Comparative Evaluation of Blockchain Technologies for IoT Energy Monitoring in Residential Settings

Azmat Ullah[1], Giuseppe Antonio Pierro[2] and Roberto Tonelli[2]

[1]*Department of Mathematics and Computer Science, University of Camerino, Camerino, Italy*
[2]*Department of Mathematics and Computer Science, University of Cagliari, Cagliari, Italy*

Abstract

In the context of energy communities, particularly for small residential apartments, the need for efficient and transparent energy consumption tracking has become increasingly important. The blockchain technology can be a major tool for helping people belonging to the energy community to improve transparency, reliability, auditing, and for tracking all single steps of energy production and consumption. Furthermore, the integration of Internet of Things (IoT) devices with such technology for monitoring energy usage provides valuable and reliable data for optimizing consumption patterns. The primary objective of this study is to develop a small-scale pipeline that facilitates the automatic flow of energy consumption data from IoT devices to a blockchain. This pipeline aims to ensure data integrity, transparency, and traceability while minimizing operational costs. This paper conducts a comparative analysis of different blockchain technologies to evaluate the feasibility and efficiency of using blockchain for IoT-based energy monitoring. Various blockchain solutions, including public and private blockchains, are evaluated in terms of their transaction costs, scalability, and the benefits they offer for energy consumption data management. This study compares Ethereum (L1), IOTA (L1), Polygon (L2), and Hyperledger Fabric (private blockchain) across key performance metrics. The metrics evaluated include transaction cost, throughput, latency, and data privacy and permissioning. Based on the results, a Layer 2 blockchain such as Polygon or, even more effectively, a private blockchain like Hyperledger Fabric appears to be the most suitable choice for integrating IoT-based energy monitoring in small-scale energy communities, offering the best balance between cost-efficiency, scalability, and data governance.

Keywords

Energy communities, IoT (Internet of Things), Energy consumption monitoring, Blockchain, Smart metering

1. Introduction

1.1. Motivations

Managing sustainable energy in small residential communities is becoming increasingly important due to the increasing global energy demands and the urgent challenges posed by climate change. Numerous studies highlight the need to improve energy efficiency in homes to mitigate environmental impacts and reduce carbon footprints. For example, K. Thabo et al. [1] emphasize the growing concern about climate change and highlight the importance of improving energy efficiency in residential buildings to address energy shortages. Similarly, the study in [2] reveals that household energy consumption accounts for 27% of total UK carbon dioxide emissions, underscoring the significant environmental impact of domestic energy use.

In addition to environmental sustainability, residential energy management systems must also address privacy and security challenges. Modern IoT-based smart home systems enable real-time energy monitoring; however, they raise concerns regarding data security, privacy, and the reliability of consumption data. As discussed in [3], many smart home solutions rely on centralized data processing architectures, which are particularly vulnerable to cyberattacks, unauthorized data manipulation, and general reliability issues. These concerns are further supported by [4], which notes that traditional

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*Corresponding author.
azmat.ullah@unicam.it (A. Ullah); giuseppea.pierro@unica.it (G. A. Pierro); roberto.tonelli@unica.it (R. Tonelli)
0009-0006-4452-3948 (A. Ullah); 0000-0002-3805-7964 (G. A. Pierro); 0000-0002-9090-7698 (R. Tonelli)

server-client models in smart grids suffer from synchronization issues and are susceptible to single-point failures.

The shortcomings of centralized architectures have led to increased interest in decentralized alternatives. Research in [4] and [5] suggests that blockchain technology provides a promising solution by offering a transparent, tamper-resistant ledger for energy data. This decentralized model not only reduces the risk of data manipulation and system failures but also enables secure peer-to-peer energy trading between local energy producers (prosumers) and consumers.

Based on these findings, our study integrates IoT-based energy monitoring with a comparative evaluation of blockchain technologies suited for a small residential house. Using accurate energy data collection from ShellyEM sensors and localized processing through Raspberry Pi-based edge computing units, the proposed system ensures the automatic and reliable transmission of data to blockchain platforms. To the best of our knowledge, this represents the first practical implementation that combines the Shelly Energy Meter with a Raspberry Pi for blockchain-based energy monitoring. This approach reinforces the benefits of decentralization outlined in previous research and contributes to the advancement of practical, secure, and efficient energy management frameworks within residential energy communities.

1.2. Novelty and Gaps

Many studies have been conducted on the use of blockchains for energy communities.

Galici et al. [6] report on a real-world pilot project carried out in an Italian municipality, where blockchain-enabled smart meters (BSM) were installed in five public institutions that function as a local energy community (LEC). This field test uncovered practical insights, such as network communication challenges, and illustrated enhanced transparency and sustainability assessment. Furthermore, Andoni et al. [7] review various global pilot projects, ranging from peer-to-peer energy trading in Germany to local blockchain-powered energy markets in France, the Netherlands, and the United States, highlighting the growing interest in applied blockchain solutions.

Previous studies [8, 9] have evaluated different blockchain solutions in the context of energy communities. Specifically, the study by G.A. Pierro et al. [8] focused on private blockchain solutions such as Besu and Quorum, aiming to identify which blockchain is most suitable for energy communities based on various metrics, including transactions per second and other relevant factors. In contrast, the study by A. Ullah [9] used a simulation program to generate potential data for an energy community and investigated how these data could be efficiently integrated into a public blockchain.

While previous studies have explored the application of blockchain in energy communities, ranging from real-world pilot projects to simulation-based analyses, most have focused either on large-scale implementations or on high-level evaluations of blockchain platforms. However, there remains a gap in research specifically addressing the integration of real-time IoT-generated energy consumption data into blockchain systems, particularly for small-scale residential energy communities. The current study aims to bridge this gap by developing and testing a lightweight and cost-effective data pipeline that connects IoT devices directly to different blockchain platforms. This approach not only ensures data integrity and traceability but also evaluates which blockchain technologies are most practical and scalable for everyday use in small residential settings.

1.3. Paper Structure

This section describes the overall structure of the paper and the logical flow of its content. Section 2.1 introduces the use case scenario and explains the data collection process using low-cost IoT devices in a residential setting. Section 3 presents the blockchain framework and methodology, including an overview of different blockchain technologies (Layer 1, Layer 2, and private blockchains). It also describes the criteria used for comparison and the design of the integration pipeline. Section 4 provides a detailed comparison of selected blockchain platforms based on performance and structural metrics. It is followed by an analysis of the most suitable technologies for small-scale energy communities.

Section 5 concludes the paper and outlines directions for future work, emphasizing the uniqueness of the proposed solution in the context of residential energy monitoring.

2. Use Case and Data Collection

2.1. Use Case

An IoT energy monitoring system was set up in a typical residential apartment, specifically located in the laundry room, to accurately assess the daily consumption of energy in the home. This location was strategically chosen for its proximity to primary appliances that significantly influence overall energy use. Two primary appliances were monitored: the washing machine and the water heater (boiler). The washing machine was selected to collect detailed data on laundry activities, including usage timing, frequency, and duration, reflecting the daily routines of the residents. Conversely, the water heater was observed to assess energy consumption during peak hours, especially in the morning and evening when hot water demand is highest.

The system has two main objectives: to monitor real-time energy consumption and to analyze user behavior within the home. High-precision ShellyEM sensors were employed to reliably capture energy data, while Raspberry Pi-based edge computing units processed this information on-site. This method ensured not only the accuracy of the recorded data but also provided insights into the relationship between daily appliance use and overall energy demand. The resulting dataset allows for a comprehensive analysis of usage patterns, leading to the development of targeted strategies for enhancing energy efficiency. This deployment underscores the transformative potential of IoT solutions in managing residential energy by linking data collection directly to effective energy-saving measures.

2.2. System Installation Procedure

The Shelly EM device was installed and connected to the home Wi-Fi network. Its energy readings are transmitted in real time to the blockchain over an encrypted communication channel (using HTTPS), ensuring that the data is protected from unauthorized access and can only be accessed by authenticated users with the appropriate credentials.

Due to the limited space within the electrical cabinet and restricted visibility, it was not possible to take high-quality photos of the entire wiring layout. However, all components were installed correctly, and their functionality has been verified. Below are the steps of the installation process:

- **Shelly EM:** Securely mounted on a wall within a dry, enclosed space to protect the device from dust, moisture, and other environmental factors.
- **Current Transformer (CT):** Properly clamped around the live conductors of the monitored appliances (washing machine and heater boiler). Special attention was paid to the directional orientation of the CT sensors to ensure an accurate measurement of current flow.
- **Power Supply:** The Shelly EM was connected to the main distribution board through its designated live (L) and neutral (N) terminals, adhering to the voltage specifications required for operation.
- **Network Configuration:** The devices were set up using a Python script with blockchain and the Telegram app, enabling integration into a secure Wi-Fi network. Secure communication protocols were used to ensure the secure transmission of monitoring data to the processing unit.

2.3. Schematic Representation of the Installation

Instead of comprehensive installation photographs, a detailed schematic diagram was developed to visually convey the physical layout and logical connections of the physical system, as shown in Fig. 1. This schematic has been carefully designed to reflect the actual installation environment and includes the following elements:

- **Electrical Wiring:** Clear representation of how power flows from the utility source through the energy meter and into the Shelly EM device.
- **CT Sensor:** Visual indicators that show the correct clamping positions and the proper directional alignment of the current transformers.
- **Data Flow Architecture:** Illustration of how measurement data is transmitted from the Shelly EM to a Raspberry Pi-based processing unit via Wi-Fi, and subsequently stored locally and sent to the blockchain platform.

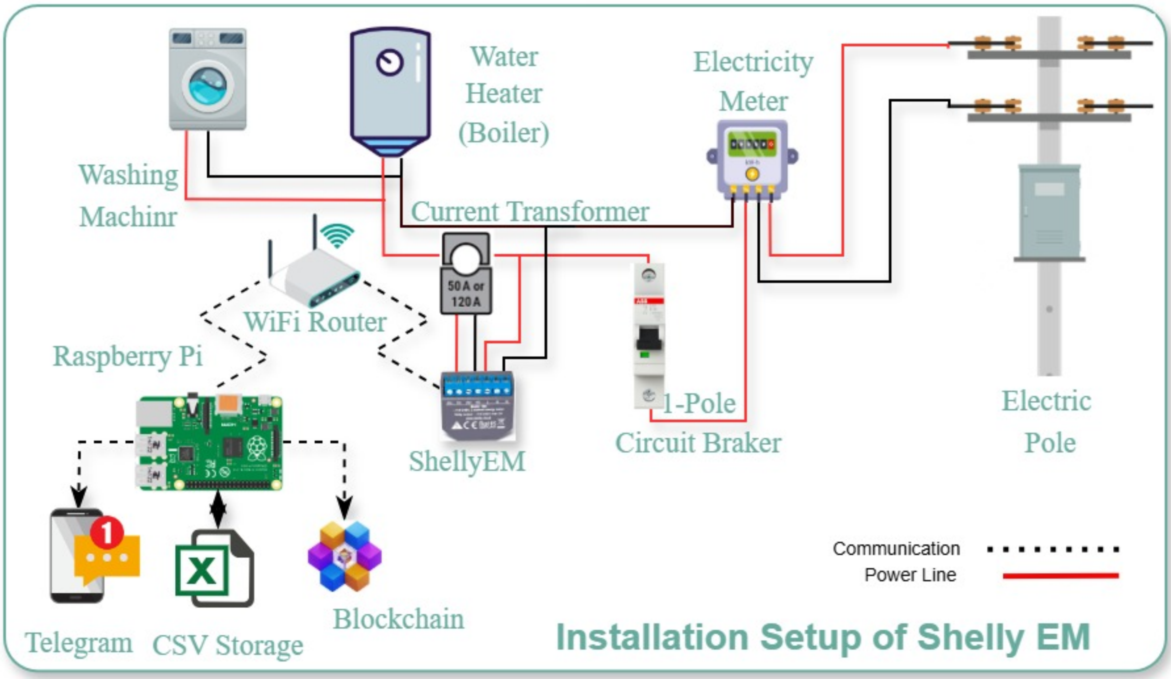

Figure 1: Real-Time Energy Monitoring Setup using Shelly EM and Raspberry Pi: This architecture demonstrates the arrangement and integration of the real system, including the Shelly EM, Raspberry Pi, CT sensor, and LCD display.

2.4. Data Collection

Figure 2 displays the electrical consumption patterns in a residential apartment, as recorded by a smart meter. The top three subplots show the instantaneous power (in watts), voltage (in volts), and current (in amps) over time, while the bottom subplot illustrates the cumulative total energy consumed (in watt-hours). Before approximately 12:00, the graph reveals short bursts of high power, with fluctuations in voltage and corresponding spikes in current, suggesting the operation of a washing machine. These events are characterized by brief periods of high energy demand.

After 12:00, the consumption profile changes. Longer periods of fluctuating power draw are observed, accompanied by changes in voltage and current. This pattern indicates the operation of a boiler. The total energy consumption gradually increases during this time, reflecting the continuous energy usage of the boiler. Intermittent drops to near-zero power and current, along with a flattening of the total energy curve, likely represent the times when the boiler's heating cycle was completed.

In summary, the graph clearly differentiates between the energy consumption patterns of the washing machine (characterized by short, high-intensity bursts) and the boiler (characterized by longer, sustained usage). This provides valuable insights into the apartment's energy consumption for these two key appliances.

Figure 3 illustrates the power consumption trend of the Shelly smart meter over a 24-hour period, measured in watts. The power usage remains consistently around 1.8 to 2.4 watts throughout the

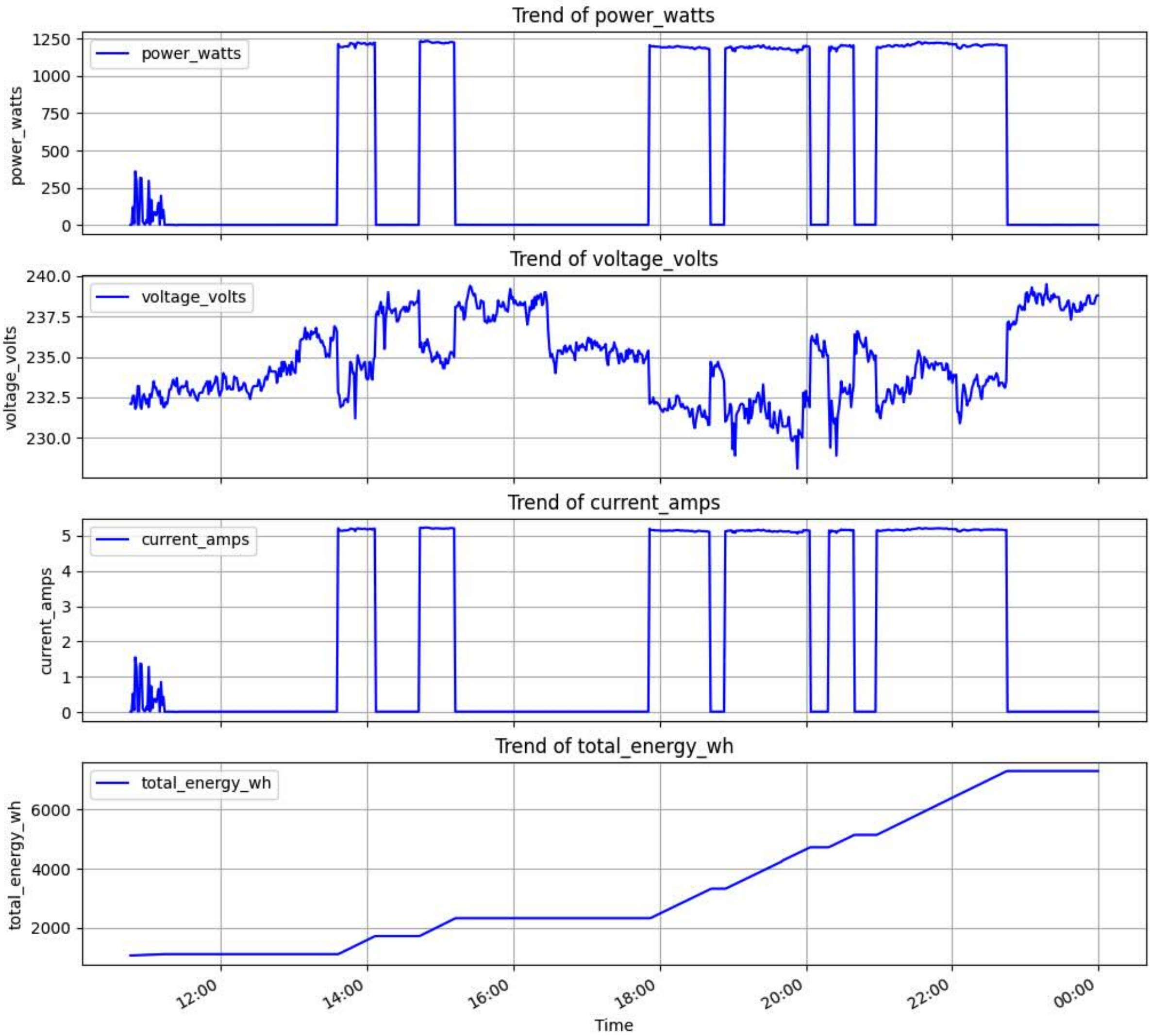

Figure 2: Energy consumption patterns in a residential apartment, showing the distinct signatures of a washing machine (short bursts) and a boiler (sustained usage).

day, indicating that the Shelly smart meter operates with remarkably low energy requirements. The relatively stable line suggests that the device does not experience significant spikes in consumption, which is beneficial for maintaining overall energy efficiency. This low power consumption is crucial for residential users, as it minimizes the impact on electricity bills. By ensuring that the smart meter does not draw substantial power, homeowners can integrate smart technology without straining their budgets.

3. Blockchain Framework and Methods

3.1. Overview of blockchain technologies (L1, L2, private)

Layer 1 (L1) blockchains, such as Ethereum [10] and IOTA [11], are the base networks where smart contracts can be written and executed. These blockchains handle transactions and ensure security. Layer 2 (L2) blockchains, built on top of L1, improve scalability and transaction speed. They process transactions off the main blockchain and then settle them on L1. Private blockchains, like Hyperledger [12], are permissioned networks that allow only authorized participants to write and execute smart contracts. They offer greater privacy and control compared to public L1 blockchains.

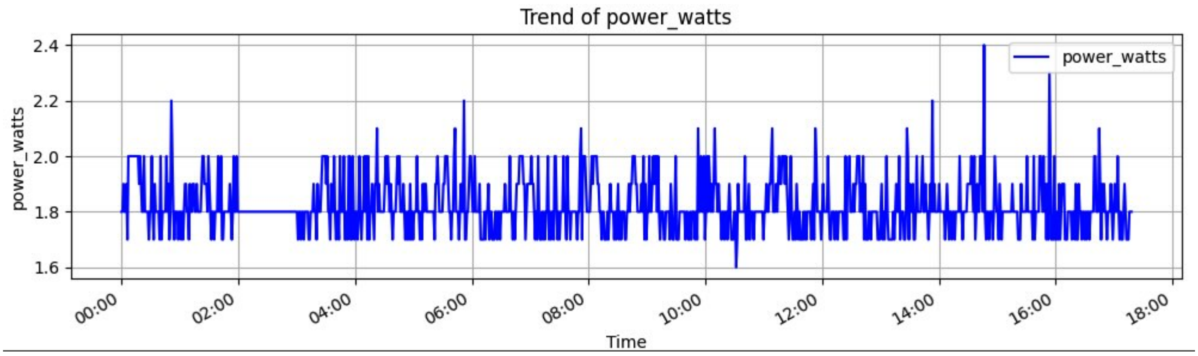

Figure 3: The Shelly smart meter operates with exceptionally low energy requirements, consuming less than 3 watts.

3.2. Criteria for comparison

To evaluate and compare different blockchain platforms, it is essential to consider a range of metrics. Each blockchain has unique characteristics, and understanding these can help determine its suitability for specific applications. The key criteria for comparison include:

- **Throughput and Scalability:** This measures how many transactions a blockchain can handle per second (TPS). Higher throughput is important for applications that require fast and large-scale processing.
- **Cost and Efficiency:** This includes transaction fees and energy usage. Blockchains based on Proof-of-Work (PoW) usually consume more energy and incur higher costs compared to energy-efficient alternatives like Proof-of-Stake (PoS).
- **Security:** The level of protection against attacks, such as double-spending or 51% attacks, is crucial. Security depends on factors like the consensus mechanism, network size, and cryptographic techniques used.
- **Decentralization:** The extent to which control is distributed across network participants affects trust and resilience. Greater decentralization generally improves censorship resistance and network stability.
- **Privacy and Confidentiality:** Some blockchains are fully transparent, while others incorporate privacy features such as zero-knowledge proofs or confidential transactions to protect user data.
- **Interoperability:** This refers to the blockchain's ability to communicate and exchange data with other blockchains or external systems. Interoperable blockchains offer more flexibility and integration possibilities.
- **Development Ecosystem and Community Support:** A strong developer ecosystem, good documentation, and active community support are important for ongoing innovation, security, and adoption.

3.3. Design of the integration pipeline

The proposed energy monitoring system is designed with a structured architecture that consists of four interconnected layers: the Hardware Layer, Edge Processing Layer, Data Management Layer, and User & Blockchain Interface Layer. Figure 4 illustrates how each layer has specific functions that facilitate seamless integration between IoT devices and blockchain technology for managing energy data.

At the foundation, the **Hardware Layer** includes two energy monitoring devices that detect input and display the output on an LCD. For example, the ShellyEM meter monitors the power usage of high-demand appliances such as washing machines and water heaters, while the ShellyPlus PlugIT tracks the power consumption of the Raspberry Pi controller. An LCD status display offers users instant visual feedback regarding the system's condition and any alerts.

To collect data from these devices using the API, the system interacts with them over the local network through simple web-based requests. For instance, it sends a GET request (similar to loading a webpage in a browser) to retrieve power data from the ShellyEM. In contrast, the ShellyPlus Plug uses a method called Remote Procedure Call (RPC), which involves sending specific commands to obtain the necessary information. This process is commonly referred to as API communication.

The **Edge Processing Layer** acts as the system's computational core, running on a Raspberry Pi equipped with Python modules for data collection and preprocessing. Data is transmitted via HTTP communication from the Hardware Layer. The Raspberry Pi establishes persistent sessions to collect information from the Shelly EM meter using asynchronous GET requests, while the ShellyPlus PlugIT is accessed through JSON-RPC. JSON-RPC is a lightweight protocol that allows commands to be sent as JSON messages over HTTP, with the device responding with structured JSON data to ensure effective communication.

To facilitate simultaneous communication with multiple devices, the system uses Python's 'asyncio' library. This allows the Raspberry Pi to handle various tasks concurrently, for instance, awaiting data from one device while still gathering data from another, without delays or interruptions. This non blocking approach is especially beneficial for real-time systems, where a steady and timely data flow is essential.

After capturing the measurements, the Sensor Data Reader processes them by confirming accuracy, performing calculations such as averaging or calibration adjustments, and organizing the results in a uniform format. Each data entry is timestamped.

The processed information is recorded in clear, user-friendly log files, with a new file created daily for each monitored device. This approach makes it easier to review historical records, aids in data management, and preserves an accurate, auditable account of the system's performance.

Once data is collected and processed, they are sent to the **Data Management Layer**, which ensures data persistence and integrity. Energy consumption data is initially logged in structured data files by a Local data Logger, allowing users to access and review historical data on-site. To protect this data from tampering, a cryptographic hash of the formatted data file is created and submitted to the blockchain at regular intervals. This process protects data privacy by avoiding the direct storage of raw data on the blockchain while providing unalterable proof of its integrity.

The final feature, the **User & Blockchain Interface Layer**, connects the system to external platforms and end users. Integration with different Blockchain testnets (e.g., IOTA, Ethereum, Assetchain, etc.) is facilitated through a Web3 wallet, which securely signs and transmits the hashed energy data to the blockchain. This process ensures that only authenticated nodes are allowed to write data to the ledger. Additionally, the user's mobile application receives a well-formatted data report that enables them to view their energy usage and confirm that their information has been securely recorded on the blockchain. This enhances usability and transparency while fostering trust in the system's decentralized energy monitoring capabilities.

4. Results and Discussion

This paper presents results based on two types of performance data. First, we obtained real empirical performance results. We achieved these results through actual prototype interactions. We tested our prototype on three blockchain infrastructures. One blockchain is public; it is IOTA. Two blockchains are private; they are BESU and Quorum. Second, we derived other performance data from existing literature [8]. This combination of real measurements and literature-based information forms the basis of our findings.

4.1. Architecture and Governance Analysis

Table 1 presents a comparison of key structural metrics for several blockchain platforms. The table outlines differences in data privacy, permissioning, consensus mechanisms, network security, and interoperability. Notably, Ethereum and Polygon are categorized as public blockchains with low data

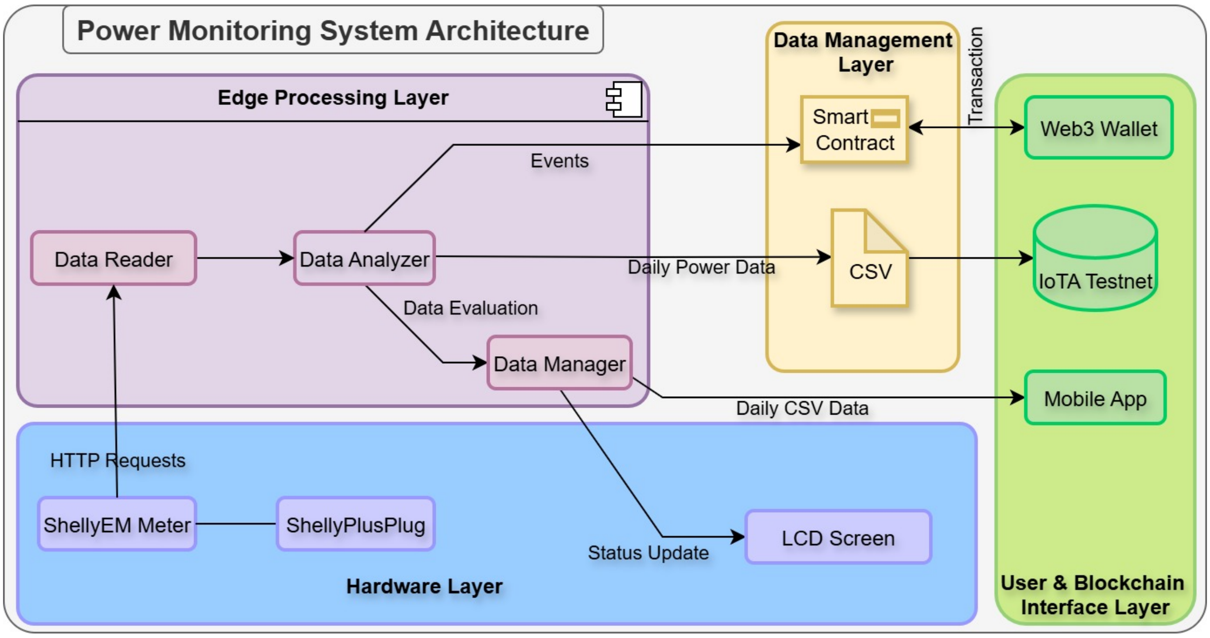

Figure 4: Decentralized Energy Monitoring System Architecture illustrates the data flow from the ShellyEM Meter through processing layers to blockchain storage and user interfaces. The system integrates IoT sensing, data analysis, local, and blockchain-based storage to ensure secure and transparent monitoring of energy consumption in residential environments.

privacy, while Besu and Quorum are private blockchains offering medium to high data privacy. The consensus mechanisms vary, ranging from Proof of Work (PoW) in Ethereum to Directed Acyclic Graph (DAG) in IOTA and Proof of Stake (PoS) in Polygon. Network security is generally high across the platforms, with Polygon having medium security. Finally, interoperability is low for Besu and Quorum, but high for Ethereum, IOTA, and Polygon.

Table 1
Comparison of Data Privacy, Permissioning, Consensus Mechanism, Network Security, and Decentralization Level for Selected Blockchain Platforms.

Blockchain Name	Data Privacy	Permissioning	Consensus Mechanism	Network Security	Decentralization Level
Ethereum	Low	Public	Proof of Work	High	High
IOTA	Medium	Public	Directed Acyclic Graph (DAG)	High	Low to Medium
Polygon	Low	Public	Proof of Stake	Medium	Medium
Besu	Medium	Private	Proof of Authority	High	Low
Quorum	High	Private	Quorum (Voting)	High	Low
Hyperledger Fabric	High	Private	Practical Byzantine Fault Tolerance (PBFT)	High	Low

This comparison highlights the strengths and weaknesses of various blockchain technologies. IOTA is ideal for low-cost, privacy-sensitive applications, while Polygon is best suited for high-throughput requirements with low latency. Ethereum, while popular, may face challenges in scalability and speed. Besu and Quorum cater to private blockchain needs, offering a balance of data privacy and controlled access.

Polygon shows the highest maximum throughput at 7000 transactions per second, indicating its suitability for high-demand applications. Ethereum, with a maximum throughput of only 30, may struggle under heavy loads.

Polygon again excels with the lowest average latency of 2 seconds, facilitating quick transaction confirmations. Ethereum has the highest latency at 20 seconds, which can hinder real-time applications.

IOTA offers high data privacy, essential for applications requiring confidentiality, while Ethereum and Polygon provide low data privacy, which may not be suitable for sensitive transactions. Besu and Quorum are better options for private use cases, offering medium to high data privacy. IOTA, Polygon, and Ethereum operate under public permissioning, promoting decentralization. In contrast, Besu and

Quorum are private, making them more appropriate for enterprise solutions where controlled access is necessary.

4.2. Cost and Performance Analysis

Table 2 presents a comparison of key performance metrics for several blockchain platforms. The table highlights differences in transaction cost, maximum throughput, average latency, scalability, energy consumption, and decentralization level. Notably, Polygon achieves the highest throughput (7000 transactions per second) and the lowest latency (2 ms), offering high scalability and medium decentralization. Ethereum, despite having a much lower throughput (30) and higher latency (20), is characterized by a high level of decentralization, which contributes to its robustness and trustworthiness. IOTA demonstrates high scalability and low energy consumption, with a decentralization level categorized as low to medium due to its reliance on the Coordinator node (though improvements are ongoing). Quorum and Besu, being private or permissioned blockchains, offer relatively low decentralization but benefit from lower energy consumption and improved latency.

Table 2
Comparison of Transaction Cost, Throughput, Latency, Scalability, Energy Consumption, and Hardware Cost for Selected Blockchain Platforms.

Blockchain Name	Transaction Cost	Max Throughput	Average Latency	Scalability	Energy Consumption	Hardware Cost
Ethereum	20-100 gwei (ETH)	30	20	Limited	0	80 euro
IOTA	0.00003 IOTA	1000	10	High	0	80 euro
Polygon	1-10 gwei (MATIC)	7000	2	High	0	80 euro
Besu	Low or 0 (Private)	1000	5	Medium	0.5 (kWh)	120 euro
Quorum	Low or 0 (Private)	3000	3	Medium	0.5 (kWh)	120 euro
Hyperledger Fabric	Low or 0 (Private)	3500	2-3	High	0.5 (kWh)	120 euro

Estimating the implementation costs of blockchain systems involves several variables. Fixed hardware costs, such as smart meters and Raspberry Pi devices for data transmission, are approximately €80 per unit. Public blockchains have the advantage of not requiring dedicated hardware infrastructure to maintain the network. In contrast, private blockchains necessitate specific hardware. In our tests, we estimated the infrastructure cost for a private blockchain at around €2,400, which corresponds to the cost of four Mac Mini M2 units. Distributed across an energy community of 60 members, this results in an estimated cost of €40 per household.

Our ShellyEM sensors send around 7.4 KB of data with each energy reading, encompassing sensor values, device states, and timestamps. With readings occurring every 30 seconds, the daily data volume per device varies from 48 to 101 KB based on activity levels and operational conditions. On average, each device transmits about 74.5 KB of data per day. This transmission volume significantly affects the energy consumption of the devices. Currently, we rely on grid power, but for off-grid or remote applications, continuous data transmission at this rate necessitates effective power management. Our estimates indicate that transmitting every 30 seconds would drain a standard 2000mAh battery in roughly 2–3 weeks. This underscores the necessity for solar recharging solutions or a reduction in transmission frequency to maintain long-term sustainability in such environments.

However, public blockchains incur transaction fees. These costs are difficult to estimate because they fluctuate according to the value of the native token, which is often volatile. For instance, IOTA demonstrates the lowest transaction cost at 0.00003 IOTA, making it particularly suitable for applications requiring frequent micro-transactions. On the other hand, Ethereum presents the highest transaction cost, potentially limiting its adoption in cost-sensitive scenarios. Table 2 summarizes all relevant cost categories. Nevertheless, determining which blockchain is more cost-effective depends heavily on the market value of the token and the local price of energy (€/kWh)—both of which are highly variable and make direct comparisons difficult.

5. Conclusion and Future Work

This study presents a contribution to the field of blockchain-enabled energy monitoring by focusing on a low-cost residential setup using standard devices. Specifically, the Shelly smart meter was deployed as an energy monitoring device due to its affordability, ease of installation, and low energy consumption. This makes it a practical solution for small-scale residential environments such as apartments and condominiums.

Through a comparative analysis of multiple blockchain platforms—including Ethereum, Polygon, IOTA, Quorum, and Besu—this work evaluated both performance and structural metrics relevant to IoT-based energy monitoring. These included transaction cost, throughput, latency, energy efficiency, data privacy, and interoperability. The results indicate that Layer 2 solutions like Polygon and private blockchains such as Hyperledger Fabric offer the most balanced trade-off between cost-efficiency, scalability, and data governance for the residential context.

Importantly, the study sheds light on the trade-offs between decentralization and operational efficiency. While Ethereum provides strong decentralization and trust, it incurs higher costs and latency. Conversely, IOTA and private solutions offer improved performance at the expense of full decentralization. Of particular note, IOTA's architecture is well-suited to IoT environments due to its low energy footprint and adaptable privacy mechanisms. Although it remains less decentralized due to the current reliance on a Coordinator node, ongoing protocol improvements may address this limitation in the future.

Future work will focus on the full integration of the proposed pipeline in real-world residential energy communities. This includes:

- Developing a complete end-to-end system for real-time data acquisition, blockchain storage, and user-friendly visualization interfaces.
- Extending the study to include more diverse residential environments and testing with multiple IoT devices and sensor types.
- Investigating the implementation of privacy-preserving techniques such as zero-knowledge proofs to enhance data confidentiality.
- Exploring dynamic pricing models and token-based incentive mechanisms that reward users for energy-saving behaviors, enabled through smart contracts.

Overall, this work demonstrates that affordable and efficient blockchain-based energy monitoring is achievable even in small-scale residential settings, paving the way for more decentralized and transparent energy communities.

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7. Declaration on Generative AI

The authors used Grammarly AI tools solely for language refinement. The scientific content, analysis, and experimental design are entirely the original work of the authors.

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