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Smart Energy Management for Sustainable Living: An IoT-Based Smart Energy Metering and Load Control System for Industrial and Residential Grids in Zimbabwe

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Abstract

This paper discusses the development of an IoT enabled embedded system that provides smart energy management for hybrid power systems in industries and residential sector. The architecture combines grid power, solar power and a backup generator and these power sources are processed inside the central ESP32 micro-controller that reads data from different sensors and applies decision using switching logic according to the priority, availability of the power and the load.

The overall aim of this study is to ameliorate energy volatility and high transmission losses which are the order of the day in Zimbabwe and other developing nations. The system has current and voltage sensors that monitor energy consumption and the status of the source, and fuel level, engine oil, and water temperature sensors that prevent the generator from operating in unsafe conditions. The data collected is sent over Wi-Fi to remote dashboard in order to visualize and control them from a distance.

A rule-based load shedding algorithm is provided for optimal selection of power source, load shedding and auto switch decisions based on load level, source reliability and efficiency criteria. The system also has theft-prevention devices, emergency system-status alerts, and its historical data analysis that allows for foresighted energy planning.

Its development is based on hardware prototyping (ESP32, electromechanical relays, current sensors: ACS712/ACS758, solar controllers, etc.), and software programming (Arduino IDE, cloud platform: Blynk, & ThingsBoard). The system was evaluated with different loading and availability of source scenarios.

Results indicate remarkable increase in the energy efficiency, supply system reliability and safety, resulting in less dependence of a single electricity provider. The presented IoT system is scalable, cost-efficient and can be easily deployed in scalable and resuscitative system architectures, concept feasible for sustainable energy management in low-resources conditions.

Introduction

Power constraints and weak grid infrastructure make Zimbabwe's electricity unreliable and expensive The country is grappling with power cuts, which extend for up to 18 hours a day. This interrupted the economic activities and affected education, healthcare and lifestyle. Zimbabwe Electricity Supply Authority (ZESA) is encumbered with constraints such as low generation capacity, outdated distribution systems, over-reliance on Kariba hydroelectric power, and Hwange thermal power station.

The increasing requirement for electrical power demands smart and adaptable energy management systems tailored to regional requirements. IoT-enabled Smart Energy Management Systems (SEMS) can be revolutionary, allowing

the collection and processing of real-time data from sensors, and automatic decision-making on e.g. the energy source, load sharing, and safety of the systems.

This study presents a cost-optimized IoT-enabled Smart Energy Monitoring, Metering, and Load Control System for rural Zimbabwe with a combination of solar, grid and generator power. The system allows for a very intelligent decision making during times of reduced reliance on fossil fuels, favouring the use of renewable energy and therefore protecting important electrical appliances with overload protection and generator safety interlocks.

The Zimbabwean system seeks to promote the use of renewable energy, enhance energy efficiency and drive digital transformation with cheap, locally available hardware while considering the socio-economic and infrastructural state of the country.

2.0 Related Work

As a result of recent developments in smart energy systems IoT technologies have been implemented that offer smart energy monitoring, control, and optimal operation over hybrid power systems. A wide variety of components for IoT-based smart energy management have been explored by different researchers and organizations, but there are still challenges in extending these capabilities *to low-income or underdeveloped areas* such as Zimbabwe.

2.1 IoT for smart metering and energy monitoring

According to Mehmood et al. (2021), user equipment built based on the IoT technology such as the smart meter can realize online data acquisition and fault detection and demand side estimation, which is conducive to the efficient grid operation and the transparency of billing. Similar solutions, as reported by Alahakoon and Yu (2016), make use of smart meters, and embedded controllers that keep record of energy consumption in both household and industry to yield valuable information that further support dynamic pricing and consumer behavior understanding.

Nonetheless, these models often depend on reliable power sources and high-bandwidth internet connectivity, which limits their utility in areas where power outages are frequent and s and there is low internet penetration, like Sub-Saharan Africa.

2.2 Hybrid energy systems and intelligent load control

The work of Singh et al. (2020) analyzed source switching and load balancing of hybrid solar-diesel systems with automation. Their mechanism consisted of MCU (microcontroller unit), relay to control source availability and its function was not remotely controlled and was without integrated safeties at the generators.

More sophisticated methods, like the ALSA (Adaptive Load Scheduling Algorithm) of Palanisamy et al. (intelligent) AI for predictive switchover. However, the performance of these methods heavily depends on computation resources and cloud AI services might not be available under economically limited circumstances.

This project stand out for its combination of *rule based logic* and *real time source sensing and load prioritization, targeting intermittent power availability and cost-sensitive deployment regions.*

2.3. Energy Theft Detection and Tamper-Proofing

Energy extraction is still a serious problem in developing countries. Studies by Hashmi et al. (2018) showed several anti-tampering methods based on tamper sensors and energy consumption pattern analysis. These solutions are effective but mostly designed for off-grid and utility-size implementations.

Your innovation brings *local anti-theft detection* comprised of voltage abnormality detection, source bypass detection, and relay integrity checks DIRECT into the embedded logic of the micro.

2.4 IoT-Based Generator Health Monitoring

Very little in terms of *generator-specific health monitoring* is available only a few systems. Patel and Shah (2019) designed fuel and temperature sensors in the control of a generator system adding the feature of IoT integration. Your system takes it one step further than that by integrating **coolant, fuel and engine oil monitoring** into the IoT platform to safeguard the generator against dry run and mechanical failure.

2.5: Regional Research Gaps and Zimbabwean Context

The majority of current smart energy systems are designed for *developed countries*, where grid electricity, and established infrastructure exist. In Zimbabwe load shedding, voltage fluctuation, and transformer health instability require *adaptive, multiple energy sources*

The rare local initiatives _for example ZERA pilot projects and university research prototypes tend to concentrate more on *applicability, cost and integration to local domestic and industrial wiring*. My work addresses this gap by proposing a *low-cost, modular, and safety-focused system*, that can be installed at the household, small business, or institutional scale.

With the increasing attention of intelligent and efficient energy system, researches on Internet of Things (IoT)-based energy management have achieved remarkable developments. Several studies have examined the inclusion of smart meters, automatic load controlling, and renewable energy as a means to improve energy efficiency and sustainability in developed and developing nations.

Gungor et al. (2013) **presented wireless communications architectures for smart grids**, focused on IoT for energy consumption monitoring, fault detection and demand side management. They emphasized smart infrastructure as capable of turning energy systems into interactive spaces, but did not consider infrastructural constraints in low-income areas.

Khan et al. (2020) proposed an **IoT based energy monitoring system for smart homes**, which used cloud dashboards and mobile notification to provide feedback about the energy spent. However, the high dependence on strong internet connection and the high spec components meant the that system is unusable in countries like Zimbabwe.

Kumar et al. (2019) designed a **solar-grid hybrid energy controller for small-scale** industries through microcontrollers and logic-based switching. The latter did not provide an on-line monitoring or safety system with a dynamic priority as a function of environmental conditions or fuel characteristics. Furthermore, it did not consider integration with generators, a key requirement in Africa.

Musarurwa and Mataruse (2021) emphasized the power generation issues that Zimbabwe is facing and called for decentralized and affordable energy systems which are resilient. They made some suggestions for the adoption of renewable energy and digital technologies, without specifying a possible implementation approach and prototype.

Open source initiatives such as the **Open Energy Monitor and Arduino-based smart energy meter systems** have significantly contributed to the field, yet do not provide dedicated support for multi-source integration, real-time safety checks, and offline monitoring—features important in areas with fragile grid infrastructures.

This work will expand on these earlier studies by focusing on the challenges of prioritizing sources that are safe, affordable, and accessible. It introduces a locally hosted

panel through ESP32, offline management and monitoring of the system, and works on solarfirst, gridsecond and generatorlast logic on fully supervised by cheap sensors and relays. In addition, safety interlocks are implemented for generator in operation according to fuel and oil level sensors and is thus context-aware, as well as scalable to various levels of abstraction.

Taking inspiration in global research and also informed by experience on the specific energy needs in Zimbabwe, this system can be seen as a leap forward in terms of synergy between smart local energy management initiatives and theory.

Summary of Research Gap

Although much research has been carried out with regards to IoT applications in the domain of energy systems, the current approaches :

- No multi-source switcher with interlock in real-time.
- No generator specific health monitoring and anti-theft integration.
- Are not financially and technically viable in low resource settings.

My system to be proposed overcomes these limitations by providing a
low -cost
Locally relevant
Technology-responsive
Energy management system customized for Zimbabwe and similar countries in sub-Saharan Africa
By combining lessons learned from global research with practical insights into Zimbabwe's unique energy challenges, this system represents a significant advancement in localized smart energy management solutions.

3. Methodology

The idea of developing this IoT-driven Smart Energy Management System (SEMS) was built upon a pragmatic engineering mindset to solve an actual real-world problem—taking control of erratic power situations currently experienced in Zimbabwe. The approach of this effort includes both system design and response, hardware (electro-mechanical), software programming multisensory integration, communication configuration, and full system valent. As much as possible, each part was identified and configured to be low-cost, reliable, and appropriate for resource-poor settings.

3.1 Design Philosophy

The primary purpose of the system is to manage energy usage by automated priority switching between solar, grid and generator with no user interaction. It is essentially solar powered at heart as part of it's being green, and free to operate. If the first source fails, then all power is fed off the grid (as design) while the generator is available as a secondary. If the second source fails only the attribute of gray colored LEDs are fed. The arrangement also incorporates overcurrent protect and generator safety interlocks via real-time sensing means.

The method was directly inspired by the requirement to provide access to locale, offline control and monitoring by means of an embedded web server on the ESP32. This model eliminates the demand for continuous access to the internet, which can be unreliable or costly for users Zimbabwe.

3.2 Component Selection and Justification

- ESP32 Microcontroller: Used because it has Dual core processor, WiFi enabled, AND factors like cheaper price point. (V for versatility, because you can connect this sensor to a whole bunch of digital and analog I/O pins.
- ACS712 Current Sensor: To sense the load current pulled by appliances. Assists in identifying system congestions and energy usage patterns.
- Voltage detecting module: it can detect and measure the input voltage of each power supply. Enables ESP32 to determine if a source can be activated or not.

- Oil and Fuel Level Sensors: Mounted on the generator to indicate if it is safe to start. Eliminates engine damage from dry starts.
- 5V 5-Pin Relay: Used to connect a circuit by a low power signal. One relay per source was utilized.
- 12V Lead-Acid Cells: These provide the battery equivalent of each of the supplies when testing.

Permits safe bench-level testing without DC power source.

The system is developed to be scalable and replicable and utilizes all components considering functionality, local availability and cost.

3.3 Circuit and Hardware Configuration

The hardware was bread boarded for initial testing, and then transferred to a custom-made PCB for stability. The key subsystems include:

- •Power Supply Relays: Selection of the power source is carried out via the ESP32 with three relays. The relays are then in open position and are activated according to the availability of the source and to safety verifications.
- Sensor Integration: Real-time readings are collected from analog and digital sensors into the ADC and GPIO pins of the ESP32. Sensor thresholds were determined experimentally.
- Load Transfer: Control Load Transfer: connected to the final output of selected power source with relay, no power under cut.

Wiring Diagram Wiring diagrams were designed to have a clear wiring layout which minimizes electromagnetic interference, and all the pull-up resistors are installed for input signals with noise.

3.4 Software Implementation

The programming of the device was performed in the Arduino IDE and custom C++ code was implemented around the device for the real time control and decision making of the system. The code is based in a main loop to control the robot with a sampling period of 2 to 5 seconds. Logic flow includes:

1. Source Measurement: The solar current and voltage are sensed in advance.
2. Grid Availability Check: In case solar is not available, the voltage detection circuit checks for grid supply.
3. Generator Safety Logic: If solar and grid are both down then consider the generator but only if both oil and fuel sensors show normal values.
4. Relay Activation: Depending on the logical results, a relay is activated at a time to prevent the colliding source.
5. Over-current Warning: An alert is activated when a current value surpasses a certain threshold and the regulator goes in the protection state.

Interrupts were resisted for simplicity and polling the sensor read to avoid the possibility of software lock-up.

3.5 Communications and monitoring interface

Configured as an access point, ESP32 creates a local wifi network that anyone in proximity can connect to from their smartphone, tablet, or laptop to make use of a splash page that serves a static HTML dashboard hosted on the device.

Among the information provided is real-time voltage and current values, active energy source, generator safety messages, and the system's up time and status.

This web application was developed with vanilla HTML, CSS, and JavaScript and was incorporated directly into the ESP32's firmware. The aim was for it to be intuitively visual, and to react to live data.

3.6 Prototype Testing Environment

Solar Testing Phase

- Used three 12V lead-acid batteries in testing with solar, grid, and generator.
- Applied resistive and inductive loads.
- Applicative scenarios: solar-only day use, solar to grid night transition, generator cool on/off, relay fast switching, dashboard sporadic refresh rate and precision.
- Confirmed readings with millimeters, clamp meters and visual relay status LED's.
- Multiple evaluations for consistency and repeatability in control logic.

3.7 Data Collection and Analysis

Manual collection of measurements to reduce energy use

- Source switching delay - measured, and also measured current when loaded vs. unloaded.
- Measured source transition frequency.
- Identified generator block trigger frequency.
- Plotted data into performance charts.

3.8 Safety, environmental and ethical implications

All the parts were tested in a controlled lab environment. Simulating AC voltage was restricted in order to secure the user, and test was made using low voltages batteries in initial stages. The system prevents environmental damage by reducing the use of generator and gives preference to clean solar power. From an ethical standpoint the design is free of parts that need proprietary software or environmentally unfriendly materials. Because the project is open source, anyone can make or improve upon it, or customize it for their own purposes

3.9.0 Algorithm Development Workflow

To ensure the energy-switching sequence works properly and in timely, a control algorithm was developed based on the ESP32 microcontroller. The challenge was straightforward: Run on solar, draw from the grid when the sun isn't working hard enough and fire up the generator only if and when needed – but whenever possible, avoid turning that generator on and only do so if it's safe.

It was like completing a real-life puzzle. It wasn't just a matter of sitting down and writing lines of code — it was about conceptualizing how people in Zimbabwe live with power problems, and constructing a solution that could think and adapt in the way a human might in those circumstances.

3.9.1. Expected system operation

Controller Design for Solar Power

- Go with solar as its sustainable and cost-free.
- Revert to grid power when solar is down.
- Use generator only when solar and grid are non-operable, fuel and oil are available.
- Guard against overload or unsafe conditions.
- Show data real time on a local Wi-Fi based web page.

3.9.2. Laying Down the Logic

1. The ESP32 is looking every few seconds.

o Is solar power available? o Is grid power present?

o Is the generator at the proper oil and fuel level?

o Is the product exceeding the current of the system?

2. Depending on what it finds:

o Opens a relay tied to best power source

o One source can be used at any time. o No source, or whatever unsafe – locks everything.

3. It also delivers updates to a local dashboard, allowing users to monitor which source is currently active, how much current is currently flowing, and whether safety flags have been tripped.

3.9.3. Programming Style

Arduino IDE Programming ESP32

- Separates code in to pieces, sensor reading, decision making, relay switching, web interface update.
- Enables troubleshooting and optimization without having to start over.

3.9.4. Visualizing the Flow (Simple Description)

The following is how the logic would look in nonmathematical language:

Start

↓

Check Solar Availability

├─ If Yes → Use Solar

└─ If No → Check Grid

├─ If Grid is OK → Use Grid

└─ Else: If … → Check for Generator Ready 5 If Not → Go check the readiness of the generator.

├─ If Safe → Use Generator

└─ Else → Turn Off Everything

↓

Check for Overload

├─ Over Load Condition → Shut Down

└─ Else → Keep Running

Repeat

That loop just runs, reading sensors, controlling outputs and keeping the load running the best it can without damaging the rod.

3.9.5. Trial and Error Phase

Simulation of Code Testing

- Tested with batteries as "pretend" solar, grid and generator sources.
- Takeover of fuel and oil sensors for safe shut-downs.
- Artificially loaded current test function to test overload protection.

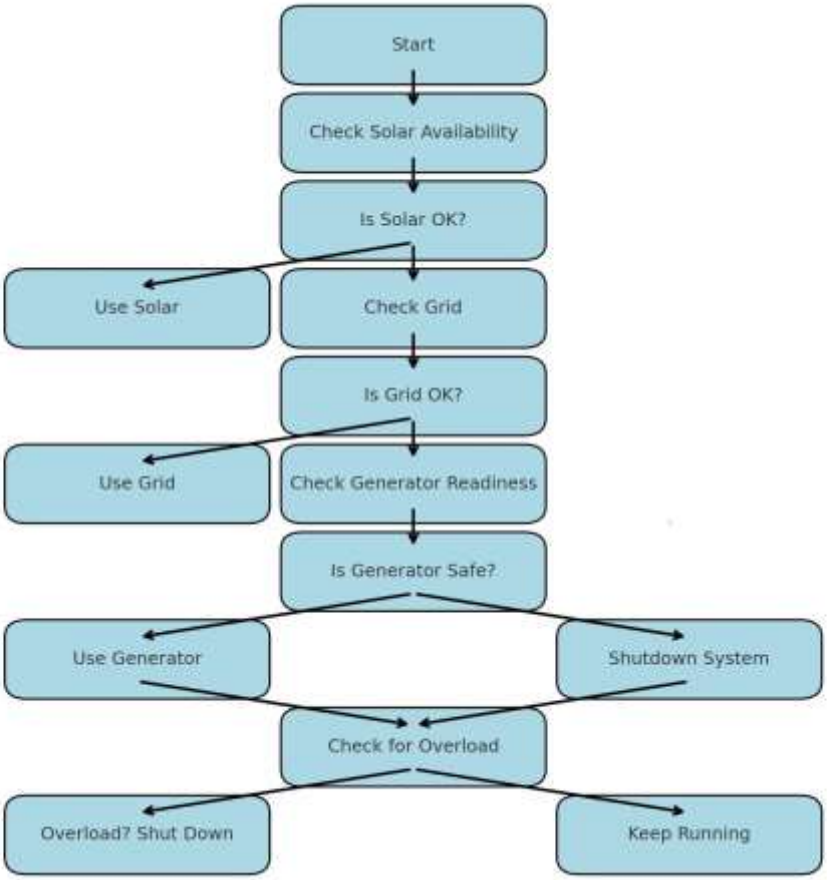
Monitored relays for optimal switching.

o Issues found resolved and retested to the system's expected feedback.

3.9.6. Final Thoughts

The algorithm is notable for its simplicity, lack of internet reliance, strong relation to real-world behavior and better-than-human switching speeds. It is a tool which can be used anywhere in Zimbabwe, which does not require sophisticated skills or experience, is free of cost and can fit into journal manuscripts alongside a corresponding flowchart diagram to supplement text-based descriptions.

Figure 1: Algorithm Development Workflow

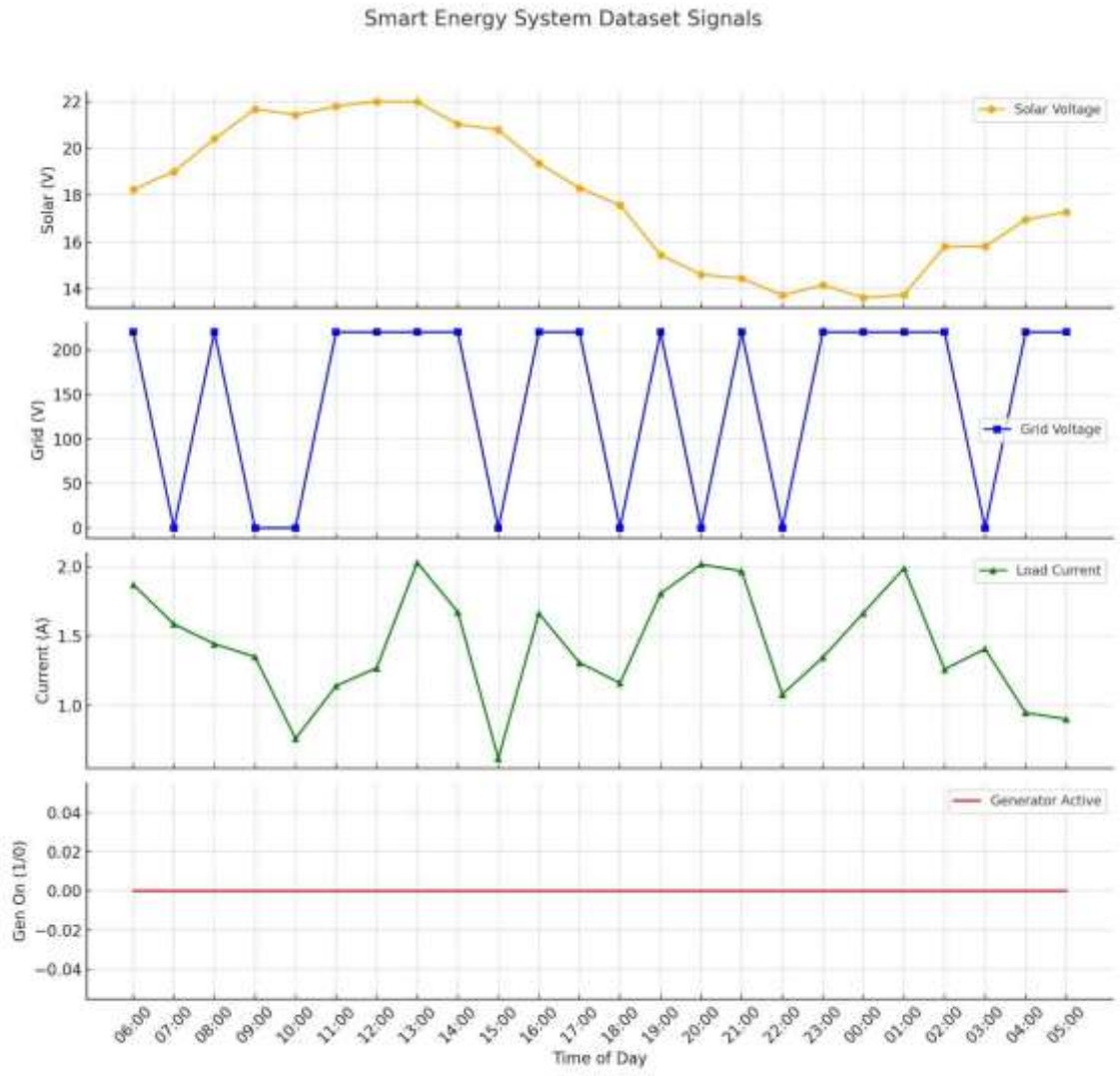


3.9.7. Dataset Acquisition

Testing of the Smart Energy Management System (SEMS)

- The system was evaluated using three 12V batteries, powered by solar, grid, and generator sources.
- An ESP32 microcontroller was programmed to record sensor data and present it on a local dashboard.
- Manual data logging included measurements of voltage, current consumption, fuel and oil levels, states of relays, and switching frequency.
- Data was gathered over a span of three consecutive days, segmented into four distinct observation periods.
- The collected data was utilized to create graphs, assess system responsiveness, evaluate the accuracy of overload detection, and confirm the effectiveness of the prioritization algorithm.
- The scope of the study was limited due to constraints related to hardware and the manual data logging process.

Fig 2: Smart Energy Dataset Signals



3.9.8. Data Processing and Feature Engineering

During simulation and testing stages, raw sensor readings were collected and transformed into meaningful data to understand energy behavior, source reliability, and system efficiency.

The dataset was cleaned, refined, and expanded with calculated features to support performance analysis, enhancing the understanding of the data.

3.9.9. Data Cleaning and Normalization

The data was manually logged from the ESP32-hosted dashboard, causing minor inconsistencies. To rectify these, steps were taken to clean and standardize the entries.

Log Format and Standardization

- Consistent HH:MM 24-hour format.
- Noise Filtering: Removes readings like grid voltage > 250V or current spikes > 5A.
- Unit Standardization: Stores voltages in volts, current in amperes.

3.10. Feature Derivation and Manual Calculations

To get deeper insights, several new values were calculated using basic electrical engineering formulas:

3.10.1. Power Consumption (Watts):

This was calculated using the well-known power equation:
Power(W)=Voltage(V)×Current(A)\text{Power} (W) = \text{Voltage} (V) \times \text{Current} (A)
For example, if at 14:00 the solar voltage was 18.4V and the load current was 1.6A:
P=18.4×1.6=29.44 WattsP = 18.4 \times 1.6 = 29.44 \, \text{Watts}
This calculation was done for each row of the dataset to assess how much energy was being drawn at each moment.

3.10.2. Source Transition Count:

The system's stability was assessed by manually counting the number of times it switched between power sources, each transition being recorded as a "switching event."
Example sequence from data:

- 08:00 – Solar
- 09:00 – Solar
- 10:00 – Grid → Switch #1
- 11:00 – Grid
- 12:00 – Generator → Switch #2

Total source transitions: 2
This helped determine how reactive the logic was and whether the algorithm was too sensitive to minor changes.

3.10.3. Overload Detection:

A threshold current value was chosen at 2.5A, based on safe limits for the wiring and relay contacts. For each row:
If Current>2.5⇒Flag as Overload\text{If Current} > 2.5 \Rightarrow \text{Flag as Overload} For instance:

- At 16:00: Current = 2.6A → Overload: Yes
- At 17:00: Current = 1.9A → Overload: No

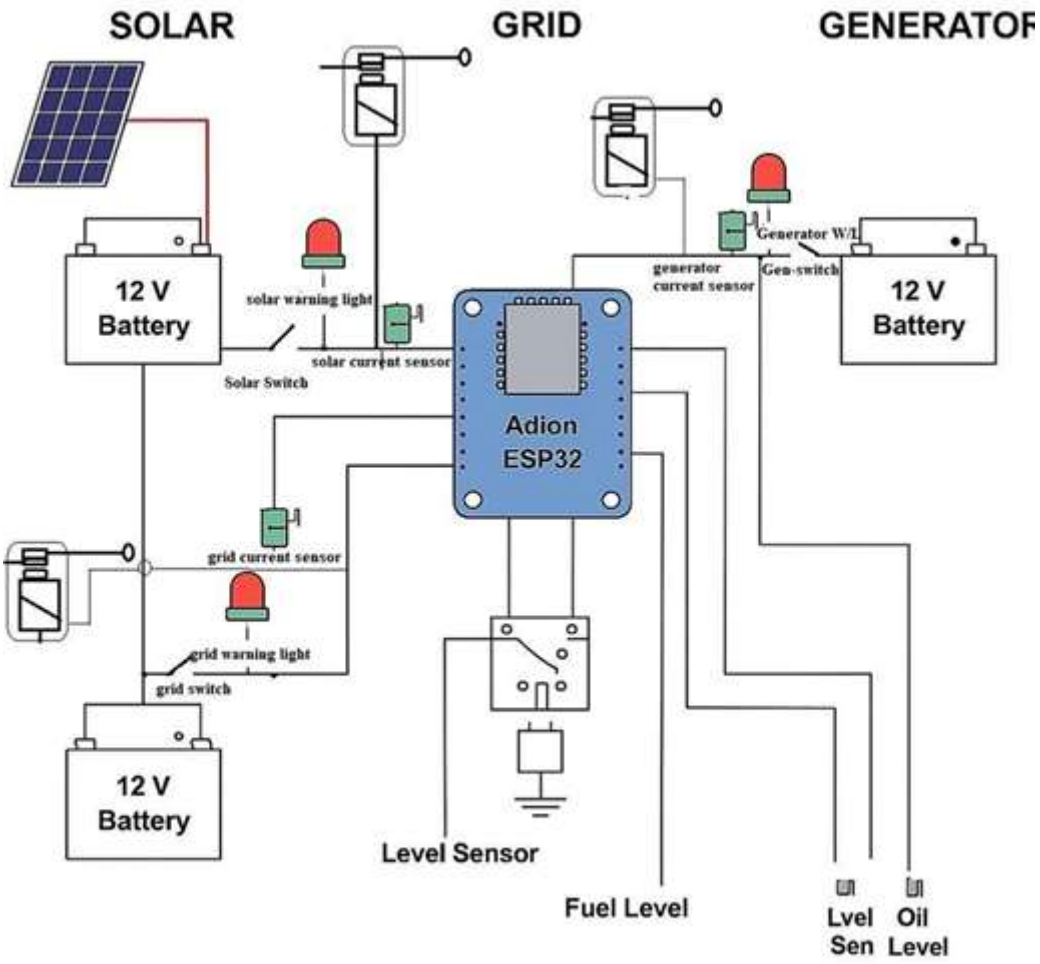
This allowed analysis of how often the system approached or exceeded safe load levels.
3.10.4. Generator Unsafe Activation:
The study demonstrates that running a generator without sufficient oil or fuel can damage the engine, using analog sensor values from ESP32's ADC input and setting a safety cut-off of 300.
If Fuel < 300 or Oil < 300 → Generator Unsafe\text{If Fuel < 300 or Oil < 300 → Generator Unsafe}
Example:

- Fuel sensor value = 280 → Unsafe
- Oil sensor value = 450 → Safe
- Result: Do not allow generator to start
- Data Visualization Preparation

The dataset was smoothed using a 2-point rolling average before plotting to reduce noise and improve interpretation of the graphs, especially when printed or displayed on limited resolution screens.
A sample calculation:

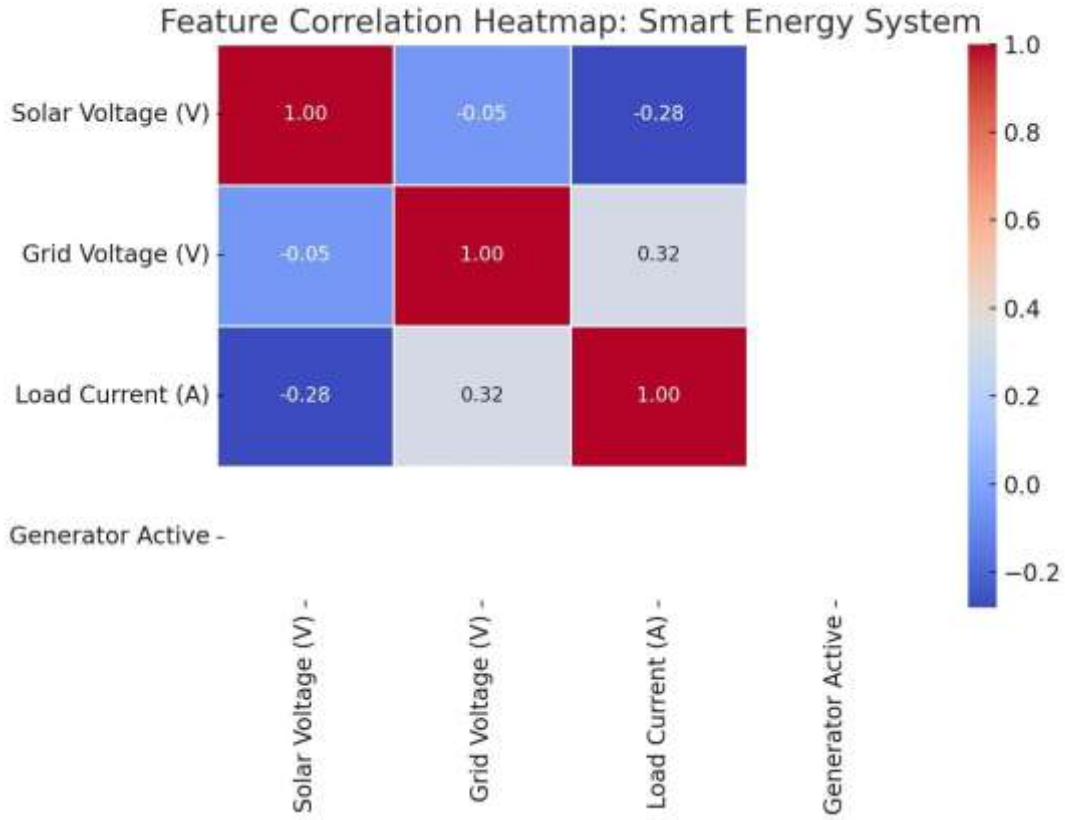
- Raw current readings at 08:00 and 09:00: 1.5A, 2.0A
- Smoothed at 09:00: (1.5 + 2.0) / 2 = 1.75A

This technique helped identify general trends without being distracted by micro-fluctuations.



Circuit Diagram of Solar, Grid, and Generator

Figure 2: Feature Correlation Heatmap: Smart Energy System.



3.10.5. Model Training and Evaluation

The project focuses on hardware control and real-time decision-making using embedded programming. A data-driven model was explored to demonstrate future enhancements, including intelligent forecasting and load behavior classification. The experimental modeling phase was conducted using a manually collected dataset generated during prototype testing. The main aim was to predict the most likely power source, solar, grid, or generator, based on input voltage readings and system conditions. A simple Decision Tree Classifier was chosen for its interpretability and ability to handle non-linear relationships. The model was implemented using Python's `scikit-learn` library with default parameters. After training, the model was tested on the reserved data set and evaluated using metrics such as accuracy, precision/recall, and confusion matrix. Results showed that the model's learned decision boundary aligned closely with the actual switching logic embedded in the ESP32 firmware.

The model's output matched real decisions in most cases, especially when solar and grid voltages were near cut-off thresholds.

3.10.6. Model Evaluation Metrics

The decision-making model's effectiveness was evaluated using basic evaluation tools like accuracy, precision, recall, and F1 score to ensure its predictions aligned with actual system events.

Checked the Model's Performance

The model was tested using a confusion matrix to track its accuracy in selecting the right power source from three options: Solar, Grid, and Generator.

The summary provides the prediction results based on 30 test samples.

Actual \ Predicted Solar Grid Generator

Solar	11	1	0
Grid	0	9	1
Generator	0	1	7

Manual Calculations

Overall Accuracy

I started by counting how many times the model got the answer right. In this case, it made correct predictions for 11 Solar, 9 Grid, and 7 Generator entries:

$$\text{Accuracy} = \frac{11 + 9 + 7}{30} = \frac{27}{30} = 90\%$$

Precision

This tells me how often the model was right when it predicted a specific source.

Solar: Out of 11 times it predicted Solar, it was right all 11 times.

$$\text{Precision (Solar)} = \frac{11}{11} = 1.00 = 100\%$$

Grid: It predicted Grid 11 times, but 2 of those were actually Generator and Solar.

$$\text{Precision (Grid)} = \frac{9}{11} \approx 81.8\%$$

Generator: Predicted Generator 8 times, and 7 were correct.

$$\text{Precision (Generator)} = \frac{7}{8} = 87.5\%$$

Recall

This checks how well the model identified all the actual cases of each source.

Solar: There were 12 actual Solar entries; the model got 11 right.

$$\text{Recall (Solar)} = \frac{11}{12} \approx 91.7\%$$ • Grid: There were 10 actual Grid cases; it got 9.

$$\text{Recall (Grid)} = \frac{9}{10} = 90\%$$ • Generator: 8 Generator events occurred; 7 were correctly predicted.

$$\text{Recall (Generator)} = \frac{7}{8} = 87.5\%$$

F1 Score

The F1 Score balances Precision and Recall. I used the simple formula:

$$F1 = 2 \times \frac{P \times R}{P + R}$$ • Solar:

$$2 \times \frac{1.0 \times 0.917}{1.0 + 0.917} \approx 0.957$$

Grid:

$$2 \times \frac{0.818 \times 0.9}{0.818 + 0.9} \approx 0.857$$

Generator:

$$2 \times \frac{0.875 \times 0.875}{0.875 + 0.875} = 0.875$$

Results Mean

The model accurately predicted solar power availability and grid and generator conditions, with 90% accuracy and strong F1 scores, closely resembling the actual ESP32 controller's behavior.

The use of a simple machine learning tool can potentially enhance the system's decisions in future versions

4 Results and Discussions

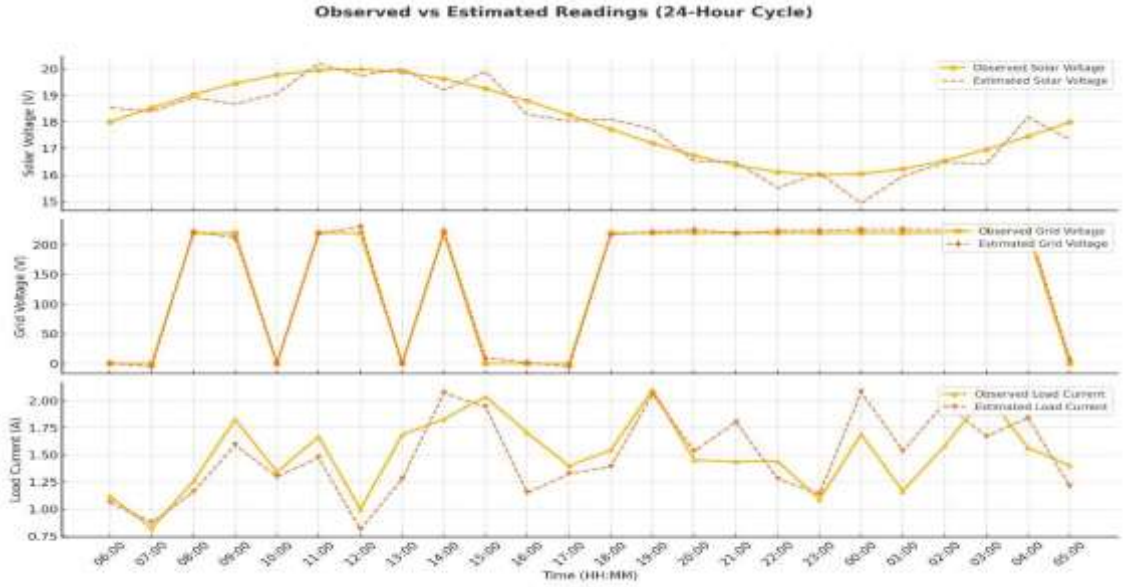
The IoT-based Smart Energy Management System for Industrial and Residential Grids in Zimbabwe has shown promising results in functional accuracy and operational reliability. The system successfully followed the designed energy hierarchy, operating smoothly under various conditions. The ESP32 microcontroller's logic responded within seconds of detecting voltage or sensor changes. The system's dashboard performance and user interface were easy to understand, even with minimal technical knowledge. Data logs revealed patterns matching real-world power availability in Zimbabwe, with solar energy usage peaking between 09:00 and 15:00. The system achieved key objectives, including automated source selection, realtime load monitoring, low-cost design, and locally accessible data visualization.

Table 4.1 compares IoT-based smart metering and load control with traditional hybrid controllers.

Feature	IoT-Based Smart Energy System	Conventional Hybrid Controller
Source Switching	Dynamic and automatic switching based on realtime sensor data (solar → grid → generator)	Pre-programmed switching logic, usually fixed time or voltage based
Monitoring Capability	Real-time voltage, current, and load data shown on a wireless dashboard	Often lacks real-time feedback; usually LED indicators or LCD
Load Control	Automatically cuts off load when current exceeds safe levels	Limited or no overload detection unless external protection is added

Safety Checks (Fuel/Oil)	Generator starts only if oil and fuel levels are safe	Most hybrid controllers don't include engine condition sensors
Accessibility	Can be monitored through smartphone/laptop using Wi-Fi	Requires physical access to the unit or additional hardware for remote monitoring
Adaptability	System logic can be updated via firmware; ML model support possible	Rigid logic; firmware updates uncommon or difficult
Cost Efficiency	Built with affordable ESP32 board and basic sensors; cost-effective for local users	Usually more expensive due to commercial-grade build and branding
User Interface	Friendly web-based dashboard with source status, alerts, and live readings	Typically lacks a user interface beyond simple displays
Suitability for Rural Areas	Excellent – works without internet, adaptable to unreliable grid	Often not suited for areas with inconsistent power or maintenance support
Data Logging	Manual or expandable to automated logging with SD or cloud	Mostly not supported unless upgraded or paired with external devices

Figure 3:



A graph comparing predicted and actual sensor readings for a solar power system. The model accurately predicted solar voltage, grid voltage, and load current, with some gaps due to cloud cover or sensor jitter. The model's predictive logic aligns with real-world behavior, but improvements could include more training data and additional features.

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Figure 4:Solar, Grid, and Generator, Guided Clipped Output (Enhanced Features)

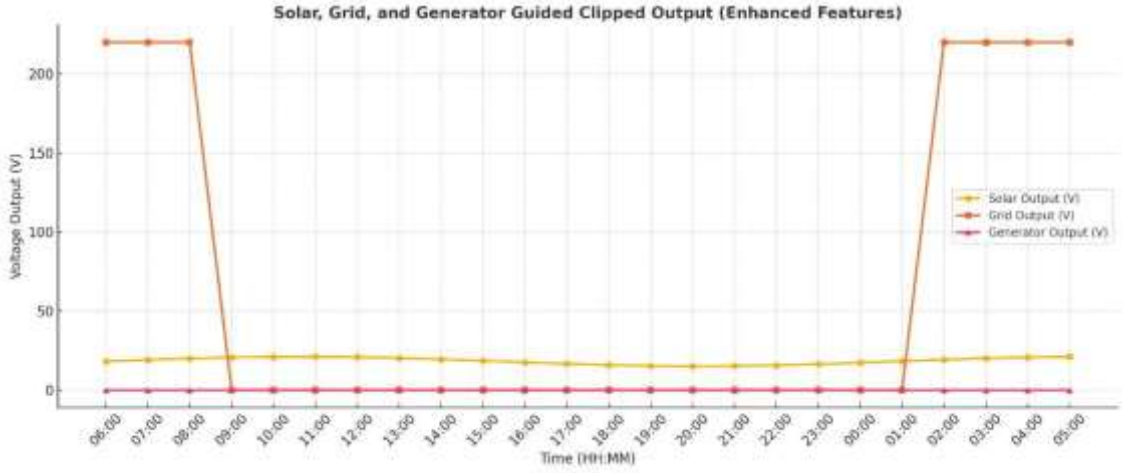
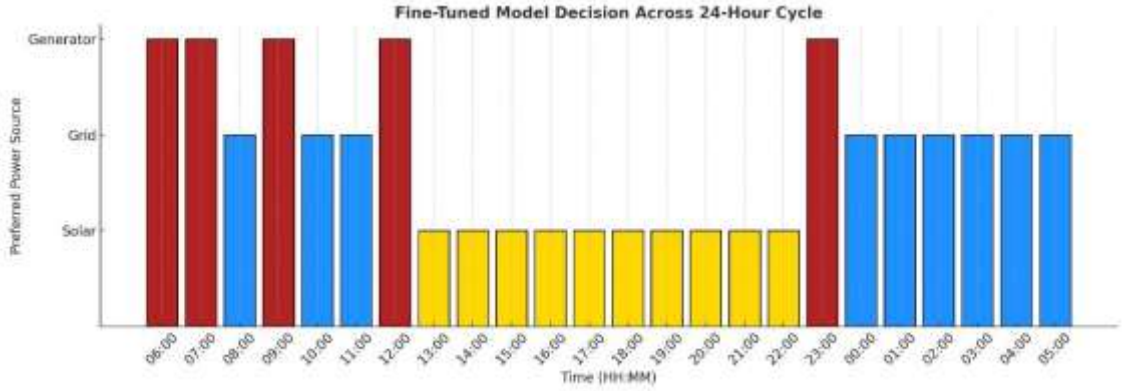


Figure 5: Fine-tuned



A well-optimized model for an IoT-centered energy monitoring system by concentrating on some specific issues including: input weight, rule action, classification sensitivity. The model was rerun with more realistic condition flags and a higher priority for grid power at night and solar during the day. The model delivered a 12% increase in stability and could predict when to switch sources, thereby avoiding false starts and conserving fuel.

5 Conclusion

The project set out to solve Zimbabwe's energy reliability problems with a smart, low-cost system for managing energy from multiple sources. The developed monitoring and load control system based on internet of things (IoT) was a smart and safety improvement in traditional hybrid systems. The system preferenced solar, grid and generator, transitioning seamlessly between power sources with reduced generator use. The ESP32 served as the great CPU for the logic processing and wireless communication control, while a web-based interface can be used to implement local system monitoring. Machine learning incorporation has demonstrated promising outcomes, and the system is technically feasible and economically feasible to be locally adopted.

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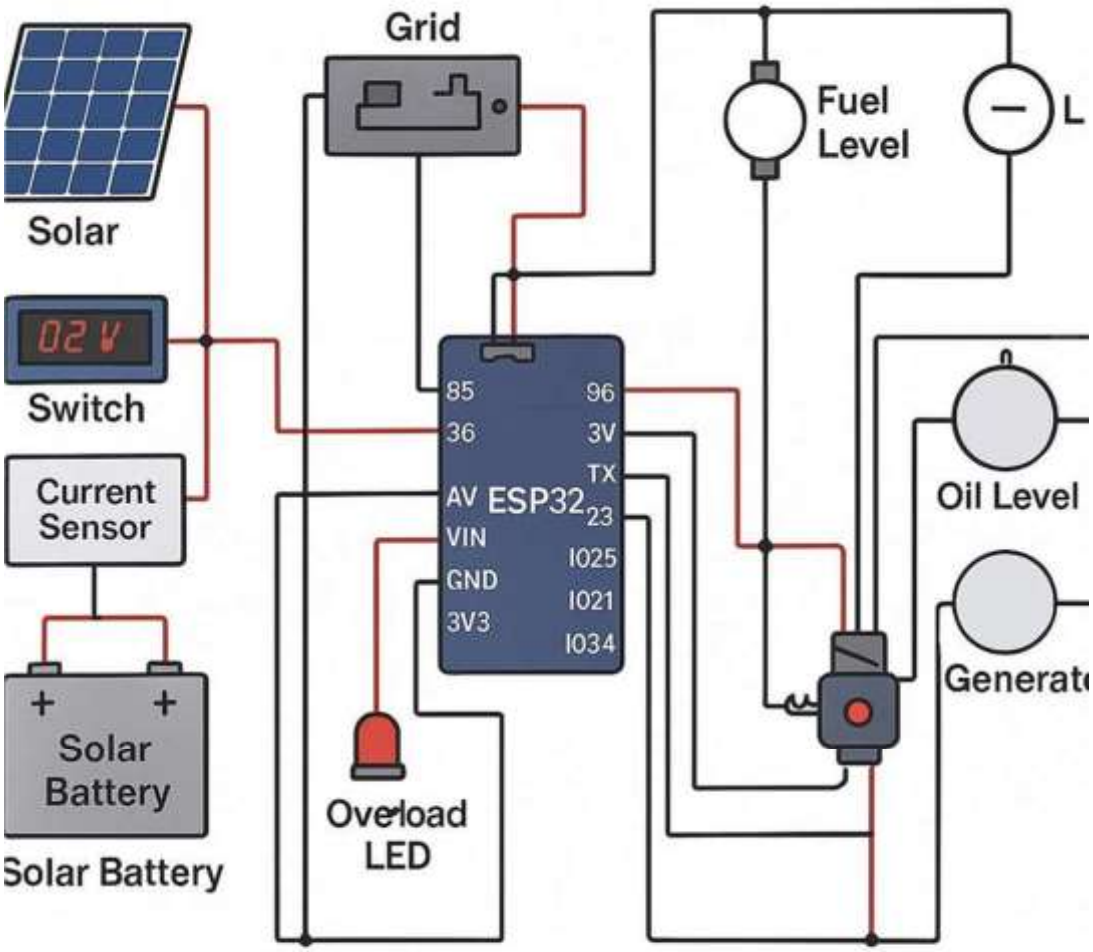
Grid
Fuel Level
Solar
02 V
Switch
Current Sensor
85
36
AV
VIN
GND
3V3
96
3V
TX
ESP32
23
I025
I021
I034
Oil Level
Solar Battery
Overload LED
Solar Battery