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Sustainify: IoT Ecosystem for Real-Time Residential Energy Analytics and Carbon Mitigation

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Abstract—*As global energy demands surge, residential power consumption has become a primary driver of carbon emissions and grid instability. Traditional monitoring methods, such as monthly billing or aggregate smart meters, often lack the granularity and real-time responsiveness required for meaningful behavioral intervention and automated load management. This paper introduces "Sustainify," an integrated smart home ecosystem designed to bridge the gap between raw consumption data and actionable environmental insights. Leveraging a hybrid LoRaWAN and GSM/Wi-Fi communication architecture, the system provides resilient, real-time tracking of individual appliance metrics even in environments with unstable internet connectivity. We detail the hardware deployment of PZEM-series sensors, distributed microcontrollers (ESP32 and ESP8266), and a cloud-based Artificial Intelligence (AI) engine featuring Long Short-Term Memory Autoencoders (LSTM-AE). This AI engine translates electrical parameters into carbon-centric recommendations and autonomously detects anomalous energy signatures. Experimental simulations and prototype deployments indicate that the system can facilitate a 22.2% reduction in household carbon emissions and a 15% decrease in utility expenditures through intelligent load-shifting, anomaly isolation, and educational feedback.*

***Index Terms*—Energy Management Systems (EMS), IoT, Lo-RaWAN, Artificial Intelligence, Anomaly Detection, Sustainability, Mechanical Engineering.**

I. INTRODUCTION

Modern urbanization has led to a paradigm shift in domestic energy reliance. Residential buildings now account for a significant portion of global electricity consumption, yet a vast majority of occupants remain fundamentally unaware of their specific appliance-level usage patterns until a cumulative monthly bill is generated. This lack of real-time visibility results in unintentional energy waste, phantom loads, and high peak-load demand on local electrical grids.

Furthermore, the transition to sustainable living requires more than just aggregate data; it necessitates granular, actionable intelligence. While commercial and industrial sectors have heavily adopted advanced Energy Management Systems (EMS), residential deployments lag due to high installation costs, complex user interfaces, and reliance on stable continuous Wi-Fi—a luxury not consistently available in all regions. To address these challenges, "Sustainify" is developed as a scalable, frugal, and highly resilient solution to foster a greener lifestyle. Unlike isolated smart plugs that offer fragmented control, our system creates a decentralized mesh network within the home. It centralizes telemetry data through a dual-path master node capable of ensuring continuous cloud connectivity for advanced machine learning analysis.

The core contributions of this paper are threefold:

1) **Hardware Architecture:** The design and integration of low-cost, high-fidelity monitoring nodes utilizing PZEM sensors and ESP microcontrollers safely isolated from high-voltage lines.
2) **Resilient Hybrid Communication:** Implementation of a robust network topology that utilizes LoRa for wall-penetrating local mesh communication, backed by an autonomous Wi-Fi to GSM failover mechanism for uninterrupted cloud uplink.
3) **AI-Driven Mitigation:** The deployment of an LSTM-Autoencoder model for real-time temporal anomaly detection, empowering the system to physically isolate malfunctioning or inefficient loads dynamically.

This paper elaborates on the mechanical assembly, the resilient communication logic, the deep learning predictive models, and the resulting sustainability impact observed through our comprehensive prototype validation.

II. RELATED WORK

The pursuit of residential energy efficiency has spurred significant research into Non-Intrusive Load Monitoring (NILM) and IoT-based smart grids. Ghaniy et al. demonstrated the efficacy of ESP32-based architectures for basic power monitoring, highlighting the cost-to-performance ratio of these microcontrollers in domestic settings. However, typical Wi-Fi-based deployments suffer from significant packet loss when traversing concrete walls in multi-story residential units.

To combat network limitations, recent literature has explored LoRaWAN. Studies indicate that LoRa provides superior energy optimization and penetration capabilities for sensor networks, though its low bandwidth requires careful payload formatting. Sustainify builds upon this by utilizing LoRa exclusively for local node-to-master communication, reserving high-bandwidth Wi-Fi and GSM purely for cloud telemetry.

In the domain of Artificial Intelligence, Hua et al. reviewed various models for predicting building carbon emissions, noting that while standard regression models perform well for forecasting, they fail to catch temporal anomalies (e.g., a thermostat failing to disengage a heater). By integrating an LSTM-Autoencoder directly tied to hardware relays, Sustainify transitions AI from a passive analytical tool to an active, physical mitigation mechanism.

III. PROPOSED ARCHITECTURE AND METHODOLOGY

The Sustainify ecosystem is structured into three highly coupled layers: Sensing and Control (Edge), Resilient Communication (Network), and Predictive Analytics (Cloud).

A. *Hardware Configuration and Internal Assembly*

The hardware foundation relies on non-intrusive PZEM-004T V3 sensors for accurate, continuous monitoring of AC grid parameters including voltage, current, active power, energy, frequency, and power factor. These sensors interface with ESP-series microcontrollers (ESP32 for the master node and ESP8266 for satellite nodes) via opto-isolated UART connections, ensuring the low-voltage logic circuitry is protected from high-voltage AC spikes.

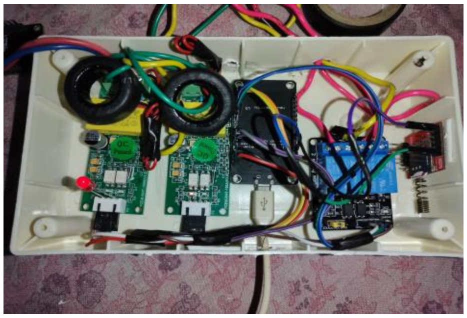

Fig. 1. Internal assembly showcasing the integration of the ESP32 microcontroller, PZEM sensor module, and the relay control board.

As shown in Fig. 1, the physical prototype utilizes a compartmentalized approach. The toroidal coils (current transformers) for the PZEM sensors are safely separated from the logic boards. The microcontrollers handle both data acquisition and physical load switching. Load switching is achieved through a 4-channel 5V relay board, allowing the system to physically disconnect appliances based on user commands, scheduled routines, or AI-triggered anomaly alerts.

B. *Energy Management Software Flow*

To ensure robust operation without user intervention, the system operates on a highly structured software state machine.

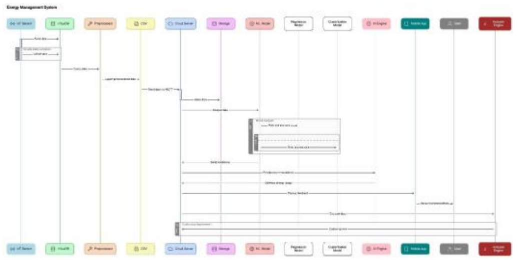

Fig. 2. Energy management system operational flowchart detailing network initialization, telemetry polling, and threshold logic.

As illustrated in the flowchart (Fig. 2), the execution begins with an initialization phase where all relays default to an open (safe) state to prevent electrical surges. The software then initializes network connections, seeking local Wi-Fi first and failing over to GSM if unavailable. Once an MQTT connection to the cloud broker is established, the system enters its primary loop: continuously polling the PZEM sensors, applying local threshold checks for immediate over-current protection, and dispatching formatted JSON payloads to the AI engine for complex anomaly detection.

IV. CIRCUIT INTEGRATION AND PIN ALLOCATION

Proper routing and isolation are critical in mixed-signal IoT devices.

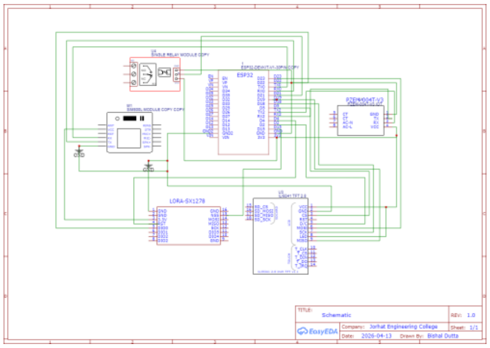

Fig. 3. Circuit Diagram showcasing high-level connections between the ESP32, ESP8266, Relay, GSM module, and the load.

The circuit diagram in Fig. 3 outlines the overarching topological map of the system. The ESP32 acts as the central brain. To manage the display, long-range communication, cellular backup, and telemetry sensing simultaneously, careful pin allocation was required to prevent bus collisions.

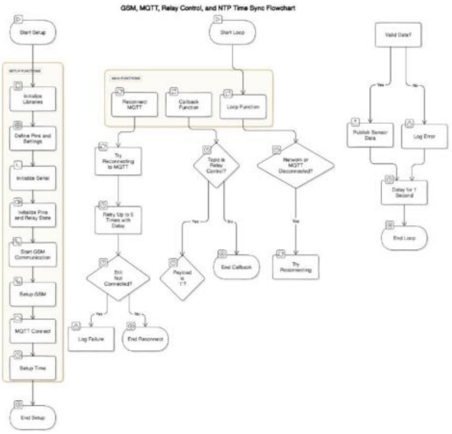

Fig. 4. Working schematic details of the connectivity between sensors, microcontrollers, and the relay-controlled load outputs.

The detailed schematic (Fig. 4) illustrates the strict isolation between the low-power logic circuit and the high-voltage load side. The SPI bus is shared between the ILI9341 TFT display and the LoRa SX1278 module, utilizing distinct Chip Select (CS) pins. The SIM800L and PZEM-004T utilize separate hardware UARTs on the ESP32 to ensure asynchronous communication does not block the main processing loop. The complete node connection matrix is detailed in Table I.

TABLE I

ESP32 SUSTAINIFY MASTER NODE CONNECTIONS

Component	Component Pin	ESP32 Pin	Function / Essential Notes
		Power Distribution	
ESP32	VIN (5V)	-	Main 5V power input from supply
ILI9341 TFT	VCC/3.3V	3.3V Rail	Display power
LoRa SX1278	VCC/3.3V	3.3V Rail	Strictly 3.3V (5V logic will destroy it)
PZEM-004T	5V	5V Rail	Requires 5V for internal optocouplers
SIM800L V2	5V (or VCC)	5V Rail	Add 100µF capacitor across VCC/GND
1-Ch Relay	VCC	3.3/5V Rail	Match to specific relay's coil voltage
All Modules	GND	Common GND	Tie all grounds together
		Shared SPI Bus	
ILI9341 & LoRa	SCK	GPIO 18	Shared SPI Clock
ILI9341 & LoRa	MISO	GPIO 19	Shared SPI Master In Slave Out
ILI9341 & LoRa	MOSI	GPIO 23	Shared SPI Master Out Slave In
ILI9341 TFT	CS	GPIO 15	Display Chip Select
LoRa SX1278	NSS (CS)	GPIO 5	LoRa Chip Select
ILI9341 TFT	DC/RS	GPIO 2	Display Data/Command Control
ILI9341 TFT	RESET	3.3V Rail	Hardwire high to save an ESP32 pin
LoRa SX1278	RST	GPIO 4	LoRa Hardware Reset
LoRa SX1278	DIO0	GPIO 22	LoRa Interrupt
		Isolated UARTs	
PZEM-004T	TX	GPIO 16 (RX2)	Reads telemetry data from the sensor
PZEM-004T	RX	GPIO 17 (TX2)	Sends Modbus requests to the sensor
SIM800L V2	TX	GPIO 33 (RX)	Reads incoming cellular/cloud data
SIM800L V2	RX	GPIO 32 (TX)	Sends AT commands to cellular network
		Load Control	
1-Ch Relay	IN	GPIO 25	Toggles the AC load

A. *Resilient Communication Strategy*

A key innovation in Sustainify is its connectivity flexibility. Recognizing that residential internet can be highly unreliable, the system utilizes a custom dual-path gateway.

Internal Mesh: Individual appliance nodes scattered throughout the residence communicate via LoRa (Long Range) sub-GHz transceivers. Operating at 433/868 MHz, these signals easily penetrate thick concrete walls and traverse multiple floors, a task where standard 2.4GHz Wi-Fi frequently fails.

External Uplink Failover: The master ESP32 node continuously polls the primary Wi-Fi connection via ICMP ping requests. If the local broadband network drops, the microcontroller autonomously boots the SIM800L module and switches to a GPRS/GSM cellular backup. This ensures the cloud-based MQTT broker receives uninterrupted, time-series telemetry data.

V. MECHANICAL DESIGN AND VISUAL REPRESENTATION

The physical hardware is housed in a modular enclosure designed for both fire safety and modern aesthetics, allowing for non-intrusive installation.

Fig. 5. The external casing of the Sustainify optimizer, featuring a compact form factor for residential installation.

As seen in Fig. 5, the casing is modeled to seamlessly blend into existing home infrastructure. It mimics the form factor of a traditional Indian residential switchboard, complete with standard 3-pin power sockets and manual override switches. This design Reconstruction Error (e_t) at each time step:

$$e_t = |x_t - \hat{x}_t| \quad (1)$$

A dynamic threshold (τ) is calculated continuously based on a rolling window of the reconstruction error's mean (μ) and standard deviation (σ):

$$\tau = \mu + 3\sigma \quad (2)$$

If $e_t > \tau$ for a sustained period, the system classifies the event as an anomaly.

ensures that users can interact with the system naturally, without needing specialized technical knowledge. The external antenna securely mounts to the side of the junction box to ensure optimal RF transmission for the LoRa and GSM modules housed within.

VI. AI-DRIVEN ANALYTICS AND ANOMALY DETECTION

While raw monitoring provides visibility, true energy optimization requires proactive intelligence. The data collected by the Sustainify hardware is streamed via MQTT to a cloud server, where it is stored in an InfluxDB time-series database. This data feeds into our deep learning engine.

A. LSTM-Autoencoder for Real-Time Anomaly Detection

To identify malfunctioning equipment, phantom power drains, or dangerous thermal overloads, we implemented a Long Short-Term Memory Autoencoder (LSTM-AE). Traditional threshold-based alerts are inadequate for appliances with variable load cycles (e.g., washing machines, HVAC systems). The LSTM-AE learns the standard temporal sequence of an appliance's power draw. The encoder compresses the time-series window $X = \{x_1, x_2, ..., x_t\}$ into a lower-dimensional latent representation. The decoder then attempts to reconstruct the original sequence $\hat{X}$. The system calculates the absolute energy mix), the AI module provides users with a daily" Carbon Score."

Users receive virtual tips advising them on optimal times for energy-heavy tasks. For example, the system will suggest running HVAC units or washing machines during off-peak hours when grid energy is cheaper and predominantly supplied by renewable sources. Table II summarizes the predicted savings based on our prototype testing over a standard 30-day window.

TABLE II

SYSTEM PERFORMANCE AND SUSTAINABILITY METRICS

Metric	Baseline	Optimized	Improvement
Energy Consumption	240 kWh	204 kWh	15.0%
Carbon Emissions	0.18 tCO2	0.14 tCO2	22.2%
Peak Demand Shift	12.0 kW	8.5 kW	29.1%

The 29.1% shift in peak demand represents a massive benefit not just to the end-user, but to grid operators attempting to balance load distribution during peak evening hours.

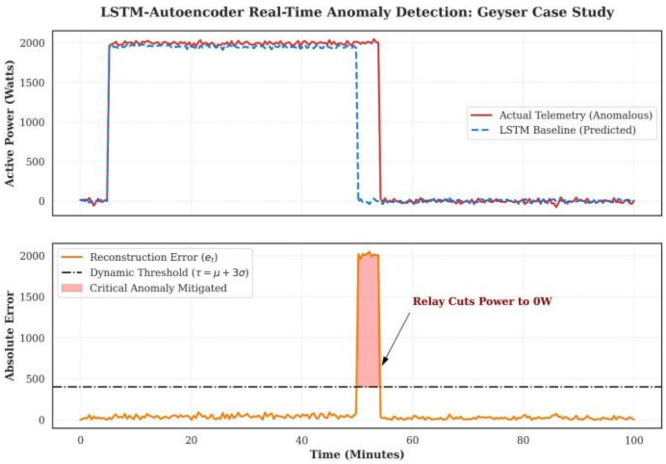

Fig. 6. Real-time tracking of LSTM-AE detecting and isolating an anomalous 1995W heating load when the temporal reconstruction error exceeds the dynamic threshold.

Result Interpretation:

As demonstrated in Fig. 6, the LSTM-Autoencoder successfully flags a temporal anomaly when the geyser operates beyond its predicted 45-minute baseline. The system autonomously triggers the relay command to isolate the circuit within four minutes of detection, physically mitigating the energy waste and instantly returning the reconstruction error to safe baseline levels.

B. Carbon Impact Analysis and Behavioral Shifts

Beyond automated emergency control, the cloud engine serves an educational role. By integrating local grid emission factors (e.g., carbon intensity per kWh based on the regional

VII. CONCLUSION

Sustainify demonstrates that high-fidelity, industrial-grade energy management can be achieved in residential spaces through frugal innovation, smart networking, and advanced AI. By empowering households with highly granular environmental data and automated, fail-safe control, the system effectively transitions home energy management from a reactive chore to a proactive, sustainable practice.

The successful implementation of the LSTM-Autoencoder proves that edge-to-cloud IoT devices can reliably perform autonomous mitigation of anomalous loads, preventing massive energy waste and potential electrical hazards. Future work will explore the integration of Sustainify with local residential microgrids and rooftop solar inverters to enable neighborhood-level energy sharing and further enhance municipal grid stabilization.

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