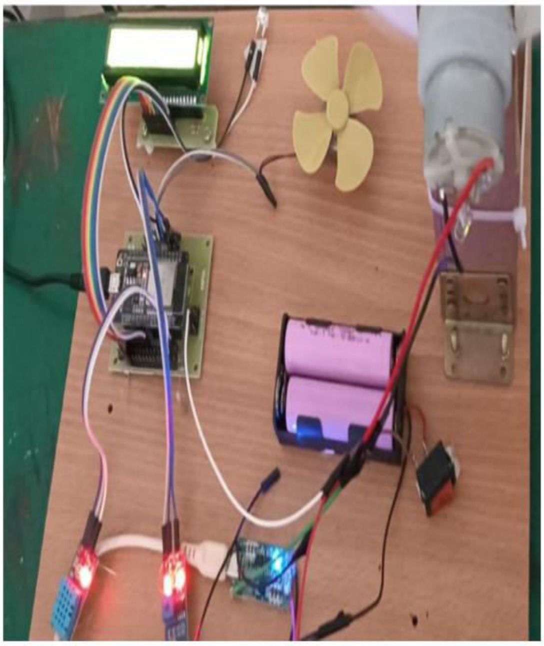

Fig 5: Real-Time Sensor Monitoring and LCD Display Output

This figure shows the real-time monitoring of sensor values such as temperature, humidity, and light intensity. The processed data is displayed on the LCD screen, providing continuous system status updates. It helps in tracking environmental conditions and controlling appliances efficiently.

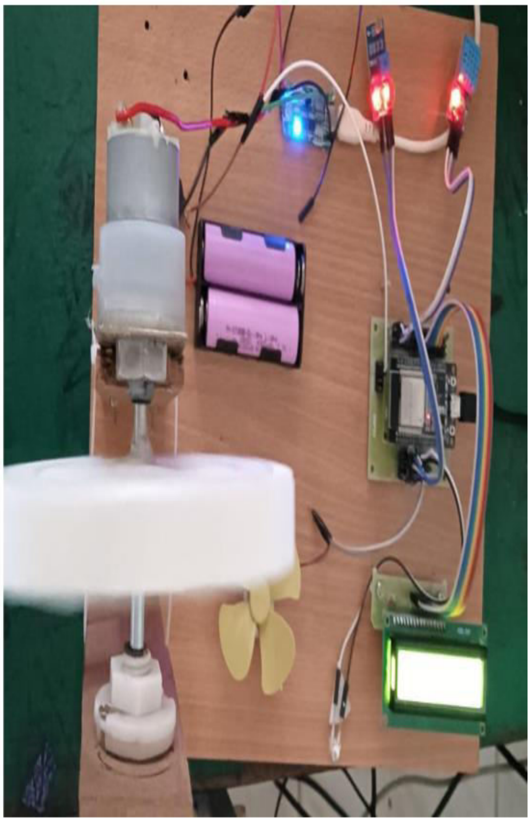

Fig 6: Turbo-Wheel Based Energy Generation and Hardware Setup

This figure illustrates the turbo-wheel mechanism used to convert physical (kinetic) energy from airflow into electrical energy. The generated power is utilized to drive the IoT-based system components. It demonstrates the practical implementation of renewable energy generation integrated with sensor monitoring and control modules.

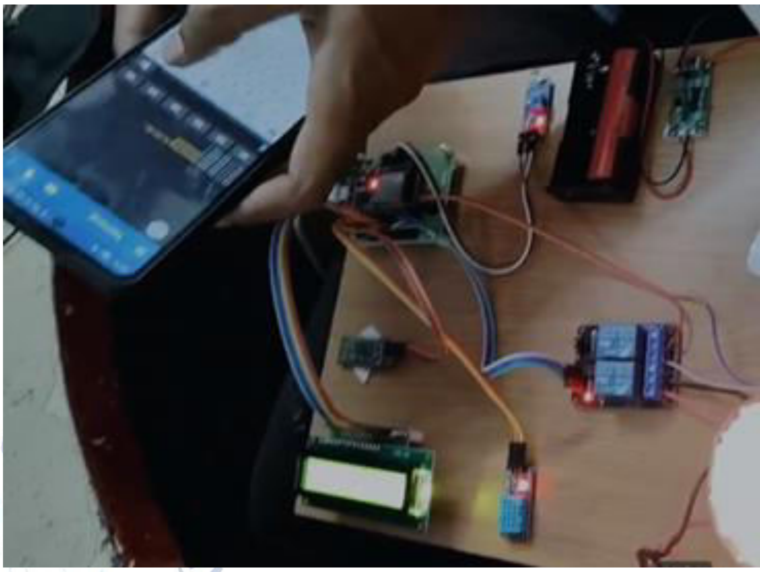

Fig 7: Automatic Operation

In Bluetooth mode, the system allows users to manually control appliances like lights and fans through a mobile device. The ESP32 receives commands via Bluetooth and performs ON/OFF operations instantly. This provides user flexibility and direct control over the system when automatic mode is not required.

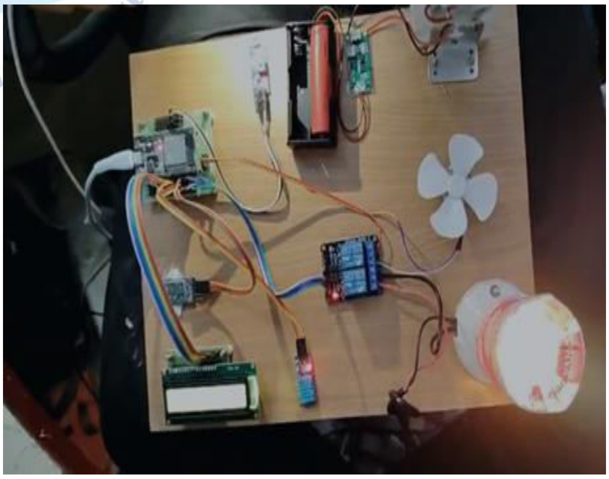

Fig 8: Manual Mode Operation

In Manual Mode, the user controls appliances based on temperature and LDR readings displayed on the platform. Using these values, the user can decide when to turn the fan or light ON/OFF as needed. This allows flexible control while still considering environmental conditions.

5. CONCLUSION

This research presents the design and implementation of an IoT-based smart home energy management system using a turbo-wheel micro turbine for small-scale renewable energy generation. The system is built around an ESP-32 microcontroller, which manages energy generation, storage, monitoring, and load control. Energy produced by the turbo-wheel micro turbine is stored in a battery bank and utilized to power household loads such as fans and LED lighting. Environmental conditions are monitored using DHT11 temperature-humidity sensors and LDR sensors to enable intelligent automation. The system supports both AUTO and MANUAL operating modes, allowing users to either rely on automatic sensor-based control or manually manage appliances. An LCD display provides real-time information about system status, energy usage, and environmental parameters. IoT connectivity enables remote monitoring and control through cloud platforms, allowing users to track system performance and energy consumption. Experimental results demonstrate improved energy efficiency, reduced dependence on grid electricity, and reliable operation. The modular and scalable architecture makes the system cost-effective and suitable for residential applications. Overall, the proposed system promotes sustainable energy utilization, smart home automation, and decentralized energy management. Future improvements may include machine learning-based optimization, expanded sensor networks, and integration with electric vehicle charging and smart grids

FUTURE SCOPE

The system can be enhanced by integrating hybrid renewable sources like solar panels to increase power generation and reliability. It can further incorporate AI-based energy prediction and smart load scheduling for automated and efficient energy management. Additionally, advanced mobile/cloud monitoring will enable real-time tracking and improved control for smart home and smart grid applications

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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