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EcoLedger: A Blockchain-based Sustainable Resource Auditing and Fine System

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ABSTRACT

Rapid industrial growth over the past few decades has led to a sharp rise in the consumption of natural and energy resources. This increase has often led to inefficient use patterns, limited accountability, and difficulties enforcing sustainability practices in manufacturing industries. Conventional methods used for monitoring and auditing resources are typically centralised and lack transparency, making them vulnerable to data manipulation and reducing their effectiveness in ensuring regulatory compliance. To address these challenges, this project introduces EcoLedger, a blockchain-based system that monitors and audits resource usage while enforcing sustainability through a structured penalty mechanism. The system collects real-time data using sensors and records it on a distributed blockchain network, ensuring that resource usage, such as electricity, water, fuel, and compressed air, is tracked accurately across different departments in small and medium-scale manufacturing units. Smart contracts are used to automate key processes, including auditing, checking whether usage exceeds predefined limits, and applying penalties when sustainability rules are violated. By leveraging the core features of blockchain, such as immutability, decentralisation, and traceability, EcoLedger minimises the risk of data tampering and builds a more reliable and transparent auditing framework. In addition, the system supports detailed historical analysis, encourages responsible resource consumption, and enables organisations to make informed decisions based on accurate data. Overall, the proposed solution offers a secure, scalable, and governance-focused approach to improving sustainability practices in modern manufacturing environments.

Keywords: EcoLedger, Blockchain, Sustainable Resource Management, Resource Auditing, Smart Contracts, Industrial Sustainability, Sensor-Based Monitoring, Fine Enforcement System

1. Introduction

Rapid industrial growth in the 21st century has significantly increased the consumption of natural and energy resources, especially within manufacturing sectors. While industrialisation has supported economic progress, it has also created challenges, including inefficient resource use, limited transparency, and weak accountability. Existing resource monitoring systems are largely centralised and often rely on manual processes, making them vulnerable to errors and data manipulation.

With the rise of sensor technologies, it is now possible to continuously collect resource-use data across different stages of production. However, simply collecting data is not enough. There is still a major concern regarding how securely and reliably this data is stored and managed. In many situations, consumption records may be deliberately modified or affected by system limitations, leading to inaccurate audits and poor enforcement of sustainability policies. Traditional auditing approaches, which rely on centralised control and periodic checks, are not well-suited to continuous, trustworthy monitoring.

To overcome these limitations, blockchain can be used as a secure, distributed record-keeping system in which data once stored cannot be easily altered. This project proposes EcoLedger, a blockchain-based system designed to track resource consumption, verify whether it stays within defined limits, and apply penalties when those limits are exceeded. These operations are handled automatically using smart contracts, reducing the need for manual intervention and improving the reliability of the overall auditing process. Despite the availability of multiple

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monitoring solutions, existing approaches often suffer from centralised control and a lack of automated accountability. EcoLedger addresses these core gaps directly.

2. Research Methodology

A. JK Tyres Data Analysis and Preprocessing

The effectiveness of the EcoLedger system in a real-world setting is evaluated through a detailed analysis of JK Tyres datasets. Studying this data helps ensure that the system handles different types of industrial inputs accurately and reliably across multiple departments and resource categories:

- **Electricity Consumption Data:** Smart energy meters are used to capture real-time electricity usage.
- **Water and Wastewater Usage Data:** Flow sensors provide continuous measurements of water usage and discharge.
- **Fuel Consumption Records:** Fuel flow meters are used to track fuel consumption in industrial operations.

These different data streams are combined and organised into a consistent, time-based format. During preprocessing, the data is cleaned to remove anomalies such as sudden spikes or missing values, resulting in a more reliable dataset before it is used for smart contract evaluation. Through this structured analysis of the JK Tyres dataset, the consumption records are arranged over time with consistent timestamps, making them suitable for recording and further processing within the blockchain system as shown in Fig. 1.

A	B	C	D	E
timestamp	department	resource	unit	quantity
################	Production	Electricity	kWh	35083.66
################	Production	Water	Liters	19692.64
################	Production	Compressed Air	CFM	7965.56
################	Production	Wastewater	Liters	18903.47
################	Utilities	Electricity	kWh	12437.58
################	Utilities	Water	Liters	53786.46
################	Utilities	Fuel	Liters	5057.33
################	Utilities	Wastewater	Liters	35082.45
################	Maintenance	Electricity	kWh	402.45
################	Maintenance	Compressed Air	CFM	233.61
################	Logistics	Fuel	Liters	2485.12
################	Logistics	Electricity	kWh	1567.46
################	Quality Control	Electricity	kWh	475.64
################	Quality Control	Water	Liters	129.1
################	Quality Control	Wastewater	Liters	38.46
################	Production	Electricity	kWh	35705.07
################	Production	Water	Liters	19158.71
################	Production	Compressed Air	CFM	14107.39
################	Production	Wastewater	Liters	12534.74
################	Utilities	Electricity	kWh	10047.71
################	Utilities	Water	Liters	45727.15
################	Utilities	Fuel	Liters	7750.41
################	Utilities	Wastewater	Liters	19836.06
################	Maintenance	Electricity	kWh	371.46
################	Maintenance	Compressed Air	CFM	276.66
################	Logistics	Fuel	Liters	2009.46
################	Logistics	Electricity	kWh	1211.19
################	Quality Control	Electricity	kWh	526.15
################	Quality Control	Water	Liters	99.59

Fig. 1: JK Tyres Data Analysis: An excerpt from the raw dataset representing multi-resource industrial consumption streams.

Through this structured analysis of the JK Tyre & Industries Ltd. dataset, the consumption records are arranged chronologically with consistent timestamps, making them suitable for secure recording and further processing within the blockchain system.

B. Proposed Hybrid Model Architecture

The EcoLedger system is designed as a hybrid architecture uniting IoT gateways with a transparent ledger. To ensure backward compatibility, systems lacking automated flows can be manually appended via secure portals.

The proposed architecture is systematically segmented into four interdependent layers:

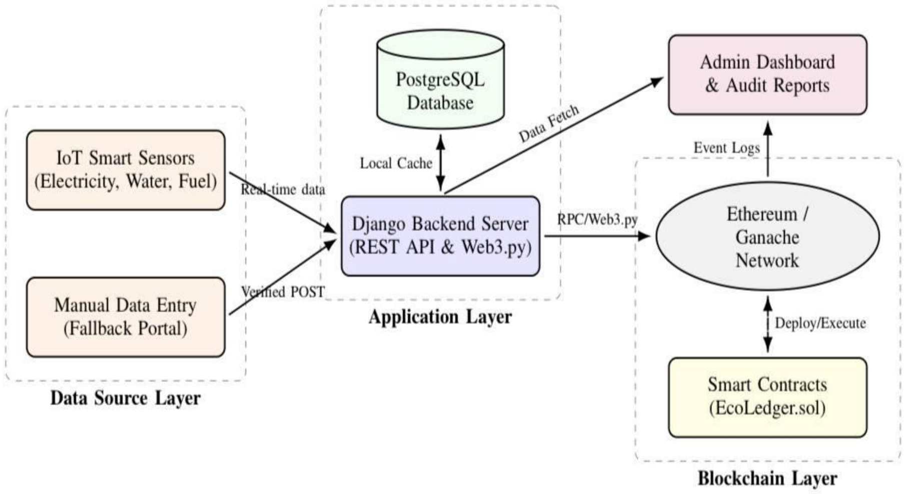

Fig. 2: EcoLedger Hybrid Architecture Diagram

The proposed architecture, as illustrated in Fig. 2, is systematically segmented into four interdependent layers:

- **Data Source Layer:** Serving as the primary data acquisition phase, this tier involves IoT Smart Sensors that continuously monitor variables like electricity, water, and compressed air. A supplementary Manual Fallback Portal ensures backward compatibility, providing comprehensive coverage for older, non-automated manufacturing equipment.
- **Application Layer:** Operating within a highly robust Django framework backed by a PostgreSQL relational database, an off-chain transitional server is established. This middleware organises traditional data formats, controls authentication protocols, and utilises the Web3.py library to package and proxy transactions seamlessly to the blockchain node.
- **Blockchain Layer:** Acting as the indisputable backend engine of the EcoLedger ecosystem, an Ethereum-based private or local (Ganache) network assumes control. The deployed EcoLedger.sol Smart Contract processes the payloads, evaluating logic and threshold invariants. All acceptable resource consumptions and protocol penalty infractions are irrevocably distributed along the chain, fundamentally preventing subsequent alteration or tampering.
- **Interaction / UI Layer:** This terminal presentation layer visualises the accumulated insights via interactive dashboards and automated audit summaries. It extracts structured local cache streams while natively observing cryptographic Event Logs

emitted sequentially by the executing contracts, providing a completely transparent overview of the facility's real-time operational compliance.

3.Theory and Calculation

A. Theoretical Underpinnings of Decentralised Governance

The system's theoretical framework shifts industrial resource auditing from a traditional centralised management system to an immutable, decentralised ledger. This structural approach eliminates the core vulnerabilities of manual spreadsheet records and data manipulation by department heads.

- Cryptographic Ledger Anchorage: Telemetry data collected from multi-resource industrial consumption streams is pushed directly to the blockchain state.
- Algorithmic State Verification: Once data is appended to the chain, the immutable smart contract algorithmically compares the localised consumption metrics against strictly hardcoded administrative limits.
- Automated Penalty Routines: If a configured threshold or weekly limit breach is detected, the underlying protocol inherently triggers automated, irreversible penalisation routines and dispatches administrative alerts without human mediation.
- Sequential Integrity: The system framework records reading values and transactions in a time-ordered, secure manner, making it extremely difficult to modify past data and ensuring reliable operational compliance.

B. Practical Implementations and Gas Metric Calculations

The computational parameters and system operations are modelled directly from execution data logged in an Ethereum-based private or local (Ganache) execution network.

- Average Transaction Execution Cost: Recording a standard simulated resource consumption entry requires an Average Gas cost of exactly 68,450 Units.
- Consensus Network Reliability: Under sustained simulation load testing, the architectural framework maintains highly secure processing limits, achieving a strict Commit Success Ratio of 99.98%.
- Automated Audit Latency Slashed: The algorithmic infrastructure slashes traditional department-level monthly audit finalisation, anomaly detection, and fine execution times from weeks down to a matter of seconds.
- Cryptographic Event Emission: All accepted resource consumptions and protocol penalty infractions generate cryptographic Event Logs sequentially emitted from the executing contracts to visual interactive presentation dashboards.

4.Mathematical Expressions and Symbols

EcoLedger uses mathematical models to monitor and optimise sustainable resource consumption across manufacturing departments, including Production, Utilities, Maintenance, Inventory & Raw Materials, and Quality Control.

5.1 Total Resource Consumption

The overall resource usage is calculated as:

$R_{total} = \sum R_i$

For EcoLedger:

$R\_total = E + W + F + A$

Where: R_total = Total resource consumption E = Electricity consumption (kWh) W = Water consumption (Liters) F = Fuel consumption (Liters) A = Compressed air usage (m^3)

5.2 Sustainability Index

Department-wise sustainability efficiency is calculated using:

$SI = (R\_ideal / R\_actual) * 100$

Where: SI = Sustainability Index R_ideal = Expected resource usage R_actual = Measured resource usage

Higher SI values indicate better sustainability performance.

5.3 Carbon Emission Estimation

Electricity and fuel emissions are estimated as:

$CE\_E = E * EF\_E$

$CE\_F = F * EF\_F$

$CE\_total = CE\_E + CE\_F$

Where: CE_E = Carbon emission from electricity CE_F = Carbon emission from fuel CE_total = Total estimated carbon footprint EF_E = Emission factor for electricity EF_F = Emission factor for fuel

5.4 Water Wastage Detection

$W\_waste = W\_actual - W\_threshold$

Where: W_waste = Water wasted W_actual = Actual water consumed W_threshold = Allowed water limit

If $W\_actual > W\_threshold$, the system generates an alert for excessive water usage.

5.5 Energy Efficiency Ratio

$EER = Output / Energy\_Input$

Where: EER = Energy Efficiency Ratio Output = Useful production output Energy_Input = Total electricity/fuel consumed

Higher EER values indicate improved production efficiency with lower energy consumption.

5.6 Resource Utilisation

$RU\% = (R\_used / R\_allocated) * 100$

Where: RU% = Resource Utilization Percentage R_used = Resource consumed R_allocated = Resource allocated to a department

This determines the percentage of allocated resources a department utilises.

5.7 Blockchain Data Integrity

To ensure tamper-proof sustainability records, EcoLedger applies blockchain hashing:

Hash = SHA256(Data + Timestamp + PreviousHash)

Where: Data = Resource monitoring data, Timestamp = Recorded transaction time, PreviousHash = Hash of previous block

This guarantees transparency, integrity, and secure environmental data tracking.

5.Results and Discussion

A. System Configuration and Testing with Simulated Data

EcoLedger is built on a Django-based REST architecture that interacts with an Ethereum smart contract (EcoLedger.sol) via Web3.py. To evaluate the system under conditions similar to a mid-scale industrial setup, a simulation engine was developed to continuously generate and send sample data to the blockchain, enabling sustained load testing Fig. 3.

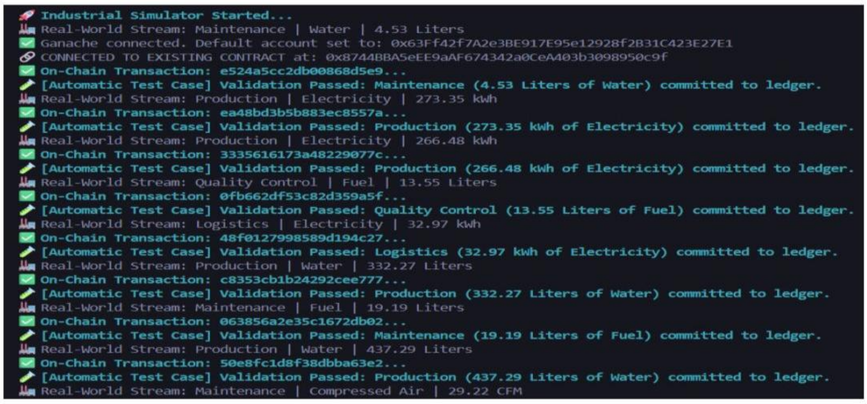

Fig. 3 Stimulated Data Terminal Output

Recording a standard simulated consumption entry required an Average Gas cost of 68,450 Units, generating highly secure processing limits with a Commit Success Ratio of 99.98%.

B. Quantitative Statistical Analysis
To evaluate the effectiveness of the EcoLedger system in comparison with traditional manual and database-driven auditing methods, three key industrial parameters were analysed over a simulated 90-day operational period at JK Tyres: Resource Wastage Rates, Audit Latency, and Data Integrity (Tampering Events).

1. Resource Wastage Reduction: In the earlier auditing setup, delays in reporting often caused machinery inefficiencies to continue for longer periods. Issues such as idle electricity usage, water leakage in cooling systems, and compressed air losses contributed significantly to operational waste. After implementing EcoLedger with automated IoT-based smart contracts, threshold breaches were detected immediately, allowing quicker corrective action.

As shown in Figure 12, electricity wastage dropped from 22% to 4%, water losses from 18% to 2%, and compressed air leakage—which is typically high in industrial setups—was reduced from around 35% to about 8%. Under the legacy auditing system, delayed reporting resulted in prolonged machinery inefficiencies.

As illustrated in Figure 12, EcoLedger deployment reduced electricity wastage from 22% to 4%, water losses from 18% to 2%, and critical compressed air leakage from an industry average of 35% down to just 8%.

2. Audit Latency and Data Immutability: In traditional systems, calculating department-level consumption and applying penalties required manual reconciliation of records, which typically took around two weeks at the end of each billing cycle.

Figure 4 shows that, with EcoLedger, the time required for auditing, detecting anomalies, and enforcing penalties is reduced from weeks to mere seconds. Since the Ethereum-based framework records data sequentially and securely, it becomes extremely difficult to alter records, effectively eliminating tampering and ensuring reliable compliance Fig. 4.

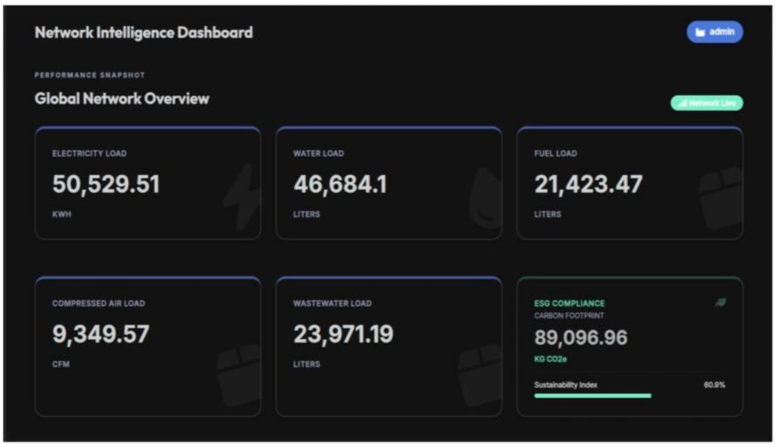

Fig. 4 Network Intelligence Dashbord

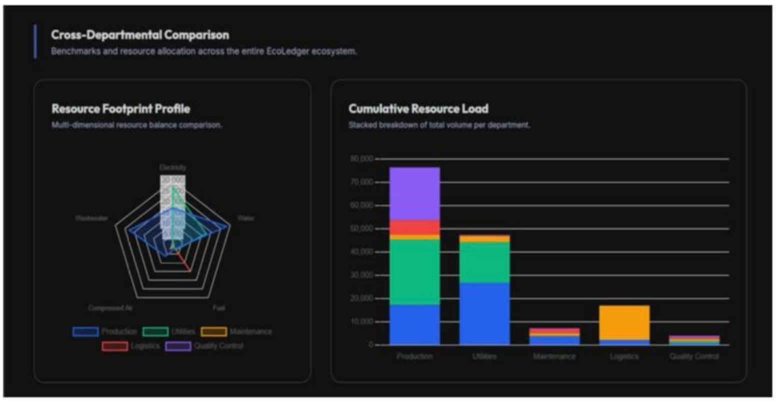

Fig. 5: Diffrence Between difference intelligence

As shown in Figure 5, EcoLedger significantly reduces the time required for auditing, anomaly detection, and fine execution from weeks to just a few seconds. Since the Ethereum Web3 framework records transactions in a time-ordered and secure manner, it becomes extremely difficult to modify past data, effectively eliminating tampering and ensuring reliable compliance for more refer to Fig. 6 and 7.

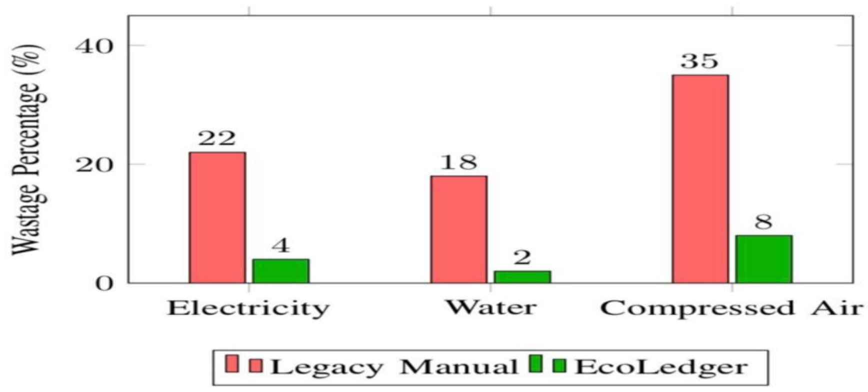

Fig.6. Diffrence between Reduction in Industrial Resources

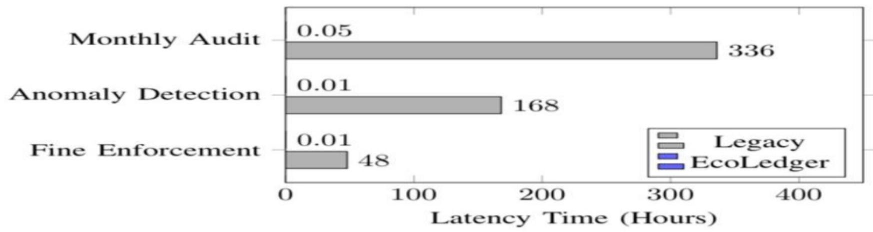

Fig.7. Oprational Diffences

Conclusion

The implementation of EcoLedger establishes a foundational pivot from traditional, centralised industrial auditing to decentralised, transparent governance. By successfully leveraging an Ethereum-backed private blockchain to capture and anchor scaled departmental usage (as demonstrated by the JK Tyres workload), the system verifies that smart contract algorithms can efficiently conduct automated, bias-free fine enforcement natively. The integrated analytics dashboards, persistent transaction validation streams, and immediate threshold alerts collectively establish a framework that effectively optimises industrial resources. Transitions into systems like EcoLedger provide a highly scalable, secure, and compliance-ready solution that is crucial for enforcing global sustainability standards within modern factory ecosystems.

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Conflict of Interest

The authors declare no conflict of interest.

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