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COLLEGE OF ENGINEERING AND TECHNOLOGY

SCHOOL OF MECHANICAL, MANUFACTURING AND MATERIALS ENGINEERING

DEPARTMENT OF MECHATRONIC ENGINEERING

FINAL YEAR PROJECT PROPOSAL (FYP 22-5)

DESIGN AND IMPLEMENTATION OF AN OPEN-SOURCE SMART AC ENERGY LOGGER + PAYGO SYSTEM

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Declaration

We hereby declare that the work contained in this report is original, researched and documented by the undersigned students. It has not been used or presented elsewhere in any form for any awards, academic qualification or otherwise. Any material obtained from other parties has been duly referenced. We have ensured that no violation of copyright or intellectual property rights has been committed.

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Abstract

The deployment of decentralized renewable energy systems has significantly increased access to electricity for household and productive-use applications in off-grid and under-served regions. Many of these systems supply alternating current (AC) power through inverter-based architectures to support conventional appliances and equipment. Despite their widespread adoption, the long-term sustainability of such systems is often constrained by limited visibility into energy usage, inadequate operational monitoring, and weak access control mechanisms. Proprietary smart metering and Pay-As-You-Go (PAYGo) solutions exist but are typically costly, inflexible, and poorly suited for local customization and academic development.

This project proposes the design and implementation of an open-source Smart AC Energy Logger with integrated PAYGo and remote monitoring capabilities for decentralized renewable energy systems. The proposed system aims to accurately measure key AC electrical parameters including voltage, current, power, energy consumption, under inverter-fed load conditions. A microcontroller-based embedded platform will be developed to perform real-time data acquisition, true RMS computation, energy logging, and intelligent load control.

The system architecture incorporates modular PAYGo functionality supporting both time-based and energy-based access control, enabling flexible financing and usage management models. Secure communication between the energy logger and a cloud-based backend will be implemented using IoT technologies to facilitate remote monitoring, data visualization, and system management. Emphasis is placed on openness, scalability, and adaptability, with all hardware designs, firmware, and software developed using open-source tools and frameworks.

The expected outcome of the project is a functional prototype that demonstrates accurate AC energy metering, reliable access control, and real-time remote monitoring across representative productive-use applications. By addressing technical, operational, and financial challenges in a unified and open architecture, the proposed system contributes toward improving the sustainability, transparency, and scalability of AC-based renewable energy solutions.

Contents

1.   Introduction

1.1   Background

Access to reliable, affordable, and sustainable electricity remains a significant challenge in many rural and semi-urban areas of Kenya and other developing regions. Despite the widespread adoption of small-scale solar photovoltaic (PV) systems, issues related to energy usage monitoring, payment enforcement, and billing transparency continue to hinder sustainable operation.

Conventional off-grid solar installations often rely on:

- Manual meter readings
- Fixed monthly payments
- Physical tokens or proprietary Pay-As-You-Go (PAYGo)devices

These approaches are prone to billing disputes, energy misuse, poor accountability, and high system costs due to vendor lock-in and lack of interoperability.

Recent advancements in IoT, embedded systems, and mobile money platforms such as M-Pesa present an opportunity to modernize decentralized energy management. By integrating smart energy metering, secure digital payments, and remote monitoring, it is possible to deliver a scalable and transparent energy access solution.

This project proposes an open-source Smart Energy Logger integrated with a PAYGo system, designed specifically for solar-based AC energy systems. The solution leverages low-cost hardware, secure cryptographic authentication, and cloud-based communication to support flexible, pay-as-you-go electricity access for off-grid users.

1.2   Objectives

1.2.1   General Objective

To design and implement an open-source Smart AC Energy Logger with integrated PAYGo and remote monitoring capabilities.

1.2.2 Specific Objectives

- To design hardware capable of accurately measuring AC electrical parameters including voltage, current, power, and energy.

- To develop embedded firmware for real-time AC energy computation, data logging, and configurable control functions.

- To implement a modular PAYGo mechanism using M-Pesa-based micro-payments supporting time-based or energy-based access control for AC loads.

- To develop a cloud-based software platform for remote data storage, visualization, analytics, and system management.

- To implement secure token-based energy unlocking using cryptographic verification.

1.3 Justification

This project is justified on several grounds:

- Social Impact: Improves access to reliable electricity in underserved communities using flexible payment models.
- Economic Sustainability: Enables micro-payments, reducing the financial burden on low-income households.
- Technological Relevance: Combines IoT, embedded systems, cybersecurity, and fintech which are key skills in modern mechatronics.
- Environmental Benefits: Promotes the adoption of clean solar energy, reducing dependence on fossil fuels.
- Policy Alignment: Supports Kenya's rural electrification, renewable energy, and financial inclusion goals.
- Local Innovation: Open-source design encourages local manufacturing, maintenance, and customization.

1.4 Scope of the Project

The project scope includes:
- Design and fabrication of smart metering hardware
- AC voltage, current, power, and energy measurement
- PAYGo payment integration using M-Pesa
- Token-based power activation and deactivation
- Secure communication via MQTT
- Web-based dashboard for monitoring energy usage and payments
- Pilot testing under controlled loads

2. Literature Review

2.1 History of Solar Power Usage

Solar power for household and small-scale consumption originated from early scientific discoveries in the 19th century, notably the photovoltaic effect identified by Edmond Becquerel in 1839. Practical solar electricity only became possible in the 1950s with the development of silicon solar cells by Bell Laboratories. Due to high costs and low efficiencies, early applications were limited to specialized uses such as satellites and remote scientific equipment rather than domestic consumption.

In the 1970s and 1980s, rising fuel prices and energy access challenges led to the adoption of solar power for off-grid and rural applications. Small solar home systems were introduced to provide basic household services such as lighting and radio power, particularly in areas without grid electricity. These early systems were predominantly DC-based and marked the first widespread use of solar energy for household consumption and water pumping.

During the 1990s and 2000s, improvements in photovoltaic efficiency, battery storage, and power electronics significantly reduced system costs and improved reliability. Solar home systems became more common, supporting household lighting, phone charging, and entertainment appliances. Advances in inverter technology also enabled the use of AC power, allowing households to operate conventional appliances and expanding solar energy use to irrigation pumps and other productive applications.

From the 2010s to the present, the adoption of solar power accelerated through the introduction of Pay-As-You-Go financing models and smart energy technologies. These innovations made solar systems more affordable and manageable for low-income households while enabling remote monitoring and usage-based control. Today, solar power is widely used not only for household consumption but also for productive purposes such as irrigation, refrigeration, and small-scale enterprises, playing a crucial role in improving energy access and economic development.

2.2   AC Energy Systems in Productive Use Applications

Alternating Current (AC) energy systems are widely used in productive-use applications due to their ability to support high power demands, standardized voltage levels, and compatibility with conventional electrical equipment. In solar and hybrid energy setups, AC power is obtained through inverters that convert DC output from photovoltaic (PV) arrays into usable AC electricity. This enables direct operation of AC motors, pumps, and industrial machinery, as well as integration with mini-grids and national utility grids.

To highlight a few examples, AC energy systems power solar-driven irrigation pumps for large farms, grain milling and maize grinding machines, milk chilling and cold storage facilities, welding and carpentry workshops, and commercial buildings such as shops, schools, and health centers. AC systems are also essential in water treatment plants, bottling lines, and small manufacturing units, where three-phase AC loads and precise motor control are required.

As the deployment of AC energy systems in productive settings increases, accurate AC energy metering becomes critical for effective operation and financial sustainability. AC metering provides insights into energy consumption, peak demand, power quality, and equipment performance, enabling system operators to optimize energy use, detect faults, manage loads, and implement fair billing mechanisms. These capabilities enhance the reliability, efficiency, and long-term viability of AC-based productive-use energy solutions.

2.3   Smart Energy Metering Technologies

Smart energy metering has evolved from basic automated meter reading (AMR) to fully integrated systems capable of real-time monitoring, logging, and remote communication. Modern smart meters measure multiple electrical parameters, including:

- Voltage and current
- Instantaneous and average power
- Power factor
- Cumulative energy consumption

In the context of renewable energy systems, smart meters serve not only billing functions but also diagnostic and control roles. Integrating energy logging with PAYGo enhances accountability and system protection. Energy metering provides insights into energy consumption patterns, peak usage times, and efficiency of appliances or systems and when integrated with control logic it enables systems to respond intelligently to overloads, inefficiencies, and fault conditions.

Recent research favors microcontroller-based metering platforms, such as those built around ESP32 or ARM-based controllers, due to their low cost, sufficient computational capability, and ease of integration with communication modules. AC metering in inverter-

driven systems presents unique challenges due to waveform distortion and rapidly changing operating conditions. Traditional metering approaches based on peak or average values lead to significant errors. As a result, literature emphasizes true RMS sampling and digital signal processing techniques for accurate energy computation.

Commonly adopted AC metering components include:

- Current transformers (CTs) for non-intrusive current measurement
- Precision voltage sensors with galvanic isolation
- High-resolution ADCs for accurate sampling

Digital computation of real power typically involves synchronized sampling of voltage and current, followed by numerical integration. Research confirms that such approaches, when properly calibrated, can achieve accuracy suitable for both operational monitoring and billing-level

2.4 PAYGo Models

Pay-As-You-Go (PAYGo) systems have become a dominant financing model for AC solar technologies. This business model began in earnest in the early 2010s with companies such as M-KOPA, BBOXX and d.light which combined low-cost hardware, mobile money (M-Pesa) and remote device management to spread the upfront cost of solar home systems across micro-payments. Time-based PAYGo grants system access for a defined duration, while energy-based PAYGo limits usage based on consumed energy units. Literature indicates that energy-based PAYGo models offer greater fairness and efficiency by aligning payment directly with energy consumption. However, they require accurate AC energy metering and robust credit enforcement mechanisms. Time-based PAYGo systems are simpler to implement and are often preferred in early deployments or shared-use scenarios. Integration of PAYGo with AC energy meters allows automatic load disconnection upon credit exhaustion, reducing operational risk and manual intervention. Secure token generation, encrypted communication, and tamper detection are widely recommended to prevent fraud and system misuse. However, most PAYGo pump solutions remain proprietary, limiting adaptability and affordability

2.5 IoT and Cloud-Based Monitoring

Recent advancements in IoT technologies have enabled remote monitoring, control, and diagnostics of AC energy systems using communication technologies such as GSM, LTE, Ethernet, and low-power wide-area networks. Smart AC meters, sensors, and gateways continuously capture electrical parameters including voltage, current, frequency, power factor, and energy consumption, transmitting this data to cloud platforms for centralized access.

Cloud-based monitoring platforms provide real-time dashboards, data logging, analytics, and alert mechanisms, allowing operators to track system performance, detect faults, and manage loads remotely. In AC solar and hybrid systems, cloud connectivity also supports remote inverter configuration, firmware updates, and predictive maintenance, improving operational efficiency and reducing downtime.

Research highlights that cloud-connected AC energy monitoring systems enhance scalability, reliability, and transparency, especially in grid-connected, mini-grid, and distributed productive-use installations. The use of open APIs and modular software architectures enables seamless integration with billing systems, mobile payment platforms, utility management software, and third-party analytics tools, supporting data-driven decision-making and sustainable operation of AC energy systems.

2.6 Security and Data Integrity

Security is a recurring concern in smart metering and remote control systems. Unauthorized pump activation, meter bypassing, and data manipulation can undermine both technical operation and financial sustainability. Studies on smart grid and IoT security recommend:

- Hardware-based key storage
- Cryptographic authentication of control commands
- Encrypted communication channels

2.7 Review of previous works on the topic

1. OpenEnergyMonitor (Emon) — This is an open-source AC energy monitoring platform (EmonTx/EmonPi, libraries like EmonLib) for measuring mains voltage/current, computing power/energy, logging, and visualizing electricity data. It demonstrates practical, field-tested approaches for true-RMS sampling, CT/voltage sensing, calibration, and community documentation — a direct template for open AC metering hardware and firmware.

2. EnAccess / OpenSmartMeter (Open hardware smart meter initiative) This is an open-hardware smart meter repository and manufacturing pack (OpenSmartMeter) intended to be replicable and compliant with basic metering needs. It provides a real example of publishing full BOMs, PCB files, firmware, and casing to enable local fabrication — aligned with the "open" objective of this proposed concept.

3. ESP32 / ESP8266-based open energy meter projects (multiple community builds articles) Several community and magazine projects (ESP32 Energy Meter, ESPHome/ESP32EnergyMon Elektor labs) show how commodity MCUs can perform energy sampling, MQTT integration, and web dashboards. It proves that low-cost MCUs can implement true-RMS

sampling, remote telemetry, local logging, and OTA updates — core capabilities for a low-cost AC logger.

4. EnergyMe / EnergyMe-Home (recent open, multi-channel smart meter projects) This is a newer open projects aiming at multi-channel, protocol-rich energy meters (MQTT, Modbus, REST) with PCB and firmware published. It shows modern feature sets (multi-channel, APIs) that is desirable in a logger that must support multiple AC circuits or monitor generation and load simultaneously.

5. Academic and industry work on accurate metering for inverter-fed AC loads - Papers and technical articles that analyse measurement errors for non-sinusoidal/inverter-fed loads and recommend true-RMS sampling, synchronized V–I sampling, and digital filtering for reliable real-power computation. Inverter-fed AC appliances (PV + inverter systems) distort waveforms. These works provide the DSP/measurement algorithms and sampling strategies needed to get billing-grade accuracy.

6. Prepaid / PAYGo system research and major implementers (M-KOPA case studies, IRENA and World Bank briefs) Extensive literature and market reports documenting PAYGo business models (time- and energy-based), lessons from M-KOPA and similar providers, and policy/market analyses by IRENA and the World Bank. These works show how PAYGo scales financially, how token workflows and mobile money integrations operate in practice, and the socio-economic tradeoffs between time- and energy-based models. They also highlight common operational constraints (connectivity, callbacks, user experience).

7. Studies and pilot reports on PAYGo for productive uses (EnDev / GIZ scoping, country case studies) These are programmatic documents and scoping studies from development partners (EnDev, GIZ) assessing PAYGo adoption for productive uses including pumps and refrigeration. They provide operational requirements and success factors (service ecosystem, local manufacturing, and financing terms) that inform how an open AC logger + PAYGo should be designed for real deployments.

8. OpenMeter and open billing platforms (usage-based billing APIs) These are open-source billing stacks designed to support usage-based billing and token generation via APIs. PAYGo systems need a backend that can securely issue tokens, reconcile payments, and provide customer management; open billing platforms demonstrate available software building blocks.

9. Open / academic prepaid and IoT meter projects (ESP32 prepaid meters, GSM-enabled prepaid meters, conference papers) Numerous academic projects demonstrate prepaid or smart prepaid meters that use GSM for notifications, CT/PT sensing, and auto-cutoff on credit exhaustion. They provide tested architectures for credit enforcement, SMS/GSM fallbacks, and tamper alerts that are directly relevant for PAYGo integration in areas with intermittent Internet.

10. Secure element and token-signing practices (Microchip ATECC608A and related

work) These are industry secure elements (e.g., ATECC608A) and academic proposals combine secure hardware with signed tokens and encrypted comms to prevent token forgery and device cloning. Applying hardware security is essential for PAYGo systems where tokens unlock physical services; this body of work shows practical ways to secure keys and authenticate devices reliably.
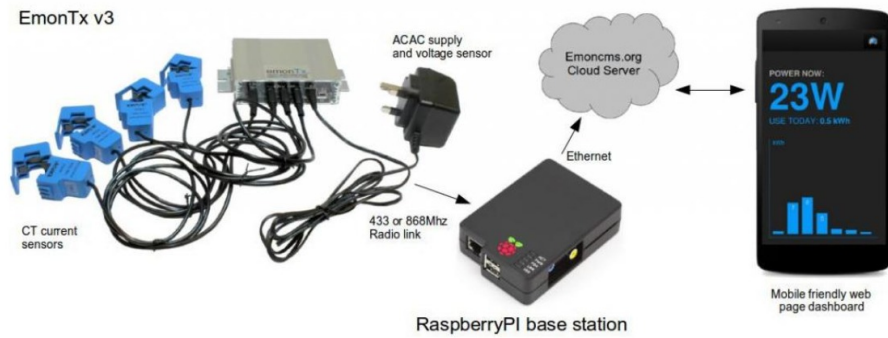
Proposed System Circuit Overview

Figure 2.1: Block level circuit diagram of the Smart AC Energy Logger with PAYGo control

2.8 Gap analysis

Previous Project / Work	Identified Limitations	How the Proposed Project Improves on the Limitations
OpenEnergyMonitor (EmonTx / EmonPi)	Focuses mainly on energy monitoring and visualization; lacks integrated PAYGo functionality and access control; limited focus on revenue-critical applications.	Integrates accurate AC metering with **PAYGo-based load control**, enabling both monitoring and controlled access suitable for productive and commercial energy use.
EnAccess Open Smart Meter Initiative	Provides open hardware designs but limited reference implementations for PAYGo logic, backend integration, and field-ready IoT deployment.	Extends open metering with a **complete end-to-end system**, including embedded PAYGo enforcement, cloud backend, and remote monitoring.
ESP32-Based Community Energy Meter Projects	Often lack metering accuracy validation, electrical isolation, and industrial robustness; security features are minimal.	Implements **true RMS AC metering**, proper isolation, protection circuitry, and secure communication suitable for real-world deployment.

Previous Project / Work	Identified Limitations	How the Proposed Project Improves on the Limitations
Academic Smart Meter Prototypes (e.g., Arduino-based meters)	Typically limited to laboratory demonstrations; do not address scalability, security, or long-term deployment.	Focuses on **prototype-level but deployment-oriented design**, including tamper resistance, modular architecture, and remote firmware support.
Commercial PAYGo Energy Systems (e.g., proprietary prepaid meters)	Closed-source hardware and firmware; limited transparency; difficult to customize or locally maintain.	Provides a **fully open-source hardware and software stack**, enabling customization, local repair, and academic reuse.
Time-Based PAYGo Systems	Do not account for actual energy consumption; may result in unfair billing for variable loads.	Supports **energy-based PAYGo**, enabling fair billing based on accurately measured AC energy usage.
Energy-Based PAYGo Systems	Require accurate metering and robust enforcement; often expensive and proprietary.	Delivers **low-cost, open, and accurate AC energy metering** integrated with PAYGo logic without vendor lock-in.
IoT Energy Monitoring Platforms	Often focus on data visualization only; lack load control and payment enforcement mechanisms.	Combines **IoT monitoring, PAYGo enforcement, and energy analytics** within a single integrated platform.
Proprietary Smart Meters	High cost, limited flexibility, and restricted access to system internals.	Emphasizes **affordability, openness, and adaptability** while retaining core smart metering functionality.
Single-Application Metering Solutions	Optimized for specific use cases, limiting reuse across applications.	Designed as an **application-agnostic AC energy logger**, adaptable to multiple productive-use and household scenarios.

Table 2.1: Comparison of Existing Smart Metering and PAYGo Systems with the Proposed Open-Source Smart AC Energy Logger

In a nutshell, existing smart metering solutions for AC renewable energy systems are predominantly proprietary, limiting transparency, adaptability, and local technical capacity. Many systems prioritize payment enforcement while providing limited insight into detailed AC energy parameters and system health. Furthermore, several academic prototypes focus on AC measurement or remote monitoring in isolation, without integrating configurable access control, secure communication, and cloud-based analytics in a single open-source platform. This project addresses these gaps by proposing a unified, open, and adaptable Smart AC Energy Logger architecture.

3. Methodology

3.1 System Overview

The proposed Smart Energy Logger with PAYGo functionality is designed as an integrated cyber-physical system combining power electronics, embedded systems, secure communication, and cloud-based software services. The system continuously measures electrical energy consumption at the load side, logs the data locally and remotely, and enforces access control based on digitally issued energy tokens. The design philosophy emphasizes safety, modularity, scalability, and security, while maintaining affordability and openness.

The system operates by placing a metering and control unit between the AC supply source and the electrical load. Electrical parameters are sensed in real time, processed by an embedded microcontroller, and used to compute instantaneous power and cumulative energy consumption. Access to the load is controlled electronically through a solid-state relay, which is activated only when a valid PAYGo token exists. Communication with the backend server enables token issuance, consumption reporting, and system monitoring

3.2 Hardware Architecture

The mechanical design of the Smart AC Energy Logger focuses on ensuring environmental protection, electrical safety, durability, tamper resistance, and ease of installation across a wide range of decentralized AC energy applications. Since the system is intended for deployment in off-grid, semi-industrial, and rural environments, the design prioritizes robustness and long-term reliability under harsh operating conditions.

A rugged enclosure will be designed using weather-resistant materials such as UV-stabilized polycarbonate, fiberglass-reinforced plastic, ABS plastic (Acrylonitrile Butadiene Styrene) or powder-coated mild steel, depending on cost and deployment requirements. The enclosure will be rated to at least IP54, with preference for IP65, to protect internal components from dust ingress, moisture, rain, insects, and accidental contact. Material selection will also consider resistance to corrosion, ultraviolet exposure, and mechanical impact.

Thermal management will be addressed through passive cooling strategies, including

ventilation slots with insect filters, internal airflow paths, and heat sinks for power-dissipating components such as relays, contactors, voltage regulators, and communication modules. Component placement will be optimized to prevent heat accumulation and to ensure reliable operation within specified temperature limits without reliance on active cooling.

The enclosure will be designed to support flexible mounting options, including wall mounting, pole mounting, or integration within existing electrical cabinets and control panels. Mounting provisions will allow installation close to the AC power source, inverter, or load distribution point to minimize cable lengths, voltage drops, and electromagnetic interference. Standardized mounting hole patterns and brackets will be used to simplify installation across different sites.

Internally, the mechanical layout will incorporate clear segregation between high-voltage AC power circuits and low-voltage control electronics. Physical barriers, insulating partitions, and adequate creepage and clearance distances will be maintained to comply with electrical safety best practices. This separation reduces electromagnetic interference, enhances measurement accuracy, and improves user safety during installation and maintenance.

Cable management will be carefully designed using appropriately sized cable glands, grommets, and strain reliefs to protect conductors from mechanical stress and environmental exposure. Clearly labeled entry points will be provided for AC supply lines, load connections, sensor wiring, and communication antennas. Internal wiring channels will promote neat routing, ease of troubleshooting, and reduced risk of accidental disconnection.

To address security and misuse concerns, the enclosure will incorporate tamper-resistant features such as lockable covers, concealed fasteners, and reinforced access points. Provisions may be included for tamper detection mechanisms, such as mechanical switches (microswitch), or sensors to detect unauthorized opening of the enclosure and trigger alerts or system responses via the control firmware.

The mechanical design will also emphasize maintainability and scalability. The enclosure will allow safe access for inspection, firmware updates, and component replacement without disturbing high-voltage wiring. Modular internal mounting rails or standoffs will enable future hardware expansion or upgrades with minimal mechanical redesign.

Overall, the mechanical design methodology ensures that the Smart AC Energy Logger is safe, robust, adaptable, and suitable for diverse productive-use energy environments, supporting reliable long-term operation while minimizing installation and maintenance complexity.

3.3 Electrical Design

This is organized into clearly defined functional blocks, each responsible for a specific task.

3.3.1 Power Supply Subsystem

The power supply subsystem is designed to provide stable and isolated low-voltage power rails required by the digital and communication components. An AC-to-DC adapter supplies an intermediate DC voltage, which is regulated using a buck converter (MP2307) to generate a stable 5 V rail. This 5 V rail supplies the GSM module and other peripheral components. A linear or low-noise regulator is then used to generate a 3.3 V rail for the ESP32 microcontroller and the secure element.

Proper decoupling capacitors are placed close to each regulator and load to minimize voltage ripple and electromagnetic interference. The separation of 5 V and 3.3 V domains ensures stable operation of sensitive digital circuits while accommodating higher current requirements of the GSM module.

3.3.2 Voltage Measurement Subsystem

Accurate voltage measurement is essential for correct power and energy computation. Since the system is designed to operate with AC voltages up to 500 V, a high-impedance resistive divider is employed to scale the mains voltage to a safe level suitable for analog-to-digital conversion.

The divider is constructed using high-value, high-voltage rated resistors arranged in series to distribute voltage stress evenly and reduce power dissipation per resistor. The divided voltage is then conditioned through filtering and level shifting before being fed into the ADC input of the ESP32 or an external ADC. This approach ensures operator safety, protects the microcontroller, and maintains measurement accuracy.

3.3.3 Current Measurement Subsystem

Current measurement is implemented using a current transformer (CT), such as the SCT-013 series. The CT provides galvanic isolation between the high-voltage AC line and the low-voltage measurement circuitry, significantly improving system safety.

The CT output current is converted into a measurable voltage using a burden resistor. The resulting signal is biased around a mid-supply reference to allow measurement of both positive and negative half-cycles of the AC waveform. This conditioned signal is then sampled by the ADC. The use of a CT allows non-intrusive current measurement and minimizes power losses in the sensing stage.

3.3.4 Processing and Control Subsystem

The ESP32-E module is selected as the main processing unit due to its high computational capability, integrated peripherals, and support for secure communication protocols. The microcontroller performs real-time sampling of voltage and current signals, calculates instantaneous power, and integrates energy over time.

In addition to metering, the ESP32 handles token validation logic, relay control, communication with the GSM module, and interaction with the secure element. The use of a real-time operating system enables efficient task scheduling and ensures reliable operation under varying system loads.

3.3.5 Load Control Subsystem

Load control is implemented using a solid-state relay (SSR), specifically the SSRD-240D40. The SSR provides electrical isolation between the low-voltage control circuitry and the high-voltage load, enhancing safety and reliability.

The SSR is driven by a digital output from the ESP32 through appropriate current-limiting circuitry. When a valid token is present and sufficient credit remains, the SSR is activated, allowing power to flow to the load. Upon token expiry or credit exhaustion, the relay is deactivated, disconnecting the load.

3.3.6 Communication Subsystem

The communication subsystem uses a GSM module (SIM7600) to provide wide-area network connectivity. GSM is chosen over consumer MiFi devices due to its direct serial interface, controllability, and suitability for embedded systems.

The GSM module enables the device to transmit energy consumption data, receive control commands, and obtain new PAYGo tokens from the backend server. Communication protocols such as MQTT or HTTPS are used to ensure reliable and secure data exchange.

3.4 Software Architecture

The software architecture is divided into firmware running on the ESP32 and backend software running on a remote server.

3.4.1 Embedded Firmware Design

The embedded firmware is responsible for sensor data acquisition, energy computation, token validation, and relay control. Voltage and current signals are sampled at a sufficient rate to accurately reconstruct the AC waveform. Instantaneous power is computed by multiplying voltage and current samples, and energy is obtained by numerical integration over time.

Token validation routines ensure that only authentic, non-expired tokens with sufficient remaining credit enable energy access. The firmware also handles fault detection, such as over-voltage or communication failures.

3.4.2 Backend System Design

The backend system manages user accounts, device registration, payment verification, token generation, and data storage. Upon confirmation of a mobile money payment, the backend generates a digitally signed token specifying the amount of energy or time purchased.

Energy usage data transmitted by the device is stored in a database and presented to users through a web-based dashboard. This enables transparency and informed energy usage decisions.

3.4.2.1 PAYGo Token Mechanism

The PAYGo token mechanism forms the core access control logic of the proposed smart energy logger. It defines how energy credit is issued, authenticated, consumed, and enforced at the device level. The design intentionally avoids physical tokens or manual entry and instead relies on cryptographically secured digital tokens generated upon successful payment confirmation.

Token Structure and Content

Each PAYGo token is generated as a structured digital payload containing all information required by the embedded device to make independent access control decisions without continuous reliance on the backend server. The token includes the following fields:

1. Token version to support future protocol updates while maintaining backward compatibility

2. Device identifier uniquely binding the token to a specific meter

3. Credit type, indicating whether the token represents time-based access or energy-based access

4. Credit value, expressed in watt-hours for energy-based tokens or seconds for time-based tokens

5. Expiry timestamp, defining the maximum validity period of the token

6. Nonce, a unique number preventing replay attacks

7. Digital signature, generated using the backend's private key

This structure ensures that tokens are self-contained, tamper-resistant, and verifiable at the device level.

Token Generation Process

Token generation begins at the backend server following confirmation of a user payment. Payment confirmation is obtained through integration with a mobile money platform, where transaction status and amount are validated. Once a payment is verified, the backend calculates the corresponding energy or time credit based on predefined tariff rules.

A token payload is then assembled using the verified payment details and the target device identifier. The payload is digitally signed using an asymmetric cryptographic algorithm. The signing key is securely stored on the backend and never exposed.

The signed token is encoded into a compact format suitable for transmission over low-bandwidth GSM networks. This encoded token is then delivered to the target device through a secure communication channel.

Token Distribution to the Device

Token delivery to the device is achieved using a push-based communication model. The backend publishes the token to a device-specific communication channel, which the embedded system subscribes to using its GSM connectivity. Upon receipt, the device stores the token temporarily in non-volatile memory. Token storage is handled carefully to prevent corruption during power interruptions. The system supports only one active token at a time to simplify enforcement and reduce attack surfaces.

Token Authentication and Verification

Once a token is received, the device initiates a verification process before granting access to electrical power. The verification process includes multiple checks:

- Validation of the digital signature using a public key stored in the secure element
- Verification that the device identifier in the token matches the local device ID
- Confirmation that the token has not expired
- Checking the nonce against previously used values to prevent replay attacks

All cryptographic operations are delegated to the ATECC608A secure element. This ensures that private keys are never exposed to firmware-level attacks and that verification remains resistant to physical tampering. Only tokens that pass all verification steps are accepted by the system.

Credit Activation and Relay Control

After successful token verification, the system transitions into an active state. The embedded controller enables the solid-state relay, allowing power to flow to the connected load.

For energy-based tokens, the firmware continuously computes energy consumption and decrements the available credit accordingly. For time-based tokens, a countdown timer is initiated at the moment of activation.

The relay remains closed only while valid credit exists. Once the credit is exhausted or the token expires, the firmware immediately disables the relay, disconnecting the load.

Credit Consumption Tracking

Energy consumption tracking is performed in real time using synchronized voltage and current measurements. Instantaneous power is calculated at each sampling interval, and energy is accumulated through numerical integration. To ensure accuracy, the firmware applies calibration constants obtained during system commissioning. Energy consumption data is logged locally and periodically transmitted to the backend for monitoring and reconciliation.

Token Expiry and Revocation

Tokens are designed to be finite and non-renewable. Once a token expires or its credit is fully consumed, it is invalidated and erased from active memory.

In exceptional cases such as suspected fraud or device malfunction, the backend may issue a revocation command. Upon receiving a revocation message, the device immediately disables the relay and clears the active token.

3.5 Expected Outcomes

- A functional prototype of an open-source Smart AC Energy Logger

- Open-source hardware schematics, PCB designs, and firmware

- A cloud-based monitoring and management interface

- Comprehensive technical documentation

- Demonstration of applicability to AC productive-use energy systems

4. Conclusion

This project proposes a secure, affordable, and open-source Smart Energy Logger integrated with a PAYGo system aimed at improving solar energy access in off-grid communities. By combining embedded systems design, IoT communication, cryptographic security, and mobile money integration, the solution addresses critical challenges in decentralized energy management.

Successful implementation will demonstrate a scalable model for transparent, sustainable, and inclusive energy access, while equipping engineering students with practical skills aligned with real-world industry needs

4.1 Timeplan

4.2 Budget

Estimated cost in Kenya shillings

Category	Component	Model	Qty	Price
Microcontroller and core control	ESP32 Dev board	ESP32-DevkitC	2	2400
	Real time clock	DS3231	2	500
	SD card module	SPI SD Module	1	400
	8Gb SD card	Sandisk 8Gb	1	500
	Hardware security chip	ATECC608A	1	7600
Power supply and regulation	AC-DC power supply	230v-12v 5A	1	2200
	DC-DC converter	LM2596 buck converter	1	300
	TVS Diode + fuse	SMBJ5.0A / Resettable fuse	2	300

Voltage and current sensing	AC voltage sensor	ZMPT101B	1	500
	AC current transformer	SCT-013-050	1	1100
Communication and network	GSM module	Sim 7600E	1	7500
Power control	NPN driver transistor + diode	2n2222 + IN4007	2	40
	Heat sink	Aluminum 25*25mm	1	100
	LiPo Charger		1	3500
	LiPo Battery	2200 mAh	1	3000
	Power relay			
Display and User interface	OLED display	0.96" 128*64	1	600
	LEDs	Green, Red, Blue	6	30
	Push button	Non self locking	10	100
Enclosure and Hardware	ABS	150 * 100 * 70mm	1	1500
	Terminal block	KF-6P	2	320
	PCB	Custom 2 layer	1	200
	Mounting screw	M3	1	200
Miscellaneous	Wire	Dupont jumper wires	3	450
			Total cost	**33,840**

4.3   References

The existence of open-source smart metering hardware and firmware platforms (EnergyMe-Home, OpenZmeter): https://hackaday.io/project/204341-energyme-home , https://www.mdpi.com/20 1050/10/11/4038?

The feasibility of IoT-based energy monitoring systems using MQTT, REST, and cloud integration : https://www.ijraset.com/research-paper/iot-based-energy-meter

Prior efforts to open-source smart meter designs that enable local fabrication and customization: https://enaccess.org/materials/smartmeter

Academic precursor platforms showing integration of energy measurement and microcontrollers (YoMo): Cornell University https://arxiv.org/abs/1409.3404

The general context of energy metering standards. Wikipedia : https://en.wikipedia.org/wiki/IEEE$_2$030

4.4 Time Plan

Week	Semester 1														Semester 2													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Proposal Presentation								▓																				
Literature review	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓
Mechanical Design					▓	▓	▓	▓	▓	▓	▓	▓	▓															
Electrical design						▓	▓	▓	▓	▓	▓	▓	▓															
Programming											▓	▓	▓	▓	▓	▓	▓	▓	▓									
Assembly											▓	▓	▓	▓	▓	▓	▓	▓	▓									
Testing											▓	▓	▓	▓	▓	▓	▓	▓	▓									
Project Presentation													▓	▓						▓	▓	▓	▓	▓	▓	▓	▓	▓
Demonstration																				▓	▓	▓	▓	▓	▓	▓	▓	▓

Figure 4.1: Project implementation time plan