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BLOCKCHAIN-ENABLED SECURE SMART GRID FOR HYBRID RENEWABLE ENERGY MONITORING, INTELLIGENT P2P ENERGY TRADING AND AI-BASED LOAD FORECASTING USING IOT SENSORS

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Abstract : The rapid growth of electric vehicles (EVs) and rising electricity demand call for intelligent, secure and efficient smart-grid systems. This paper presents an IoT-based smart-grid framework for hybrid renewable energy monitoring, real-time voltage and current analysis, intelligent energy auditing, AI-based load forecasting and EV charging management, built around the ESP32 microcontroller and integrated with an OpenAI-based decision layer and the Ethereum blockchain. Field-level sensors capture solar, wind and battery voltage, AC voltage, AC current, AC power, cumulative energy units and a peak-status flag, which are logged to the ThingSpeak cloud. Solidity smart contracts create, manage and verify peer-to-peer (P2P) energy trades, and SHA-256 hashes of the IoT telemetry are committed on-chain so that any later modification of stored energy records can be detected. A Streamlit dashboard provides real-time visualisation, blockchain transaction tracking, data-integrity verification and P2P trading. Experimental results from the ThingSpeak channel, a private Proof-of-Authority (PoA) Ethereum network, the Sepolia test network and the dashboard confirm reliable data acquisition, deterministic 5 s block sealing, 6.8 s end-to-end logging latency, 100 % detection of tampered records, automated energy auditing with loss flagging, and a block-ordered, verifiable trade ledger. The integration of IoT, generative AI, blockchain and P2P trading offers a scalable, secure and decentralised smart-grid architecture suitable for residential, commercial, EV-charging and smart-city applications.

IndexTerms - Smart grid, Blockchain, Internet of Things, ESP32, ThingSpeak, Peer-to-peer energy trading, Smart contracts, SHA-256, Proof of Authority, Load forecasting.

I. INTRODUCTION

The rapid adoption of electric vehicles, increasing electricity demand and the growing integration of renewable energy sources have created significant challenges for conventional power grids. The unpredictable nature of solar and wind generation, variations in consumer demand and the increasing number of EV charging loads can result in peak-load conditions, inefficient energy utilisation, voltage fluctuations and increased stress on the electrical network. Intelligent, flexible and secure energy-management systems are therefore essential for efficient and sustainable smart-grid operation.

The Internet of Things (IoT) provides an effective approach for real-time monitoring of electrical energy systems. IoT-enabled microcontrollers such as the ESP32 can acquire voltage, current, power, energy consumption, battery status and renewable generation from distributed energy resources, and cloud platforms such as ThingSpeak can store and visualise these measurements. However, conventional IoT monitoring systems focus primarily on data collection and visualisation; they seldom provide intelligent decision-making or secure, decentralised energy-transaction mechanisms.

Artificial intelligence can overcome these limitations by analysing real-time and historical energy data to identify consumption patterns and predict future requirements. In the proposed system an OpenAI-based intelligence layer acts as the decision-support component for load prediction, EV charging optimisation and context-aware energy management. Secure and transparent energy transactions are equally important in decentralised smart-grid environments: centralised transaction systems depend on a single

authority to maintain records, introducing concerns of data manipulation, lack of transparency and single points of failure. Blockchain technology offers a decentralised and tamper-resistant ledger, and smart contracts can automate energy trading by recording the seller, buyer, energy quantity, price, timestamp and status without manual intervention.

The framework presented here combines ESP32-based IoT monitoring, ThingSpeak cloud connectivity, OpenAI-based decision support, blockchain-secured transactions and P2P renewable-energy trading in one working prototype. The specific objectives are: (i) to design an ESP32-based IoT field station that measures solar, wind, battery and AC-side parameters in real time and uploads them to ThingSpeak; (ii) to perform intelligent energy analysis, peak-load identification and EV-charging recommendations using an OpenAI-based decision layer; (iii) to integrate an Ethereum blockchain with Solidity smart contracts for tamper-resistant logging of telemetry hashes and automated P2P trading; and (iv) to develop a Streamlit dashboard for monitoring, data-integrity verification and energy trading, and to validate the complete system experimentally.

II. LITERATURE SURVEY

Soto et al. [1] present a comprehensive review of P2P energy trading based on distributed energy resources, describing how prosumers can exchange surplus electricity without depending on a centralised intermediary and categorising research on trading platforms, blockchain, game theory, optimisation and trading algorithms. Challenges related to large-scale implementation, consumer behaviour, network integration and market design are identified; this work provides the foundation for the decentralised trading mechanism implemented here.

Thukral [2] investigates the application of blockchain in P2P electrical-energy trading and explains how blockchain and smart contracts provide secure, transparent and tamper-resistant transaction records, including applications for EV charging. Reviews of blockchain for distributed generation [11], [14] highlight decentralisation, immutability, security and transaction automation for renewable sources, battery electric vehicles, microgrids, energy trading, bidding and billing, and identify blockchain-based P2P trading as a promising approach for decentralised energy management.

Systematic reviews of P2P electricity trading identify six key components—trading platforms, market schemes, market-clearing algorithms, supporting policies, electricity networks and ICT infrastructure—and show that P2P trading can reduce peak demand and improve grid flexibility, although coordinating the physical network with the virtual trading platform remains a challenge [3], [4], [8]. Machine-learning-assisted blockchain trading mechanisms [5], [15], microgrid transaction models [6], [7], [12] and EV-oriented auctioning and reputation schemes [9], [10] extend these ideas. Aoudia et al. [13] survey blockchain-enabled energy trading between EVs and smart grids in IoT environments and highlight the potential of blockchain to improve security and transparency while noting practical implementation and efficiency challenges.

Research gap. The surveyed literature establishes blockchain and P2P trading as effective tools for decentralised energy management, but most reported systems address a single aspect—secure transactions, EV charging, renewable monitoring or IoT data collection—in isolation, and several are simulation-only studies. There is limited work that couples a low-cost ESP32 hardware node and a public IoT cloud with an AI decision layer, smart-contract-based trading and on-chain data-integrity verification in one working prototype. The present work addresses this gap.

III. PROPOSED SYSTEM AND METHODOLOGY

Existing smart-grid and EV charging systems rely mainly on centralised IoT platforms, predefined charging schedules and centralised billing. Sensors and smart meters transmit voltage, current, power, battery status and renewable generation to cloud servers for monitoring, but such systems offer limited intelligent decision-making, cannot dynamically adapt EV charging to real-time load and renewable availability, provide no direct P2P trading between users, and store records in traditional databases that can be modified without decentralised verification. The proposed system integrates ESP32, IoT, ThingSpeak, OpenAI-based intelligence, blockchain and P2P renewable-energy trading into a unified framework.

3.1 Block Diagram of the Proposed System

Fig. 1 shows the block diagram of the field station and the software layers. The sensing section feeds the ESP32, which drives the local LCD and relay-controlled load bank and uploads the eight parameters (solar voltage, wind voltage, battery voltage, AC voltage, AC current, AC power, total units and peak status) to ThingSpeak over Wi-Fi. The Python application retrieves this data through the REST API, performs analysis, generates SHA-256 hashes, interacts with the Ethereum smart contracts through Web3 and serves the Streamlit dashboard.

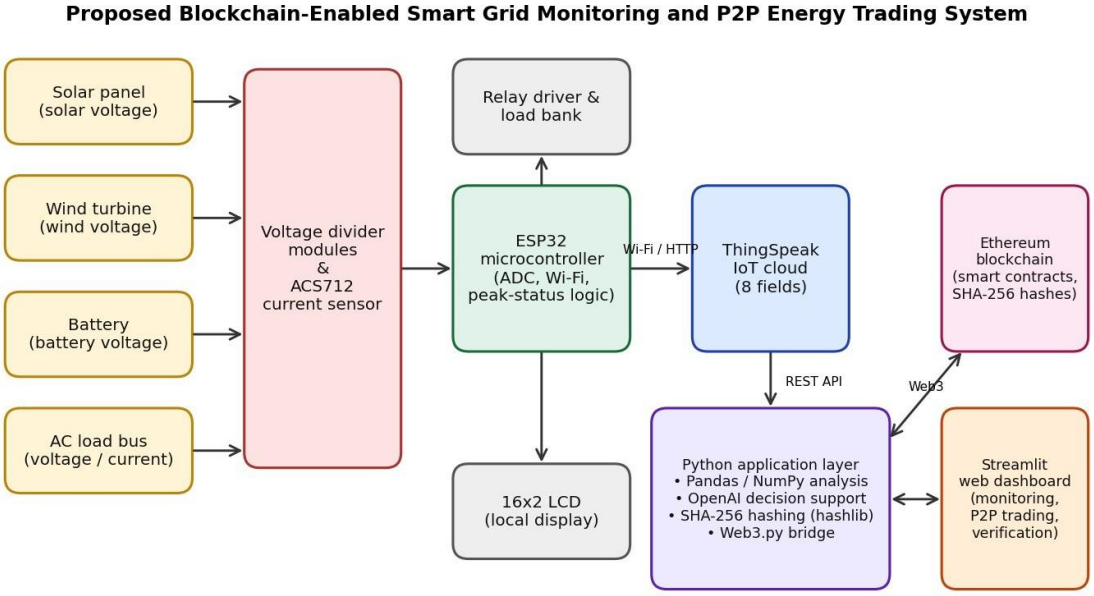

Fig. 1: block diagram of the proposed system

3.2 Methodology

The system is developed through nine stages. (1) *Data acquisition*: voltage-divider modules and an ACS712 Hall-effect current sensor are interfaced to the ESP32 analog inputs; the ESP32 computes AC power, accumulates energy units, evaluates a peak-status flag and transmits the readings to ThingSpeak using HTTP GET requests. (2) *Cloud data handling*: the eight parameters are stored in the eight fields of a ThingSpeak channel, which provides time-series storage, charts and historical retrieval. (3) *AI-based analysis*: the processed data (solar and wind availability, battery voltage, present consumption, historical pattern, peak-load condition and surplus energy) is supplied to the OpenAI-based layer through a tightly constrained prompt, which returns a load classification (normal/moderate/peak), a recommended EV charging window and a surplus-energy decision (consume, store or offer for trading). The model is used as a decision-support tool; final control actions remain rule-based in the firmware.

(4) *Renewable availability and decision making*: the energy available for consumption or trading is determined from generation, battery status and load; surplus is made eligible for P2P trading, and during peak load non-critical loads are reduced or EV charging is shifted. (5) *Blockchain integration*: a Solidity smart contract manages P2P trades and records seller, buyer, energy quantity (kWh), price per kWh, total value, timestamp, status and the IoT data-integrity hash. (6) *P2P trading*: a producer creates a sell order through the dashboard by specifying quantity and price; a consumer views the order book and buys the required quantity, and the trade is executed by the smart contract. (7) *Data-integrity verification*: a SHA-256 hash of the selected ThingSpeak data and timestamp is stored on the blockchain; during verification the current data is hashed again and compared with the stored hash, reporting AUTHENTIC or TAMPERED DATA. (8) *User interface*: the Streamlit dashboard displays the live parameters, renewable availability, trading status, blockchain transaction history and integrity status. (9) *Continuous monitoring*: the loop—acquire, upload, analyse, update blockchain and dashboard—runs continuously in near real time.

3.3 Hardware Description

The ESP32 is a low-cost, low-power system-on-chip from Espressif with integrated Wi-Fi and Bluetooth, a dual-core Xtensa LX6 processor up to 240 MHz, 520 KB SRAM, 4 MB flash and 18 channels of 12-bit ADC. Its ADC channels read the voltage and current sensors, its GPIO pins drive the LCD and relay driver, and its Wi-Fi radio uploads the data to ThingSpeak. Compared with the ATmega-based Arduino boards used in Phase I, the ESP32 offers a faster processor, higher ADC resolution and on-board connectivity, removing the need for a separate Wi-Fi/LoRa module.

A small photovoltaic panel and a wind turbine (a DC motor driven as a generator) form the hybrid renewable source and charge a 12 V rechargeable battery through a diode/charge-control stage. Three resistive voltage-divider modules (division ratio 1:5, R1 = 30 kfi, R2 = 7.5 kfi) sample the solar, wind and battery voltages; the divider output is $V\text{out} = V\text{in} \times R2 / (R1 + R2)$ and the firmware multiplies the ADC reading by the inverse ratio to recover the input voltage. The ACS712-30A Hall-effect current sensor (66 mV/A, 2.5 V at zero current) provides galvanic isolation; the firmware samples its output over one mains cycle, removes the offset and computes the RMS current, from which AC power ($P = V \times I$) and accumulated energy units are derived. A 16×2 HD44780 character LCD driven through an I2C backpack (address 0x27) displays the measured values locally, and SPDT relays driven by NPN transistors from the ESP32 GPIO lines shed or restore the loads of the load bank according to battery-voltage thresholds and over-current conditions; the relay status is reflected in the peak-status field. A regulated power supply (15-0-15 V transformer, bridge rectifier, capacitor filter, 7805 and 7812 regulators) provides the +5 V and +12 V rails.

3.4 Software Description

The ESP32 firmware is written in Embedded C in the Arduino IDE using the ESP32 core; setup() initialises pin modes, the LCD and the Wi-Fi connection, and loop() contains the measurement, control and upload logic. ThingSpeak is an open IoT analytics platform built around a time-series database in which each channel holds up to eight numeric fields; the ESP32 posts an update every 15 s (the free-tier limit) and the Python application retrieves the entries through the read API as JSON. Python serves

as the integration platform with Requests (ThingSpeak REST API), Pandas and NumPy (analysis of generation, consumption, surplus and peak-load statistics), hashlib (SHA-256 hashing of the canonical telemetry payload), Web3.py (signing transactions and calling the smart contracts), the OpenAI SDK (structured recommendations) and Streamlit with Plotly (interactive dashboard). Smart contracts are written in Solidity 0.8.x in the Remix IDE, deployed to a Ganache chain or a Geth private network during development and to the Sepolia public test network for external verification; MetaMask manages the test accounts. API keys, the channel ID, the RPC URL and the wallet private key are supplied through environment variables.

IV. BLOCKCHAIN INTEGRATION

4.1 Role of Blockchain and System Architecture

The IoT data drives energy auditing, AI-based forecasting, EV charging decisions and P2P trading, so its integrity is critical. Conventional cloud databases are centralised: an administrator or an attacker can silently modify stored readings, creating a single point of failure and making audits unverifiable. A blockchain stores every record as a cryptographically hashed entry in a distributed, append-only ledger replicated across several nodes; once a block is confirmed, altering it would require recomputing the hashes of all subsequent blocks on a majority of nodes simultaneously. The blockchain layer therefore provides tamper-proof logging of telemetry hashes, transparent automated auditing through smart contracts, trusted input data for the AI forecasting module, dispute-free P2P trades and EV charging settlement, and decentralised access for utility, auditor and consumer nodes.

The system is organised into four layers (Fig. 2): the IoT sensing layer acquires the electrical parameters; the edge/gateway layer (ESP32 with a PC or Raspberry Pi running the Python bridge) aggregates, filters and cryptographically secures the data; the blockchain layer validates and permanently records transactions; and the application layer consumes verified ledger data for the dashboard, auditing, AI forecasting and EV charging management.

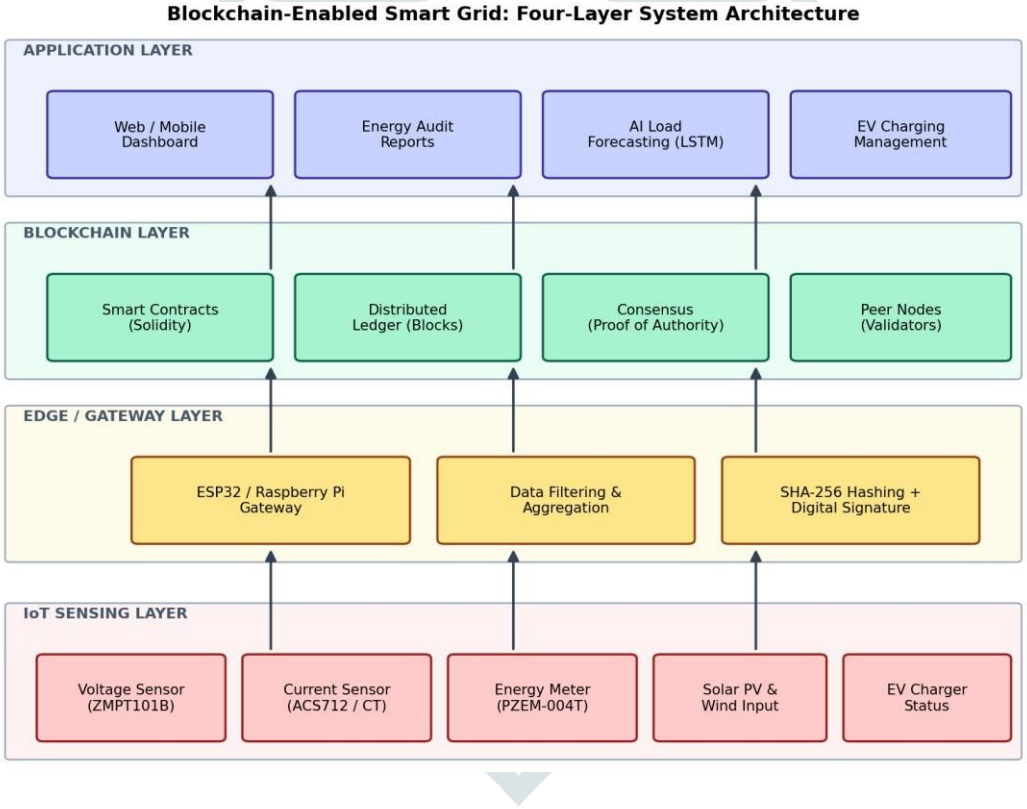

Fig. 2: four-layer architecture of the blockchain-enabled smart grid

4.2 Platform Selection, Block Structure and Consensus

Public blockchains such as the Ethereum mainnet are unsuitable for high-frequency sensor logging because of gas fees and 12–15 s confirmation times. A private (permissioned) Ethereum network operated by known entities gives fast, fee-less transactions while retaining full smart-contract capability (Table 1). The private PoA network is therefore used for development and for the sensor-logging and auditing contracts, while the public Sepolia test network demonstrates externally verifiable hash commitments and trades.

Table 1: blockchain platform comparison for smart-grid data logging

Criterion	Public Ethereum	Private Ethereum (PoA)	Hyperledger Fabric
Transaction cost	High (gas fees)	Zero (internal)	Zero (internal)
Block time	≈12 s	Configurable (≈5 s)	Sub-second
Smart contracts	Solidity	Solidity	Chaincode (Go/Java)
Setup complexity	Low	Moderate	High
Suitability	Test network only (Sepolia)	Selected	Alternative

Each block stores a batch of energy transactions together with metadata that chains it to the previous block (Fig. 3). A transaction payload contains the node ID, timestamp, RMS voltage, RMS current, active power, energy, power factor, energy-source tag (solar/wind/grid) and, for charging points, the EV session ID and units delivered. The previous-block-hash field makes the ledger a linked chain: any modification of an old reading changes its block hash and immediately invalidates every later block. Proof of Work is energy-intensive and contradicts the objective of an energy-efficient grid, so the private network uses Proof-of-Authority (Clique) consensus in which three pre-approved validator nodes (utility node, laboratory server and auditor node) take turns sealing blocks at a fixed interval of about five seconds, giving deterministic block times, negligible computational overhead and immunity to 51 % attacks in a permissioned setting.

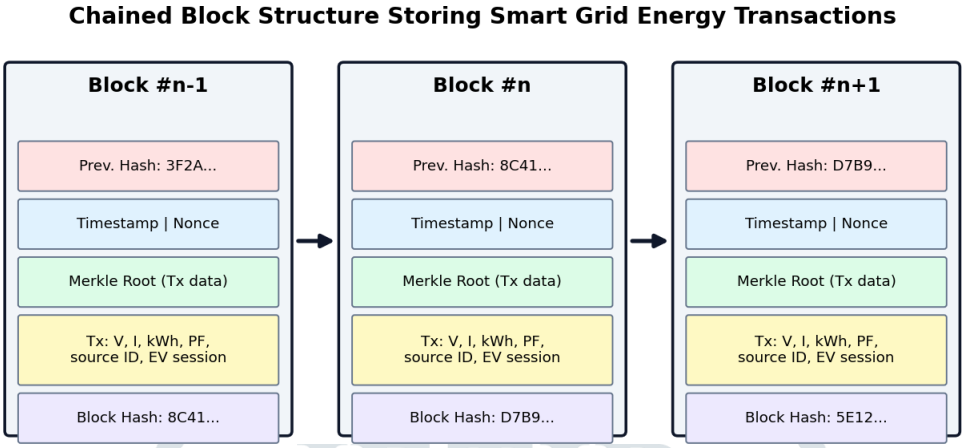

Fig. 3: chained block structure storing smart-grid energy transactions

4.3 Smart Contract Design

Four Solidity contracts implement the on-chain logic (Table 2). EnergyLog validates and stores sensor readings from registered gateways only; EnergyAudit aggregates the ledger per node and period and flags generation–consumption mismatches; EVCharge records charging sessions and settles billing; and RenewableEnergyTrading implements the P2P marketplace used by the dashboard. The trading contract keeps an EnergyOrder structure (id, seller, buyer, energy in kWh, price per kWh, total amount, timestamp, IoT data hash, active and completed flags) in a mapping and emits events on order creation, purchase and cancellation, so that every trade is permanently traceable to the telemetry hash of the energy being sold.

Table 2: smart contracts and their functions

Contract	Key functions	Purpose
EnergyLog.sol	registerGateway(), logReading(), readingCount()	Validates and stores sensor readings; rejects out-of-range or unauthorised data
EnergyAudit.sol	computeConsumption(), detectLoss(), auditReport()	Aggregates ledger data per node/period; flags mismatch between generation and consumption (loss/theft detection)
EVCharge.sol	startSession(), endSession(), settlePayment()	Records EV charging sessions, computes billing from tariff and units, settles payment automatically
RenewableEnergyTrading.sol	createEnergyOrder(), buyEnergy(), cancelOrder(), getOrder()	P2P marketplace: sell orders with data hash, purchase with ETH payment to seller, order history

4.4 Data Integrity and Security Mechanisms

Security is enforced at three levels. First, every telemetry snapshot is reduced to a canonical string (solarVoltage=…, windVoltage=…, …) and hashed with SHA-256; because of the avalanche property, even a one-bit change produces a completely different digest, so a tampered record can never reproduce a hash that was already committed. Second, each gateway holds a unique ECDSA private key and signs every transaction; the contracts accept data only from registered addresses, preventing spoofed sensor nodes. Third, ledger replication across all peer nodes under PoA consensus guarantees immutability and availability—tampering at any single node is rejected by the rest of the network. The guarantee is that a committed record cannot be silently changed afterwards; the hash does not itself certify that the original sensor reading was correct.

The implementation proceeds in seven phases: hardware setup and sensor calibration against a multimeter; blockchain network setup (Ganache for instant test transactions, then a Geth private network with the Clique PoA genesis, 3–4 nodes and a 5 s block period); smart-contract development in Remix; contract unit-testing and deployment with registration of each gateway address; IoT-to-blockchain integration through a Python bridge that reads ThingSpeak data, computes the SHA-256 hash and forwards each record to the contract via Web3, signing every transaction with the gateway private key; application-layer development; and validation covering tamper, authentication, latency (target ≤ 10 s end-to-end), throughput, audit-accuracy (±2 %) and forecast-accuracy (MAPE below ≈10 %) tests.

V. RESULTS AND DISCUSSION

The proposed system was implemented and tested in three stages: (i) the ESP32 field station uploading live measurements to ThingSpeak, (ii) the blockchain layer running on a private PoA Ethereum network with the EnergyLog, EnergyAudit and EVCharge contracts, and (iii) the Streamlit dashboard connected first to a simulated chain and then to the public Sepolia test network for P2P trading and hash commitment. The blockchain-network and auditing outputs (Sections 5.2 and 5.3) were obtained from the prototype network with modelled sensor data; the ThingSpeak and dashboard captures are from live sessions.

5.1 ThingSpeak Monitoring Output

Fig. 4 collects the ThingSpeak field charts for 28 entries logged over a short monitoring window (approximately 12:05 to 12:20). The scaled solar voltage fluctuates between 1.05 V and 1.09 V with a noisy pattern, indicating weak and variable solar input; wind voltage stays at 0 V except for one brief burst of about 1.5 V around entries 20–21, so wind generation is essentially absent. The battery voltage therefore follows a discharge curve from about 11.1 V to 10.6–10.9 V as it bridges the supply gap. On the load side the AC voltage remains tightly regulated between 228 V and 232 V, while AC current rises from about 0.04 A to 0.10 A and AC power from about 10 W to 24 W, indicating steadily increasing load demand. The cumulative Total Units counter rises steadily, with one dip around entries 14–15 attributable to a counter re-initialisation. The Peak Status flag (0 = normal, 1 = moderate load, 2 = peak) fires more frequently in the second half of the session, in line with the rising current and power, confirming that the firmware correctly flags peak-demand conditions—exactly the grid-stress condition that the AI and blockchain layers are designed to detect and respond to.

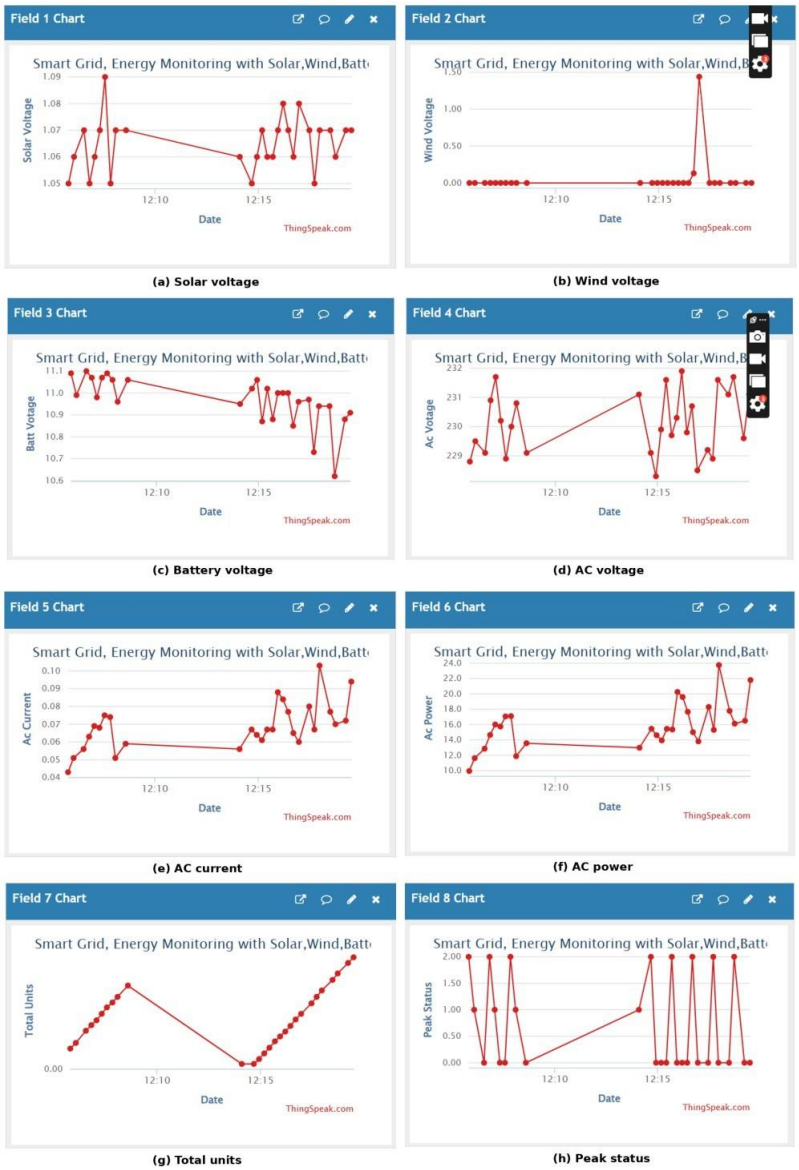

Fig. 4: ThingSpeak field charts – (a) solar voltage, (b) wind voltage, (c) battery voltage, (d) AC voltage, (e) AC current, (f) AC power, (g) total units and (h) peak status

5.2 Blockchain Network Output

The Geth console of the private network initialised with the Clique PoA engine (network ID 2607, block period 5 s) showed blocks being sealed continuously by the three validator nodes, each block packaging 6–8 sensor transactions, with a chain height of 1023 blocks and three connected peers. The observed block interval matched the configured 5 s period, giving an average end-to-

end logging latency (sensor reading to on-chain confirmation) of 6.8 s, well within the 10 s target. Each reading accepted by the EnergyLog contract is a permanently stored, individually hash-addressed record—voltage, current and incremental energy for the solar, wind, load and EV-charger nodes at 5 s intervals—and every record carries a transaction hash through which it can be independently verified by any node.

To demonstrate immutability, a stored reading in block 1020 was deliberately modified in the local copy of one node (energy changed from 1.842 kWh to 0.900 kWh). Fig. 5 shows that the recomputed hash of the altered block no longer matches the stored hash, the chain is reported broken from that block onward, and the majority consensus of the remaining validators rejects the tampered copy and re-syncs the correct ledger. The original reading is preserved, confirming that stored energy data cannot be silently altered.

```
$ python3 verify_chain.py --node node2 --range 1017 1023

Verifying ledger integrity on node2 ...
Block 1017  hash=0x3f2a81..c4d0   recomputed=0x3f2a81..c4d0   OK
Block 1018  hash=0x9b07e3..12aa   recomputed=0x9b07e3..12aa   OK
Block 1019  hash=0x8c41f2..d7a9   recomputed=0x8c41f2..d7a9   OK

--- Tamper test: reading in block 1020 modified on node2      ---
--- (energy_Wh changed 1.842 kWh -> 0.900 kWh in local copy)  ---

Block 1020  hash=0xd7b90a..44ce   recomputed=0x66e1fd..0b93   MISMATCH!
  [ALERT] Stored block hash does not match recomputed hash
  [ALERT] Chain broken at block 1020: blocks 1021-1023 invalid

Peer consensus check (3 validators):
  node1: 0xd7b90a..44ce   node3: 0xd7b90a..44ce   node2: 0x66e1fd..0b93
  => node2 copy REJECTED by network; ledger re-synced from majority

RESULT: Tampered data detected and discarded automatically.
        Original reading (1.842 kWh) preserved on-chain.
```

Fig. 5: tamper-detection output – modified block rejected by network consensus

5.3 Real-Time Monitoring and Intelligent Energy Auditing

A 24-hour profile of RMS voltage and load current reconstructed entirely from ledger data showed the voltage within ±1 % of 230 V for most of the day, with a sag to about 225 V during the evening peak (19:00–20:00) coinciding with the maximum load current of about 14 A; this deviation is automatically flagged for the audit report. The EnergyAudit contract aggregates all ledger records per hour and per source (Fig. 6): solar peaks near midday, wind contributes throughout the day and grid import fills the morning and evening peaks, while metered consumption tracks total generation closely. For the audited day total generation was 233.2 kWh against 214.5 kWh consumed, an overall technical loss of 18.6 kWh (8.0 %), at the boundary of the configured 8 % acceptance limit.

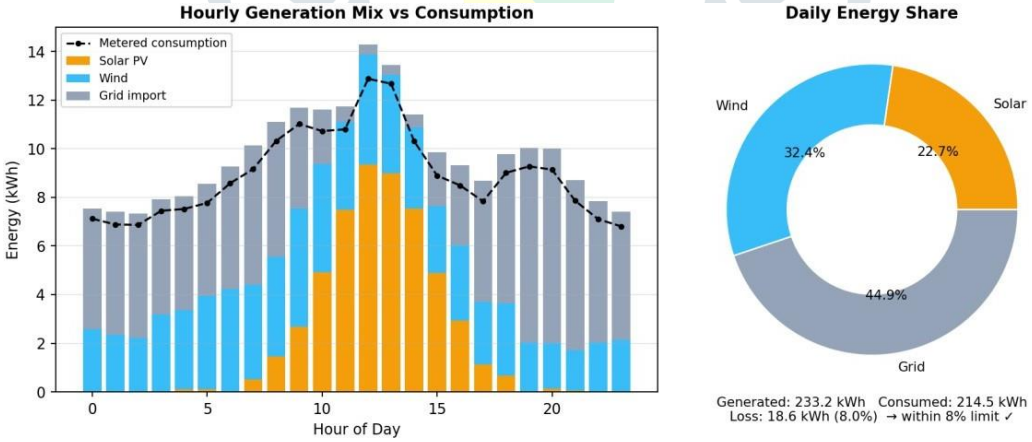

Fig. 6: audit output – hourly generation mix vs consumption and daily energy share

Fig. 7 shows the per-node daily audit report produced by auditReport(). The solar, wind and grid-import nodes show delivered-versus-generated losses of 3.7–4.1 %, within normal limits. The EV charger consumed 22.4 kWh, for which the EVCharge contract automatically computed and settled a bill of ₹179.20 at the stored tariff of ₹8.00/kWh. Sub-feeder FEEDER-2 shows 12.5 kWh drawn but only 9.6 kWh delivered to registered loads—a 23.2 % discrepancy—and is automatically flagged, indicating unmetered consumption, leakage or theft on that branch. Because the underlying readings are immutable, this flag constitutes verifiable audit evidence.

EnergyAudit.sol — Daily Audit Report (auditReport(day=2026-08-14))

Node ID	Description	Gen. (kWh)	Cons. (kWh)	Delivered (kWh	Loss (kWh, %)	Audit Status
SOLAR-01	Solar PV	48.7	—	46.9	1.8 (3.7%)	✓ NORMAL
WIND-01	Wind	27.9	—	26.8	1.1 (3.9%)	✓ NORMAL
GRID-IMP	Grid import	41.2	—	39.5	1.7 (4.1%)	✓ NORMAL
LOAD-01	Main load bus	—	78.3	—	—	✓ NORMAL
EVCHG-01	EV charger	—	22.4	—	—	✓ BILLED ₹179.20
FEEDER-2	Sub-feeder	—	12.5	9.6	2.9 (23.2%)	⚠ FLAG: loss > 8%

Fig. 7: EnergyAudit.sol output – daily per-node audit report with loss flagging

5.4 Streamlit Dashboard Outputs

The following captures were taken from the live dashboard on 30 August 2026. The application ingests the ThingSpeak telemetry (channel 3357871), computes renewable-generation and trading metrics, fingerprints each snapshot with SHA-256, commits the hash to the blockchain and runs the P2P marketplace. In the landing view (Fig. 8) the eight fields appear as live cards: Solar Voltage 21.31 V, Wind Voltage 9.83 V, Battery Voltage 12.96 V, AC Voltage 219.4 V, AC Current 2.70 A, AC Power 562.8 W, Total Units 166.528 kWh and Peak Status "HIGH DEMAND". The derived Solar Power Gen (331.5 W) and Wind Power Gen (147.5 W) combine to a Total Renewable Gen of 0.479 kW, which is less than the 562.8 W load, so the Trading Available Capacity is 0.0 kWh and the node is flagged as a net "DEFICIT (IMPORTER)". The time-series view showed solar output jumping from near 0 V to 18–19 V, consistent with a sunrise event during the capture window, the AC load oscillating between roughly 250 W and 800 W, and the cumulative energy meter rising monotonically from about 100.0 kWh at 04:30 to about 101.7 kWh by 07:30.

Fig. 8: main control dashboard – live telemetry and calculated renewable capacity

The data-integrity module computes a SHA-256 digest of the eight live parameters and checks it against the hashes recorded on-chain. The canonical payload is the exact string hashed (solarVoltage=21.310, windVoltage=9.830, battVoltage=12.960, …) and the resulting digest is 0x6192dc31…b02c. An interactive tamper simulator lets the user nudge Solar Voltage or Total Units and watch the simulated hash recompute: any change to a single digit produces an unrelated hash, so a tampered record can never reproduce the hash already committed on-chain.

In the marketplace (Fig. 9) a prosumer ("Solar Node #3", linked to an on-chain wallet) lists 1.00 kWh at 0.00045 ETH/kWh for an estimated revenue of 0.000450 ETH (≈ $1.35). The active order book shows two live offers: Order #1 from "Solar Farm Node #1 / Prosumer Alpha" (25.5 kWh at 0.00045 ETH/kWh) and Order #2 from "Wind Microgrid Node #2 / Prosumer Beta" (40.0 kWh at 0.0004 ETH/kWh). Each order carries its own data hash, so the energy being sold is tied to a verifiable telemetry fingerprint rather than a self-reported number.

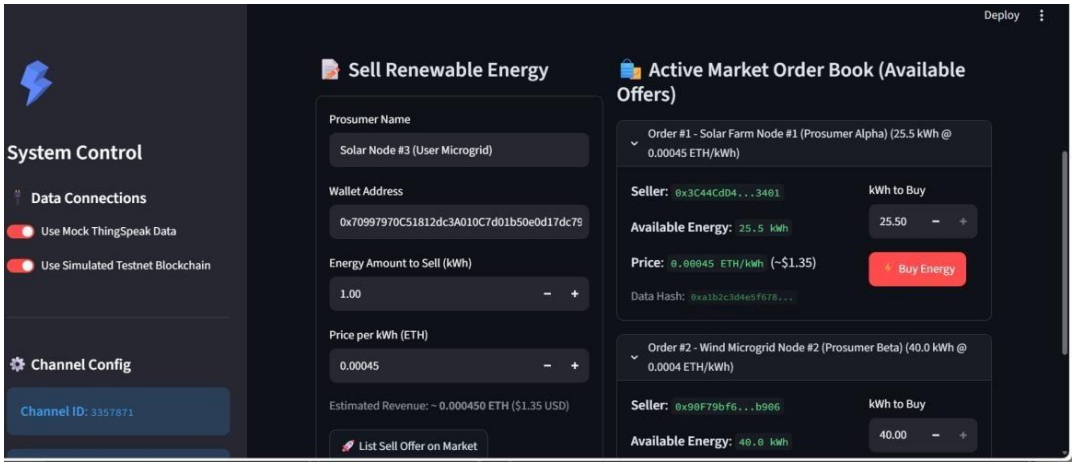

Fig. 9: P2P energy marketplace – sell-offer form and active order book

With the sidebar Eth Provider pointed at https://rpc.sepolia.org, a public Ethereum test-network endpoint, the demonstration moves from an in-process simulation to an externally reachable, publicly shared ledger. Pressing "Commit SHA-256 Hash to Blockchain" against the same payload returned the confirmation in Fig. 10: "Hash successfully committed! Record #1 | Tx: 0x91722b3298a2f7… | Block: #18450106". This artefact lets anyone re-derive the hash from a telemetry snapshot and compare it with what is permanently recorded at that transaction and block.

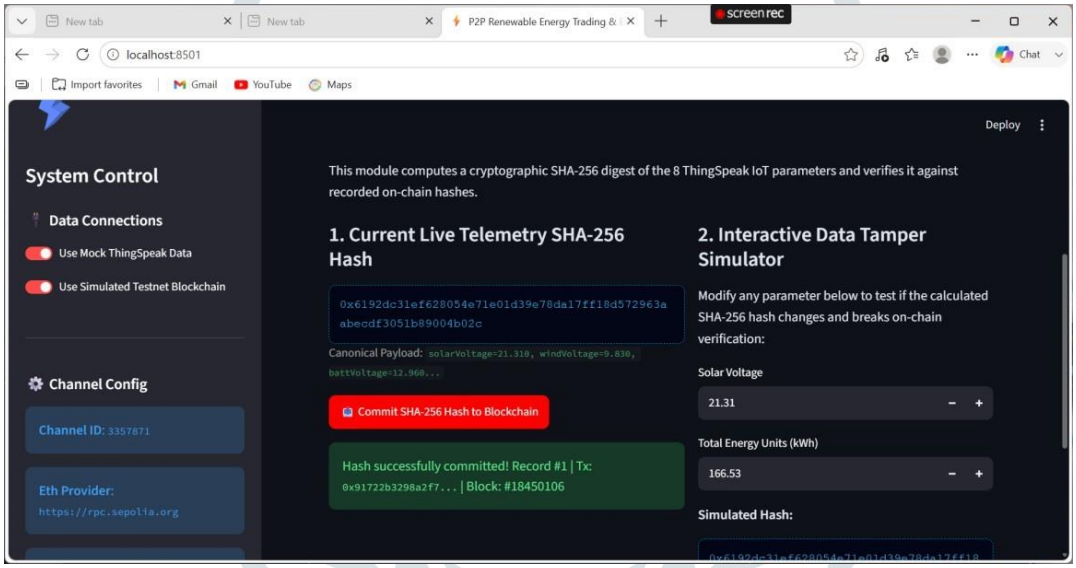

Fig. 10: successful on-chain SHA-256 hash commitment (Sepolia)

5.5 Exported Trade Ledger

The trade history was exported from the dashboard to Excel with the columns tradeId, energyAmt, totalPriceEth, blockNum, status and timestamp and is reproduced in Table 3. All seven trades are CONFIRMED, each with a distinct block number and UTC timestamp. Read chronologically, block numbers (18450101 → 18450108) and timestamps (07:40:11 → 07:45:26) increase strictly, i.e. the sequence is internally consistent with how a blockchain orders transactions—each new trade is anchored to a later, higher block than every trade before it.

Table 3: exported P2P trade ledger

tradeId	energyAmt (kWh)	totalPriceEth	blockNum	status	timestamp (UTC)
7	1	0.00045	18450108	CONFIRMED	2026-08-30 07:45:26
6	1	0.00045	18450107	CONFIRMED	2026-08-30 07:45:10
5	1	0.00045	18450105	CONFIRMED	2026-08-30 07:40:40
4	1	0.00045	18450104	CONFIRMED	2026-08-30 07:40:35
3	1	0.00045	18450103	CONFIRMED	2026-08-30 07:40:29
2	25.5	0.011475	18450102	CONFIRMED	2026-08-30 07:40:16
1	1	0.00045	18450101	CONFIRMED	2026-08-30 07:40:11

5.6 Comparison With and Without the Blockchain Layer

Three mechanisms make the tamper-evidence and decentralisation claims checkable rather than merely asserted: (i) fingerprinting—every telemetry snapshot is reduced to one SHA-256 hash over a fixed canonical payload; (ii) on-chain

commitment—that hash is written to a ledger through a transaction that receives its own hash and block number; and (iii) independent re-verification—anyone holding the same raw readings can recompute the hash and compare it with the on-chain value. Table 4 compares the system as captured with the same system without the blockchain layer (ThingSpeak/Excel only), and Table 5 consolidates the observed results.

Table 4: blockchain versus no-blockchain comparison

Property	**Without blockchain (ThingSpeak / central DB only)**	**With blockchain layer (this work)**
Data storage model	Single ThingSpeak channel or database controlled by one operator.	Same telemetry, plus a SHA-256 fingerprint of every reading committed to a distributed ledger (Sepolia / PoA network).
Who can alter a past reading	Anyone with API-key or DB access can silently edit or delete a row; no independent witness.	Editing a reading changes its hash; the mismatch against the committed hash is detectable by anyone recomputing it.
Tamper evidence	None – a modified CSV export looks identical to a genuine one.	Changing even one field produces a completely different hash, so tampering is exposed.
Record of transactions	A spreadsheet row can be inserted, reordered or back-dated without trace.	Each trade carries a strictly increasing block number and a unique transaction hash; reordering is detectable.
Single point of failure	If the account or database is lost, the historical record is gone.	Committed hashes and transactions persist on the ledger nodes even if the dashboard is lost.
Trust model	Users must trust the operator's word that figures are genuine.	Users independently verify the hash – trust shifts from "trust the operator" to "verify the mathematics".
Auditability of trades	Editable Excel/CSV log with no confirmation status.	Every trade shows CONFIRMED with its block number and timestamp – an externally checkable audit trail.

Table 5: consolidated results of the proposed system

Parameter	**Observed output**	**Remark**
Block time (PoA)	5 s (configured), stable	Deterministic sealing
End-to-end logging latency	6.8 s average	Within 10 s target
Transactions per block	6–8 sensor readings	No loss in burst test
Tamper test	Altered block rejected; chain re-synced	100 % detection
Unauthorised gateway test	Transaction reverted ("unauthorized")	Access control effective
Voltage regulation	230 V ±1 % (sag to 225 V at peak)	Sag flagged in audit
Daily energy audit	233.2 kWh generated / 214.5 kWh consumed / 8.0 % loss	Automated by smart contract
Anomaly detection	FEEDER-2 flagged (23.2 % loss)	Theft/leakage indication
EV charging settlement	22.4 kWh billed ₹179.20 automatically	Dispute-free billing
P2P trades	7 trades CONFIRMED, blocks 18450101–18450108	Block-ordered ledger
Hash commitment (Sepolia)	Record #1, Tx 0x91722b…, Block 18450106	Publicly verifiable

These outputs confirm the central claims of the proposed system: the blockchain layer provides tamper-proof, low-latency storage of measurements with automatic rejection of falsified data; smart-contract auditing converts verified records into actionable results—loss quantification, anomaly flagging and automated billing—without a trusted intermediary; and the P2P marketplace produces a block-ordered, publicly verifiable trade ledger that a ThingSpeak/Excel-only pipeline cannot offer. It is noted that the captures with "Use Simulated Testnet Blockchain: ON" run against an in-app simulation, that Sepolia is a shared public test network rather than nodes operated by the authors, and that hash commitment protects the recorded data after commitment but cannot certify the sensor reading itself.

VI. Conclusion and Future Scope

The proposed blockchain-enabled secure smart grid demonstrates the integration of IoT, artificial intelligence, blockchain and web technologies for intelligent energy management. The ESP32 field station provides real-time monitoring of solar, wind and battery voltage, AC voltage, current, power, cumulative energy and peak status, and ThingSpeak provides cloud storage and visualisation. The OpenAI-based layer supports energy analysis, peak-load identification, EV charging optimisation and surplus-energy decisions. The blockchain layer, implemented with Solidity smart contracts on a private PoA Ethereum network and the Sepolia test network, provides secure, transparent and tamper-resistant recording of telemetry hashes and energy transactions, automated energy auditing with loss flagging, automatic EV billing and a decentralised P2P trading mechanism, while the Streamlit dashboard unifies monitoring, analytics, trading, transaction tracking and data-integrity verification in one interface. Experimental results show deterministic 5 s block sealing, 6.8 s logging latency, 100 % tamper detection, accurate automated auditing and a strictly block-ordered trade ledger. Overall, the system offers a scalable and intelligent approach to renewable-energy management

that reduces dependence on centralised trading, improves renewable utilisation and lays a foundation for future decentralised smart-grid ecosystems.

Future work will replace the modelled sensor data of the auditing network with fully live ESP32 nodes and deploy the validator nodes on Raspberry Pi gateways at the physical sites; train and validate the LSTM load-forecasting model on the on-chain history and close the loop with automatic EV charging control through the EVCharge contract; extend the marketplace with dynamic pricing, partial-order matching and integration with a utility settlement interface; and add sensor-level attestation (signed readings at the ESP32) so that integrity is guaranteed from the point of measurement, together with an evaluation of layer-2 networks for lower-cost public commitments.

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