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Carbon Footprint EcoSync: Smart IoT-Based Carbon Footprint Monitoring and Sustainable Energy Management System

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Abstract: The growing challenges of urbanization, rising electricity consumption, and poor waste management in India have worsened environmental conditions. Existing environmental monitoring systems are primarily designed for industries and corporations, lacking real-time feedback and incentive mechanisms for individual users. Most household-level systems require manual data entry, do not offer carbon emission tracking, and remain financially inaccessible to common users. This paper presents Carbon Footprint EcoSync — a low-cost, smart IoT-based monitoring system designed to track electricity consumption and estimate carbon emissions in real time. The system uses an ESP32 microcontroller integrated with voltage, current, and air quality sensors (MQ135), an OLED display, a relay module for automated appliance control, and Wi-Fi-enabled cloud connectivity. EcoSync calculates carbon emissions using standard emission conversion factors and displays results both locally and on a cloud dashboard. The system targets homes, hostels, and small offices, helping users identify high-energy appliances and encouraging sustainable energy behavior through real-time feedback. Studies show that real-time energy feedback can reduce consumption by 15–25%, demonstrating the potential impact of EcoSync on promoting eco-friendly living and supporting climate action goals.
Keywords: Carbon Footprint, Sustainability, IoT, Environmental Monitoring, Waste Management, Smart System, Eco-Friendly Technology

I. INTRODUCTION

Environmental pollution and climate change have become major global concerns due to rapid industrialization, urbanization, and excessive consumption of natural resources. Increasing carbon emissions from transportation, electricity usage, and improper waste management have significantly contributed to global warming and environmental degradation. According to recent environmental studies, rising greenhouse gas emissions are one of the primary causes of climate imbalance, affecting both human health and ecosystems worldwide.

In today's modern lifestyle, individuals and households contribute substantially to carbon emissions through daily activities such as electricity consumption, fuel usage, and waste generation. However, most people remain unaware of their personal carbon footprint and its environmental impact. Existing environmental monitoring systems are mainly designed for industries and large organizations, making them costly and inaccessible for common users. Moreover, traditional systems often lack real-time monitoring, user-friendly interfaces, and awareness-based engagement features.

To address these challenges, the proposed system — Carbon Footprint EcoSync — is developed as a smart carbon footprint monitoring and sustainable energy management solution. EcoSync aims to help users monitor their daily environmental impact by tracking electricity consumption and waste management activities. The system utilizes modern technologies such as Internet of Things (IoT), cloud computing, and embedded systems to provide real-time environmental monitoring and eco-friendly recommendations.

The proposed system not only increases environmental awareness but also encourages sustainable practices through real-time alerts and analytical reports. By integrating technology with environmental sustainability, EcoSync provides an efficient, affordable, and user-friendly platform for promoting green living and supporting smart city initiatives.

II. OBJECTIVES

The main objectives of the proposed EcoSync system are as follows:

1) To monitor and analyze the carbon footprint generated by daily human activities.

2) To track electricity and energy consumption using smart IoT-based monitoring techniques.
3) To encourage proper energy utilization and environmentally friendly practices.
4) To provide users with real-time environmental data and eco-friendly recommendations.
5) To increase awareness regarding environmental conservation and sustainable living practices.
6) To integrate IoT and cloud technologies for efficient and low-cost environmental monitoring.
7) To promote user participation through real-time alerts and automated appliance control for reducing carbon emissions.
8) To support smart city and green technology initiatives for a sustainable future.

III. LITERATURE REVIEW

This section reviews key prior works related to IoT-based carbon monitoring and smart energy systems.

[1] Al-Fuqaha et al., "Internet of Things: A Survey on Enabling Technologies, Protocols and Applications," IEEE, 2015. This paper explains IoT architecture, communication protocols, sensors, and cloud integration. It provides a strong technical foundation for real-time monitoring systems. Relevant to EcoSync's communication and sensor design.

[2] He Zhang et al., "Smart Carbon Monitoring Platform under IoT-Cloud Architecture for Small Cities in B5G," Wireless Networks, 2021. Proposes an IoT-cloud system for real-time carbon emission monitoring in small cities using long-term sensor data. EcoSync adapts similar principles for household-level monitoring.

[3] Ali Yavari et al., "ArtEMon: AI and IoT Powered Greenhouse Gas Sensing for Real-Time Emissions Monitoring," Sensors, 2023. Combines AI with IoT sensors for improved greenhouse gas detection accuracy. Useful for future EcoSync upgrades integrating AI analytics.

[4] Huiru Yang, "Study on Real-Time Estimation of Carbon Emissions Based on Non-Intrusive Power Load Monitoring," 2024. Estimates carbon emissions from electricity load data at low cost without per-appliance sensors. Directly relevant to EcoSync's smart energy monitoring approach.

[5] Kavishka Jayakodi et al., "IoT Enabled Carbon Emission Monitoring in Residential Buildings: A Bibliometric Analysis," 2024. Reviews IoT-based carbon monitoring in homes and confirms residential adoption is growing but still limited. Highly relevant to EcoSync's target application domain.

[6] Guang-Li Huang et al., "IoT-based Analysis for Smart Energy Management," arXiv, 2023. Studies IoT systems for appliance-level energy monitoring and demonstrates improved efficiency. Useful for EcoSync's dashboard design and logic.

[7] Thibault Pirson et al., "Assessing the Embodied Carbon Footprint of IoT Edge Devices," arXiv, 2021. Analyzes carbon impact of IoT device manufacturing. Important for sustainable hardware selection in EcoSync.

[8] Demetris Trihinas et al., "Towards Energy Consumption and Carbon Footprint Testing for AI-driven IoT Services," arXiv, 2023. Evaluates power usage and emissions of AI-enabled IoT systems. Useful for future EcoSync cloud optimization.

[9] Amal Roy et al., "IoT-Based Automatic Power Factor Correction with Real-Time Carbon Footprint Estimation," 2026. Combines power factor correction with real-time carbon estimation, demonstrating dual efficiency benefits.

[10] Neer Patel et al., "Carbon Footprint Tracker Using IoT and AI for Vehicle Emission Control," 2025. Uses IoT gas sensors and AI to classify vehicle emissions. Useful as a future extension of EcoSync beyond electricity monitoring.

IV. METHODOLOGY

A. PROBLEM IDENTIFICATION

Rapid growth in electricity consumption and improper energy utilization have become major environmental concerns. Excessive usage of electrical appliances leads to increased carbon emissions, contributing to global warming and environmental pollution. Most existing systems do not provide real-time monitoring of electricity consumption and carbon emissions, making users unaware of their environmental impact.

In many households and institutions, energy usage is not monitored efficiently, resulting in unnecessary wastage of electricity and increased operational costs. Therefore, there is a need for a smart and automated system capable of continuously monitoring energy consumption, estimating carbon emissions, and promoting environmental awareness.

V. HARDWARE AND SOFTWARE DESIGN

A. SYSTEM OVERVIEW

The proposed Carbon Footprint EcoSync system is a smart IoT-based carbon footprint monitoring system designed to measure electricity consumption and estimate carbon emissions in real time. The system combines sensors, an ESP32 microcontroller, relay modules, and cloud connectivity for continuous monitoring and energy management.

The system helps users track their energy consumption, reduce unnecessary electricity wastage, and increase awareness regarding environmental sustainability. It also provides automated monitoring, alert generation, and cloud-based data storage for efficient energy management.

B. SYSTEM BLOCK DIAGRAM

The overall working structure of the EcoSync system is as follows:

Power Supply → Voltage Sensor → Current Sensor → ESP32 Microcontroller

MQ135 Gas Sensor → ESP32 Controller

ESP32 → Wi-Fi Module / Cloud Dashboard

ESP32 → Relay Module → Appliance Control

The voltage and current sensors continuously measure electrical parameters, while the MQ135 sensor monitors environmental air quality. The ESP32 processes the collected data and uploads it to the cloud dashboard through Wi-Fi connectivity. The relay module controls electrical appliances whenever energy usage exceeds predefined threshold limits.

C. COMPONENTS USED IN THE SYSTEM

1) ESP32 Microcontroller

The ESP32 microcontroller acts as the main controller of the system. It receives sensor data, performs calculations, processes information, and controls all output devices. The controller also provides Wi-Fi connectivity for cloud communication and IoT applications.

2) Current Sensor

The current sensor measures the amount of current consumed by electrical appliances. The obtained readings are used for calculating real-time power consumption and monitoring electricity usage.

3) Voltage Sensor

The voltage sensor measures the supply voltage of the connected electrical load. It works together with the current sensor for accurate power calculation and monitoring.

4) MQ135 Gas Sensor

The MQ135 gas sensor detects harmful gases and monitors air quality. It adds environmental monitoring capability to the project and helps analyze pollution levels.

5) OLED Display

The OLED display provides real-time monitoring information including voltage, current, power consumption, and estimated carbon emissions. It offers a simple and user-friendly interface for continuous monitoring.

6) Relay Module

The relay module automatically switches off electrical appliances when excessive power consumption is detected. This helps reduce electricity wastage and improves energy efficiency and safety.

7) IoT Cloud Dashboard

The cloud-based IoT dashboard stores historical monitoring data and enables remote monitoring through mobile or web applications. Users can analyze energy consumption patterns and carbon emission trends efficiently.

D. IMPLEMENTATION DETAILS

1) Sensor Interfacing

All sensors are connected to the ESP32 microcontroller using analog and digital input pins. The sensors continuously send real-time data to the controller for processing and monitoring.

2) Programming

The complete system was programmed using the Arduino IDE platform with Embedded C language. The ESP32 continuously processes sensor data and performs all required calculations.

3) Power Consumption Calculation

Electrical power consumption was calculated using the standard formula: $P = V \times I$, where P = Power (watts), V = Voltage (volts), and I = Current (amperes). The system continuously calculates power consumption using real-time sensor readings.

4) Carbon Emission Calculation

The measured energy consumption values were converted into estimated carbon emissions using the standard formula: CO_2 Emission = Energy Consumed × Emission Factor. This calculation helps users understand the environmental impact of their electricity usage.

5) Data Display and Cloud Upload

The calculated values are displayed on the OLED screen in real time. Simultaneously, the ESP32 uploads monitoring data to the cloud platform through Wi-Fi connectivity, allowing remote access, reporting, and analysis.

E. SYSTEM ALGORITHM

1) Initialize ESP32 microcontroller and all sensors.
2) Read voltage, current, and gas sensor values.
3) Calculate power consumption using $P = V \times I$.
4) Measure energy consumed over time.
5) Convert energy usage into CO_2 emission values using the emission factor.
6) Display all readings on the OLED screen.
7) Upload collected data to the cloud dashboard.
8) Compare readings with predefined threshold limits.
9) Generate alerts or switch off load using relay module if limits are exceeded.
10) Repeat the monitoring process continuously.

VI. EXPERIMENTAL RESULTS AND ANALYSIS

A. EXPERIMENTAL SETUP

The experimental setup of the proposed EcoSync system was developed to monitor real-time electricity consumption and estimate carbon emissions. The setup consists of an ESP32 microcontroller, current sensor, voltage sensor, MQ135 gas sensor, OLED display, relay module, and Wi-Fi connectivity module.

The current and voltage sensors were connected to various household electrical appliances including LED bulbs, ceiling fans, mobile chargers, and computers to measure electrical parameters in real time. The ESP32 continuously collected sensor readings and calculated power consumption. The measured energy consumption was further converted into estimated carbon emission values using standard emission conversion factors. Different electrical loads were tested under normal operating conditions to verify system performance and accuracy.

B. EXPERIMENTAL OBSERVATION TABLE

Sr. No.	Appliance Used	Voltage (V)	Current (A)	Power Consumption (W)	Estimated CO_2 Emission (g/hr)	Observation
1	LED Bulb	230	0.04	9.2	7	Very low power consumption
2	Mobile Charger	230	0.03	6.9	5	Low energy usage
3	Ceiling Fan	230	0.32	73.6	58	Moderate power consumption
4	Laptop / Computer	230	0.48	110.4	87	Highest energy consumption

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Sr. No.	Appliance Used	Voltage (V)	Current (A)	Power Consumption (W)	Estimated CO_2 Emission (g/hr)	Observation
5	Television	230	0.21	48.3	38	Average energy usage

Table I: Experimental Observation of Appliance Power Consumption and CO_2 Emissions

VII. CONCLUSION

The proposed Carbon Footprint EcoSync system provides an efficient and reliable solution for real-time monitoring of electricity consumption and carbon emissions. The system successfully integrates IoT technology, an ESP32 microcontroller, environmental sensors, relay modules, and cloud connectivity for smart energy management.

The system continuously monitors electrical parameters such as voltage, current, and power consumption while estimating carbon emissions generated by different electrical appliances. The obtained results demonstrate that the system can effectively identify high energy-consuming devices and promote energy-saving behavior among users.

The implementation of real-time monitoring, automatic alert generation, and cloud-based data storage improves environmental awareness and encourages sustainable energy utilization. The relay module further helps reduce electricity wastage by controlling appliance operation whenever predefined limits are exceeded.

The experimental analysis confirms that the EcoSync system provides accurate monitoring, fast response, low power consumption, and reliable performance for household and small-scale applications. The project serves as a low-cost and practical solution for smart carbon footprint monitoring and sustainable energy management.

Overall, the Carbon Footprint EcoSync system contributes toward environmental conservation, reduction of carbon emissions, and promotion of smart and sustainable living practices through modern IoT technology.

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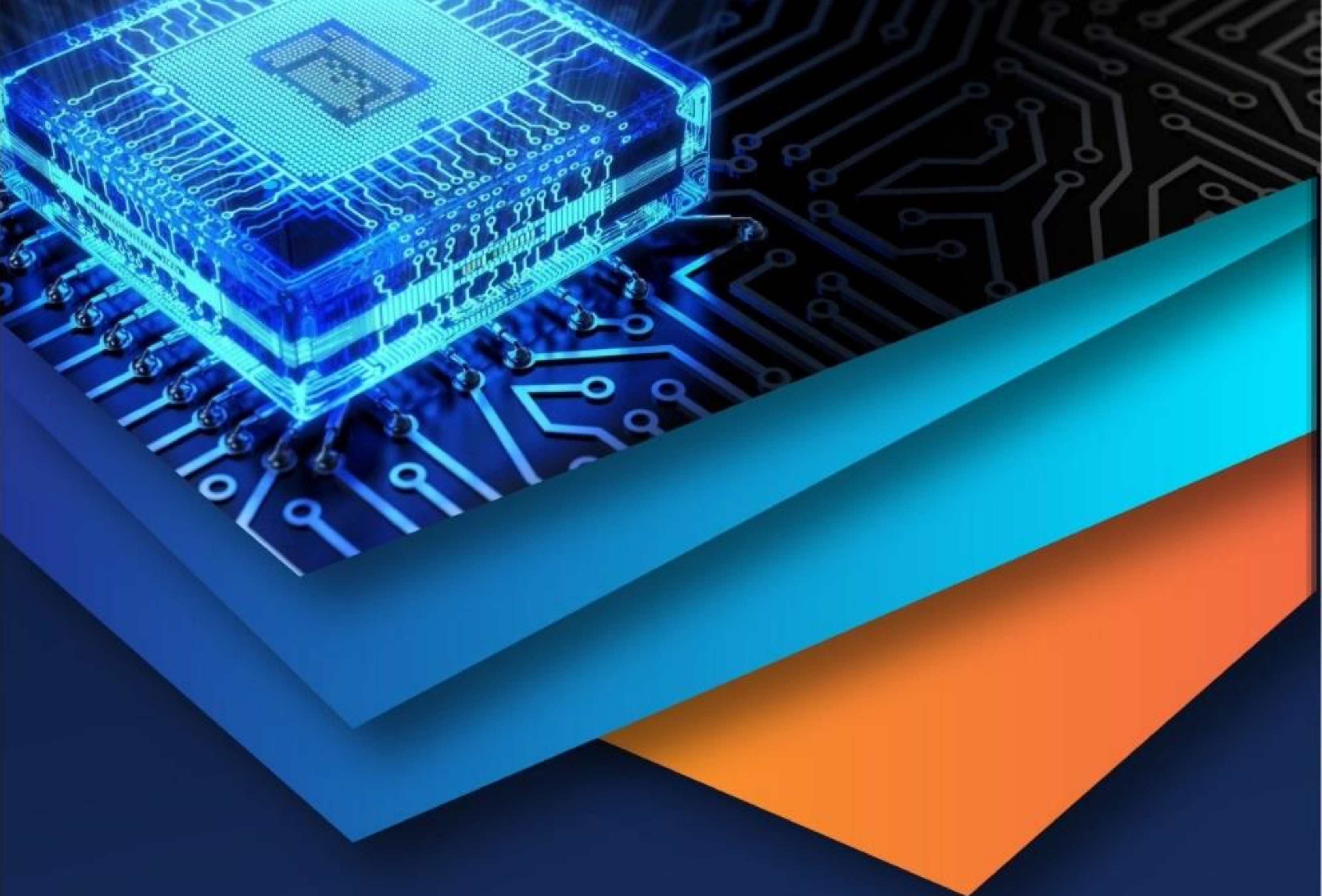

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