DOI: 10.15514/ISPRAS-2024-36(6)-10

Secure and Efficient Data Model for Public Lighting in México with AMI/IoT: Implementing LZ4 Compression, IPFS, and Blockchain

[1] *R. García Reyes, ORCID: 0009-0002-7395-9362 <d21ce036@cenidet.tecnm.mx>*
[1] *J. Ortiz-Hernandez, ORCID: 0000-0002-6481-1537 <javier.oh@cenidet.tecnm.mx>*
[2] *R. Mijarez, ORCID: 0000-0001-8369-4092 <r.mijarez.c@gmail.com>*
[3] *J. A. Hernández-Aguilar, ORCID: 0000-0002-5184-0005 <jose_hernandez@uaem.mx>*
[1] *Y. Hernández, ORCID: 0000-0002-8842-0899 <yasmin.hp@cenidet.tecnm.mx>*

[1] *National Technological Institute of Mexico, National Center for Research and Technological Development, Cuernavaca, México.*
[2] *National Institute of Electricity and Clean Energy, Cuernavaca, México.*
[3] *Autonomous University of the State of Morelos, Cuernavaca, México.*

Abstract. The advent of digitalization and Internet of things (IoT) technologies brings new challenges to the management of electric metering systems. Integrating institutional energy billing systems with government Ambient Intelligence (AMI) systems is essential for effective management. Blockchain technology is proposed to maintain data integrity through automated energy readings. This study introduces an innovative model designed to enhance public lighting in Mexico by integrating AMI and IoT, and employing LZ4 and IPFS for data compression. This approach aims to optimize the handling of large data volumes, resulting in improved data efficiency, enhanced security, cost reductions, and better energy resource management.

Keywords: blockchain; Internet of things (IoT); advanced metering infrastructure (AMI); inter planetary file system (IPFS); LZ4; public lighting.

For citation: García Reyes R., Ortiz-Hernandez J., Mijarez R., Hernández-Aguilar J. A., Hernández Y. Secure and Efficient Data Model for Public Lighting in México with AMI/IoT: Implementing LZ4 Compression, IPFS, and Blockchain. Trudy ISP RAN/Proc. ISP RAS, vol. 36, issue 6, 2024. pp. 179-194. DOI: 10.15514/ISPRAS-2024-36(6)-10.

Acknowledgements. This research was supported by the National Center for Research and Technological Development (CENIDET) through the CONACYT doctoral scholarship. RGR acknowledges the financial support of CONACYT, Mexico.

Безопасная и эффективная модель данных для электрического освещения общественного пространства в Мексике с AMI/IoT: реализация сжатия LZ4, IPFS и блокчейна

[1] *Р. Гарсия Рейес, ORCID: 0009-0002-7395-9362 <d21ce036@cenidet.tecnm.mx>*
[1] *Х. Ортис-Эрнандес, ORCID: 0000-0002-6481-1537 <javier.oh@cenidet.tecnm.mx>*
[2] *Р. Михарес, ORCID: 0000-0001-8369-4092 <r.mijarez.c@gmail.com>*
[3] *Х. А. Эрнандес-Агилар, ORCID: 0000-0002-5184-0005 <jose_hernandez@uaem.mx>*
[1] *Я. Эрнандес, ORCID: 0000-0002-8842-0899 <yasmin.hp@cenidet.tecnm.mx>*

[1] *Национальный центр технологических исследований и разработок Мексики, Куэрнавака, Мексика.*
[2] *Национальный институт электроэнергии и чистой энергетики, Куэрнавака, Морелос, Мексика.*
[3] *Автономный университет штата Морелос, Куэрнавака, Мексика.*

Аннотация. Появление цифровизации и технологий Интернета вещей (IoT) ставит новые задачи по управлению системами учета электроэнергии. Интеграция институциональных систем выставления счетов за электроэнергию с государственными измерительными инфраструктурными системами (AMI) имеет важное значение для эффективного управления. Для обеспечения целостности данных при автоматизации снятия показаний электроэнергии предлагается использовать технологию распределенного реестра (блокчейн). Настоящая работа описывает инновационную модель, предназначенную для улучшения освещения общественного пространства в Мексике путем интеграции систем AMI и IoT, а также использования алгоритмов LZ4 и IPFS для сжатия данных. Выбранный подход направлен на оптимизацию обработки больших объемов данных, его использование приводит к повышению эффективности данных, повышению безопасности, снижению затрат и улучшению управления энергоресурсами.

Ключевые слова: блокчейн; интернет вещей (IoT); окружающий интеллект (AMI); межпланетная файловая система (IPFS); алгоритм сжатия LZ4; электрическое освещение общественного пространства.

Для цитирования: Гарсия-Рейес Р., Ортис-Эрнандес Х., Михарес Р., Эрнандес-Агилар Х. А., Эрнандес Я. Безопасная и эффективная модель данных для электрического освещения общественного пространства в Мексике с AMI/IoT: реализация сжатия LZ4, IPFS и блокчейна. Труды ИСП РАН, том 36, вып. 6, 2024 г., стр. 179–194 (на английском языке). DOI: 10.15514/ISPRAS–2024–36(6)–10.

Благодарности. Выполнение исследования поддерживалось Национальным центром исследований и технологического развития (CENIDET) через докторскую стипендию CONACYT. Первый автор выражает благодарность за финансовую поддержку CONACYT, Мексика.

1. Introduction

Blockchain technology, through its distributed ledger technology (DLT), offers enhanced security and transparency for energy transactions, particularly in peer-to-peer (P2P) trading. Despite facing challenges in technology, economy, society, and regulation, its potential to revolutionize microgrid management and automate billing processes is significant [1]. In Mexico's advanced metering infrastructure (AMI) for public lighting, has improved real-time energy management and billing, but discrepancies due to system differences and manual interventions can lead to billing inaccuracies and loss of consumer trust [2]. Blockchain could address these issues by providing immutable and transparent records, acting as an integration bridge between institutional and proprietary AMI systems in public lighting. Beyond finance, real estate, insurance, and supply chain sectors, blockchain demonstrates its value in solving complex energy management problems.

2. Definition of the problem

In Mexico, the use of IoT electric meters is limited and involves addressing security, privacy, and reliability concerns in critical environments, with blockchain, IPFS (Inter Planetary File System) [3], and LZ4 [4] proposed for secure data handling and distribution.

The research aims to develop a model for securely managing AMI/IoT meter data in public lighting systems, which handle thousands of devices per customer and seek improved billing processes. Integrating blockchain in public lighting presents challenges, including the need for a robust infrastructure to support secure P2P transactions [5-6], addressing increased bandwidth and latency issues and handling high data volumes efficiently [7].

2.1 Objectives

1. Propose a Model: Develop a data integration model to secure and protect information from IoT devices in utility power grids, such as street lighting, handling thousands of AMI/IoT devices.
2. Implement Protection Mechanisms: Use IPFS and Blockchain for data integrity and authenticity, with LZ4 for additional compression.
3. Evaluate Effectiveness: Assess the system’s security, performance, and scalability in IoT meter power grid environments.

2.2 Hypothesis

The combination of Blockchain, IPFS, and LZ4 aims to secure and optimize IoT data integration in utility power grids, like street lighting. Unlike existing models, which focus on domestic and industrial uses, this solution targets IoT meters for single customers, such as street lighting. It will enhance data efficiency and security, lower costs, and improve energy management while ensuring data integrity in dynamic environments with numerous AMI/IoT devices.

2.3 Contribution

This work’s main contribution is a new model for addressing security and privacy challenges in AMI/IoT data integration for utility power grids. By combining IPFS and Blockchain with LZ4 compression, the model offers a robust solution that enhances the reliability and security of power grids, leading to more efficient and secure services for users.

3. Related work

In recent years, AMI has transformed energy measurement and management, including in street lighting [8]. However, the integration of various systems has created operational challenges [9]. Blockchain technology offers a potential solution for data integrity, decentralization, and transparency [10], with ongoing studies examining its use in the energy sector [11].

The rapid evolution of smart grids and smart meters has raised significant data security and communication challenges. These meters, crucial for AMI, are exposed to cyber-attacks through public channels, such as data theft and unauthorized access [12]. Islam's study [12] proposes using blockchain to secure AMI communication, addressing issues with traditional cryptographic solutions that rely on trusted third parties. Their blockchain-based approach, using smart contracts and PBFT, aims to reduce costs and enhance security in AMI systems.

The Decentralized Autonomous Area (D3A) model uses blockchain and smart contracts to enhance and decentralize the power grid, improving the integration of renewable resources and system resilience by fostering transparency and competition [13]. It also securely integrates IoT data, addressing power grid security challenges.

The article "Decentralized Energy Networks Based on Blockchain" [14] highlights the role of blockchain in the decentralization of the energy sector, including local renewable energy communities and P2P markets. This context is relevant for understanding how IPFS and blockchain can facilitate secure transitions in energy systems.

The TWACS (Two Way Automatic Communication System) telemetering system [15], used by CFE in Mexico [16], faced security issues due to its centralized structure and lack of blockchain and IPFS integration. While it managed large volumes of data efficiently, its vulnerability to file modifications highlighted the need for improved security and decentralized data management.

3.1. Blockchain and IPFS on AMI systems

Blockchain technology, introduced by Satoshi Nakamoto in 2008 and launched in 2009, is a decentralized digital ledger that stores encrypted information, ensuring data integrity and preventing tampering [17]. Each block is linked to previous ones, and replication across multiple nodes guarantees data originality. This technology holds significant promise for transforming AMI by offering a secure, transparent foundation for operations [18].

Originally associated with cryptocurrencies, blockchain's potential for AMI systems has become evident. There are two main types of blockchains: public (permissionless) and private (permissioned). Public blockchains are open to all, while private ones restrict participation to selected nodes, balancing transparency with privacy for AMI systems [17-18]. Smart contracts, which automate processes like reading and billing, reduce costs by eliminating intermediaries [19].

The Hyperledger Fabric (HLF) platform by IBM is a notable example of blockchain technology applied to IoT/AMI systems. It features an "execute-order" model, optimizing performance and confidentiality, crucial for dynamic AMI environments [20].

The article "Blockchain-Based Applications for Smart Grids: An Umbrella Review" [21] provides a comprehensive review of blockchain applications in smart grids, synthesizing findings from various studies to address technical inaccuracies and highlight blockchain's transformative potential for modernizing power grids.

The Umbrella review model is presented in Fig. 1 with the most representative elements of the work.

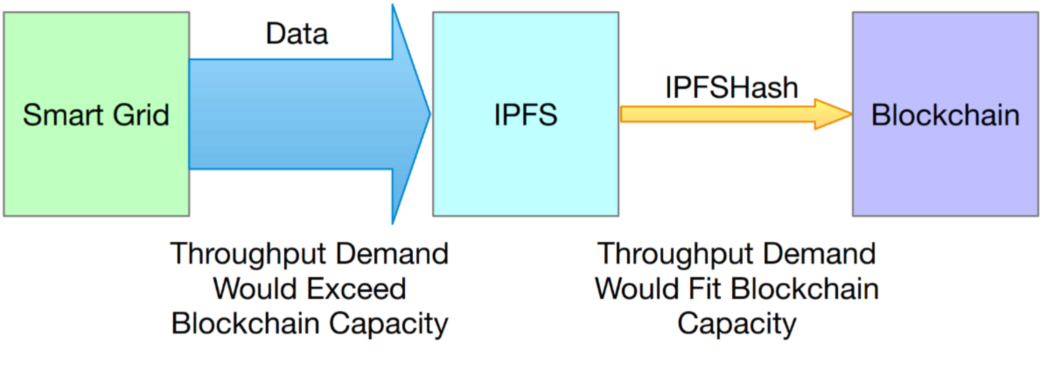

Fig. 1. Data flow of the Blockchain-Based Applications for Smart Grids: An Umbrella Review model [20].

Méndez [22] suggests developing dynamic smart communities in Mexico to promote energy savings through smart interfaces. The study notes that the residential sector consumed nearly 39% of electricity in 2021 and emphasizes the impact of user habits on consumption. It advocates for using gamification and artificial neural networks (ANNs) to improve user interaction and design more personalized, energy-efficient systems.

Electricity losses, including theft and billing irregularities, pose a major challenge globally, especially in developing countries [23]. Innovative approaches to consumption, management, and billing are needed.

Current systems, even with measures like prepaid metering, have limited impact on reducing losses [23]. Strengthening regulations and security measures, along with improving customer relationships, could be more effective. The proposed model addresses environmental concerns by using less energy-intensive consensus mechanisms like Proof-of-Stake (PoS) or Proof-of-Authority (PoA), aligning with sustainability goals [24].

Blockchain's ability to facilitate secure, direct transactions between prosumers without intermediaries enhances privacy and trust in energy trading [25]. Integrating blockchain with AMI systems can reduce billing irregularities and fraud, automate processes, and build trust between customers and utilities.

The article "Managing the computational load in a Blockchain-based multilevel IoT network" [26] discusses optimizing computational load by dividing the IoT network into layers, blending centralized IoT with blockchain distribution to avoid disrupting existing applications. This work helps understand blockchain integration in IoT networks and informs the design of similar models for utility power grids.

The paper "A Method for Protecting Private Data in IPFS" describes a method combining blockchain and enhanced IPFS to protect private data by managing permissions and file organization [27]. This approach could enhance data security and privacy in the developed model for IoT and street lighting systems.

Another model, the "Blockchain-based multilayer model," divides data into four layers to improve public information integrity and security, using different consensus algorithms for each layer to ensure decentralization and transaction speed [28]. This model aims to provide secure and transparent digital government services.

Fig. 2 shows the general diagram of the proposed model, with its most important and representative elements, as well as the stakeholders involved in the processes.

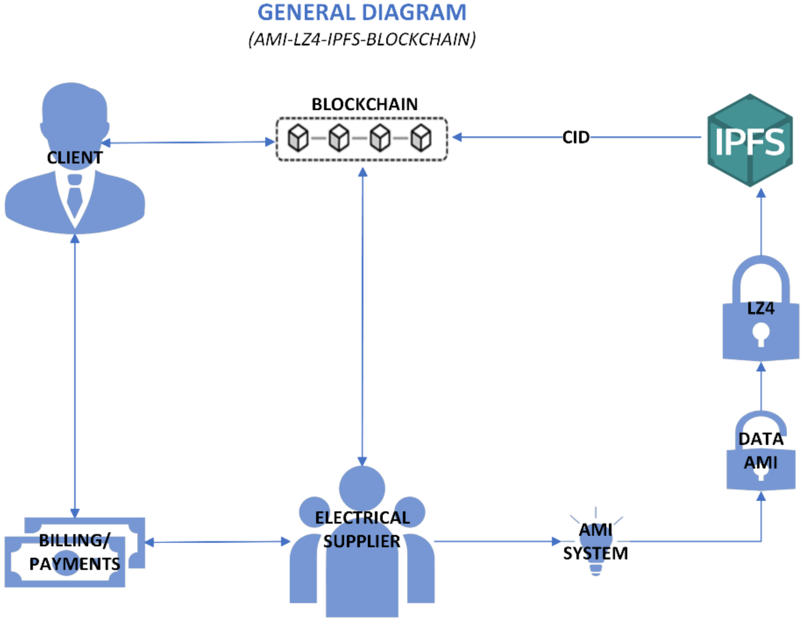

Fig. 2. General diagram, own elaboration.

3.2 Methodology

- Problem Definition:
- Create a model for secure AMI/IoT data integration in Mexico's power grids using blockchain, IPFS, and LZ4.
- Define data flow and security requirements.
- Specification of Requirements:
- Set objectives for data security and access.
- Define software-level requirements.

1. Research Question Posing:
   - Formulate questions on technologies and methods.
   - Explore development approaches.
2. Review of Methods:
   - Review existing AMI/IoT data integration projects.
3. Identification of Relevance:
   - Assess the proposed solution's relevance and effectiveness.
4. Design and Development:
   - Develop a blockchain and IPFS solution with strong security and consensus protocols.
5. Expert Feedback:
   - Gather and incorporate expert feedback.

4. Model development

The model aimed to improve street lighting under APBT and APMT tariffs [29] using AMI and IoT technologies. These tariffs (see Table 1), previously 5 and 5A, were reformed in Mexico in 2014 and split into basic supply and distribution in 2016 [30-31].

Current AMI/IoT models focus on domestic and commercial sectors, where each meter serves an individual customer. In Mexico, municipalities face a unique challenge with a single account managing thousands of devices. This case study highlights the need for scalable, interoperable, and secure AMI/IoT solutions to handle the complexities of large-scale public lighting.

Table 1. Classification of electricity tariffs in Mexico by customer, energy demand, and associated AMI/IoT meter model

Tariff Category	Description	Previous Tariff	Commercial Model
Domestic	Domestic Low Voltage	1, 1A-F	1 customer - 1 meter
PDBT	Small Demand Low Voltage	2, 6	1 customer - 1 meter
GDBT	Large Demand Low Voltage	3, 6	1 customer - 1 meter
RABT	Agricultural Irrigation Low Voltage	9	1 customer - 1 meter
APBT	Public Lighting Low Voltage	5	1 customer - Thousands of meters
APMT	Public Lighting Medium Voltage	5A	1 customer - Thousands of meters
GDMTH	Large Demand Hourly Medium Voltage	HM, HMC, 6	1 customer - 1 meter
GDMTO	Large Demand Ordinary Medium Voltage	OM, 6	1 customer - 1 meter
RAMT	Agricultural Irrigation Medium Voltage	9M	1 customer - 1 meter
DIST	Industrial Sub Transmission	HS, HSL	1 customer - 1 meter
DIT	Industrial Transmission	HT, HTL	1 customer - 1 meter

From a technical standpoint, the AMI/IoT system designed by INEEL in Mexico [32] is used within the Enabling Technologies Division's Control, Electronics, and Communications department. This system utilizes RF communication and ARM architecture, as shown in Fig. 3.

Three Meters generates their files using the JSON format, with the structure depicted in Fig. 4.

Fig. 3. AMI/IoT meter, property of INEE.


```
{    "Id": "7538PH",    "Consumo": 37354,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "0000CU",    "Consumo": 45096,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "0000NC",    "Consumo": 70776,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "00010C",    "Consumo": 58442,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "00010G",    "Consumo": 93780,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "00010J",    "Consumo": 85023,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "00010Q",    "Consumo": 83475,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "00010T",    "Consumo": 71758,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "00010X",    "Consumo": 10805,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "0001AL",    "Consumo": 56274,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "0001BD",    "Consumo": 27011,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "0001CH",    "Consumo": 33659,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "0001CI",    "Consumo": 52655,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "0001DP",    "Consumo": 51635,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "0001FL",    "Consumo": 54779,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "0001GH",    "Consumo": 38015,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "0001HV",    "Consumo": 62393,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "0001ID",    "Consumo": 70423,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "0001LB",    "Consumo": 25809,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "0001OD",    "Consumo": 57701,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "0001PH",    "Consumo": 64308,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "0001QK",    "Consumo": 24803,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "0001TH",    "Consumo": 16732,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "0001VY",    "Consumo": 43254,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "0001XU",    "Consumo": 95622,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "0002BV",    "Consumo": 15112,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "0002BZ",    "Consumo": 71163,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
{    "Id": "0002DI",    "Consumo": 85645,    "Fecha": "45105",    "TipoMedidor": 1,    "Notas": ""  },
```


Fig 4. AMI/IoT file structure, property of INEEL.

The data format used is JSON, but XML or plain text are also common in the AMI industry. Meters include an ID, date, and type. To simulate a large-scale scenario with thousands of AMI/IoT meters for street lighting, synthetic data subsets were created, recording only consumption in kWh under low-voltage conditions. Data size is further reduced using LZ4 compression before being transferred to IPFS, adding an extra layer of security. The compressed files can be previewed in a text editor, as shown in Fig. 5.

The LZ4 algorithm was chosen for its excellent compatibility with the data, as well as its efficient transfer, compression, and decompression capabilities. Its ease of integration into Visual Studio Community 2022, due to the availability of libraries and resources, further supported its selection. Fig. 6 illustrates LZ4's performance in compression, transfer, and decompression.

After compressing AMI/IoT files with LZ4, they are transferred to the IPFS, a distributed file system that decentralizes file storage and distribution across multiple nodes instead of relying on a single server.

To transfer files to IPFS, follow these steps:

- Initialize IPFS Node: Install IPFS software on the device and run the initialization command.
- Add Files: Upload LZ4-compressed AMI files to IPFS using the command, which assigns a unique CID to each file.
- Distribute Files: IPFS automatically propagates the files to other nodes in the network for efficiency and redundancy.
- Access Files: Retrieve files using their CID, which provides a unique address for access from any IPFS node.

Fig. 7 shows files loaded into IPFS with LZ4 compression applied. Fig. 8 illustrates the generation of a CID (Content Identifier) in IPFS, which enables easy retrieval from anywhere in the distributed network. This process also applies to files with synthetic data.

Using IPFS for storing and distributing LZ4-compressed AMI files offers an efficient, cost-effective, and resilient solution:

- Reduced Bandwidth Usage: IPFS's decentralized network distributes content across multiple nodes, decreasing load on any single server and reducing bandwidth usage.
- Lower Storage Cost: IPFS utilizes storage across various nodes, minimizing the need for a large centralized server and cutting storage costs.
- Censorship Resistance: IPFS's decentralized nature prevents censorship and single points of failure, ensuring long-term availability and access by all relevant parties.

Fig. 5. File structure with the LZ4 [4] algorithm applied.

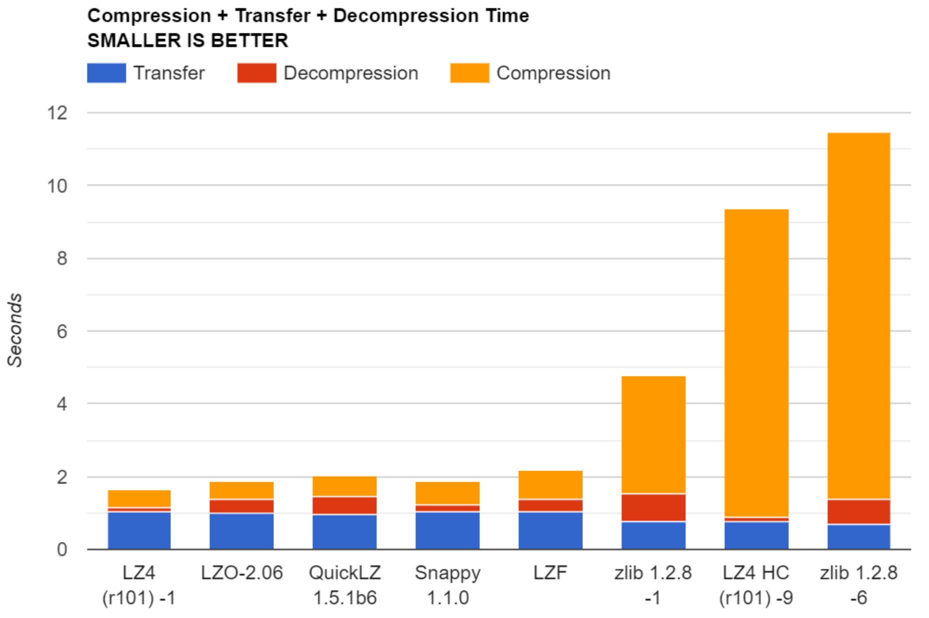

Fig. 6. Comparison of compression, transfer, and decompression levels with working times of the LZ4 algorithm [4].

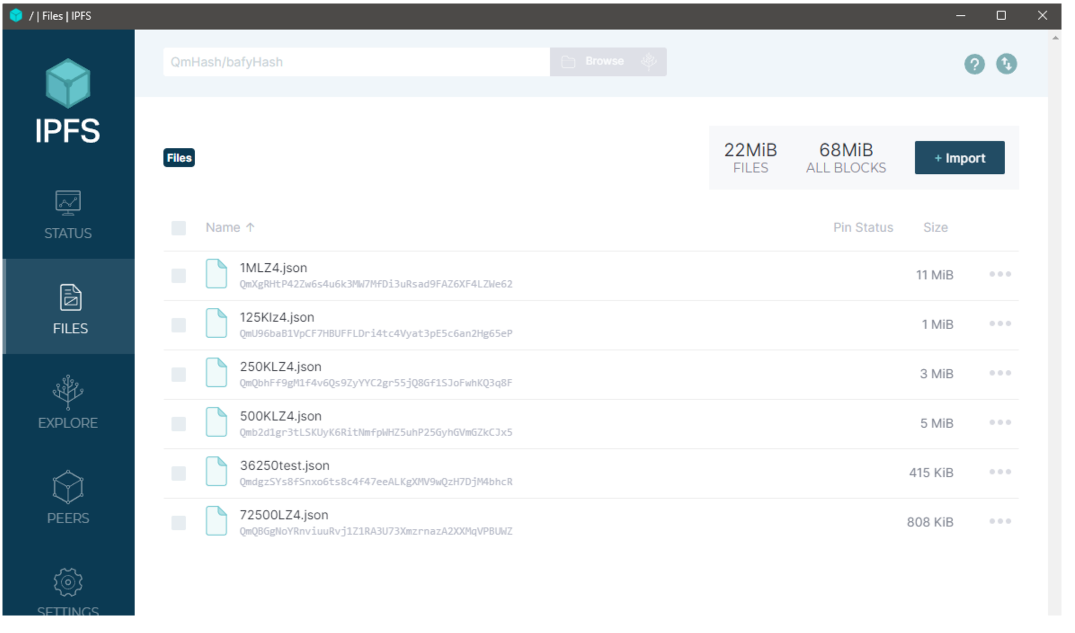

Fig. 7. View of files loaded in the IPFS already with LZ4 compression applied.

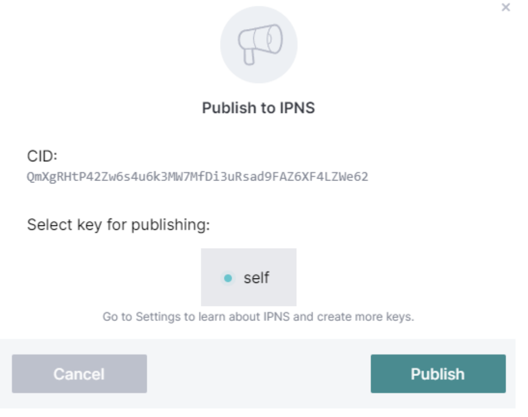

Fig. 8. CID (Content Identifier) generation in IPFS.

Table 2 provides comprehensive data on the optimization process, presenting file sizes before and after compression, optimization percentages, and associated costs in Ether (ETH), USD, and MXN. The table highlights the substantial reductions in both file size and costs, demonstrating improvements in system efficiency through the use of LZ4 and JWT compression.

Table 2. Final results.

Readings per meter	File Size (kB)	File Size after LZ4 and JWT (kB)	% Optimization	Cost in Ether (ETH)	Cost (USD)	Estimated Gas Required	Total Cost to Upload to Blockchain USD (original size)	Total Cost to Upload to Blockchain USD (optimized)	Cost in MXN Optimized	Cost in MXN Unoptimized
1M	106446	11172	89.5	0.0002	0.31	200000	$ 31.58	$ 0.31	$ 5.56	$ 99.71
500K	50787	5564	89.04	0.00015	0.23	150000	$ 15.79	$ 0.23	$ 4.12	$ 73.98
250K	25391	2763	89.12	0.0001	0.16	100000	$ 7.89	$ 0.16	$ 2.87	$ 51.46
125K	12696	1362	89.27	0.00008	0.12	80000	$ 3.95	$ 0.12	$ 2.15	$ 38.60
72.5K	7364	809	89.01	0.00006	0.09	60000	$ 2.30	$ 0.09	$ 1.61	$ 28.95
36.2K	3682	416	88.7	0.00004	0.06	40000	$ 1.15	$ 0.06	$ 1.08	$ 19.30

The model effectively reduces file size using LZ4 and JWT, while IPFS and blockchain ensure efficient data management and integrity.

Results indicate a significant reduction in storage and transaction costs through data compression. The combination of LZ4 and JWT with IPFS and blockchain enhances data management by offering efficiency, robustness, and cost-effectiveness.

The proposed model, integrating advanced compression and distributed storage, surpasses traditional AMI systems. Unlike centralized systems, this model leverages blockchain's immutable security and IPFS's distributed nature, which together prevent data manipulation and increase resilience.

Though blockchain storage incurs transaction costs, the reduction in file sizes and the use of IPFS counterbalance this expense, leading to long-term savings and improved data management.

Fig. 9 illustrates the AMI-LZ4-IPFS-HASH (ALIH) model, comprising four layers:

1. AMI/IoT Data Layer: Generates and loads data from the Smart Grid.
2. LZ4 Compression Layer: Applies compression to the data.

3. IPFS Layer: Stores and distributes the compressed data.
4. Hash-CID Layer: Manages file identification and retrieval via CID.

Table 3 compares a traditional AMI system with the enhanced model using IPFS and blockchain. The enhanced model provides superior data protection, integrity, and resilience through decentralized storage and immutable verification, resulting in reduced costs and improved security over the traditional centralized approach.

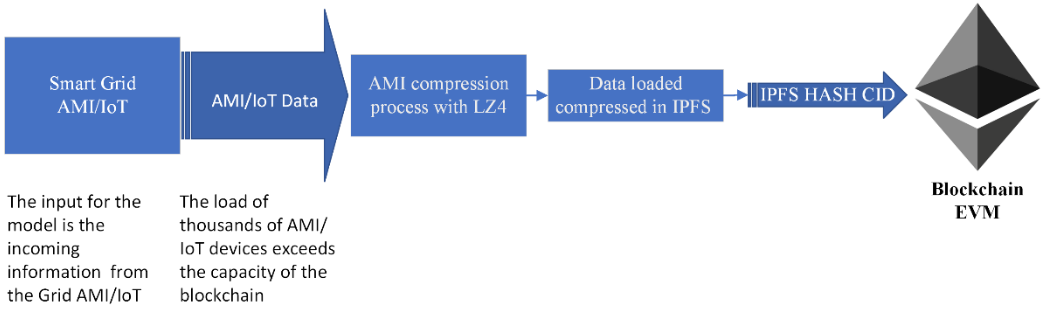

Fig. 9. ALIH Model Diagram of Blocks.

Table 3. Traditional AMI System versus Proposed Model.

Aspect	Traditional AMI System	Enhanced Model with IPFS, LZ4 and Blockchain
Encryption Standards	AES-128 and AES-256 for encryption in transit and at rest.	LZ4 for compression, JWT for authentication, Blockchain for integrity.
Data Protection	Centralized protection, depends on server and network security.	Decentralized protection, immutable verification via blockchain.
Data Authenticity	Based on internal verification mechanisms, vulnerable to attacks.	Ensured by JWT and immutable records in the blockchain.
Data Integrity	Controlled by audit logs and access controls, susceptible to alterations.	Ensured by cryptographic hashes in blockchain (SHA-256).
Resilience	Depending on server and network redundancy, may fail under DDoS attacks.	High resilience through distributed storage in IPFS and immutable copies in blockchain.
Data Availability	May be affected by server or network failures.	High availability ensured by distribution across IPFS nodes and replication in blockchain.
Storage Costs	High due to centralized infrastructure and server maintenance.	Reduced through compression and distributed storage in IPFS; gas costs on blockchain offset by reduced file size.
Security against Tampering	Vulnerable to internal manipulations and attacks if central server is compromised.	Robust protection through blockchain immutability and cryptographic verification.
Transaction and Gas Costs	Not applicable, costs are mainly related to central infrastructure.	Costs related to blockchain gas; significant optimization due to reduced file size.

5. Conclusions

The proposed ALIH model has proven effective in terms of both security and economic efficiency, as supported by the data in Table 2 and the completion of planned activities. Key aspects include:

5.1 Benefits

Security: LZ4 compression enhances security by reducing file size, making data tampering harder. IPFS ensures integrity and decentralization, reducing the risk of data alteration or loss.

Economic Efficiency: LZ4 compression significantly cuts storage and transfer costs on the blockchain, improving cost management.

Practical Implementation: The model successfully executed all planned tasks, including JSON file generation, LZ4 compression, and IPFS uploading, validating its effectiveness in security and cost efficiency.

5.2 Limitations

Blockchain Costs: Gas fees can still be a limiting factor, especially for large-scale implementations.

Scalability: Further exploration is needed to ensure consistent performance with very high data volumes or varying network conditions.

5.3 Future Research

Performance Optimization: Focus on enhancing compression and blockchain integration to further reduce costs and boost speed.

Scalability Studies: Investigate the model's performance across different network environments and data volumes.

Security Enhancements: Explore advanced encryption and multi-factor authentication to strengthen security.

In summary, the ALIH model addresses security and economic challenges in AMI data management, with successful implementation and cost reductions validating its potential. Future research should refine and expand the model's capabilities for broader application.

Conflict of interest

The authors declare that they have no conflicts of interest.

References

[1]. Evens, M., Ercoli, P., & Arteconi, A., "Blockchain-Enabled Microgrids: Toward Peer-to-Peer Energy Trading and Flexible Demand Management", Energies, vol. 16, no. 16, p. 6741, 2023. [Online]. Available: https://doi.org/10.3390/en16186741.

[2]. CONUEE, "Proyecto piloto de tele gestión en alumbrado público", Dirección de Fomento, Difusión e Innovación, Comisión Nacional para el Uso Eficiente de la Energía, January 2023. [Online]. Available: https://www.gob.mx/conuee/articulos/publica-la-conuee-el-informe-del-proyecto-piloto-de-telegestion?idiom=es.

[3]. IPFS "For Developers: Navigating IPFS", IPFS.tech. [Online]. Disponible en: https://ipfs.tech/developers/. [Access: 4 may 2024].

[4]. LZ4 Block Format Description. [Online]. Disponible en: https://lz4.org/ [Access: 4 may 2024]

[5]. Choobineh, M., Paaso, A., Arabnya, A., Sohrabi, B., & Khodaei, A. (2023). Blockchain technology in energy systems: A state-of-the-art review. IET Blockchain, 3(1), 35–59. https://doi.org/10.1049/blc2.12020.

[6]. Andoni, M., Robu, V., Flynn, D., Abram, S., Geach, D., Jenkins, D., et al.: Blockchain technology in the energy sector: A systematic review of challenges and opportunities. Renewable Sustainable Energy Rev. 100,143–174 (2019).

[7]. Meeuw, A., Schopfer, S., Wortmann, F.: Experimental bandwidth benchmarking for P2P markets in blockchain managed microgrids. Energy Procedia. 159, 370–375 (2019).

[8]. Gungor, V. C., Sahin, D., Kocak, T., Ergut, S., Buccella, C., Cecati, C., & Hancke, G. P. (2013). "Smart Grid and Smart Homes: Key Players and Pilot Projects", IEEE Industrial Electronics Magazine, 7(4), 18- 34.

[9]. Zanella, A., Bui, N., Castellani, A., Vangelista, L., & Zorzi, M. (2014). Internet of Things for Smart Cities. IEEE Internet of Things Journal, 1(1), 22-32.

[10]. Narayanan, A., Bonneau, J., Felten, E., Miller, A., & Goldfeder, S. (2016). Bitcoin and Cryptocurrency Technologies: A Comprehensive Introduction. Princeton: Princeton University Press.

[11]. Mengelkamp, E., Notheisen, B., Beer, C., Dauer, D., & Weinhardt, C. (2018). A blockchain-based smart grid: towards sustainable local energy markets. Computer Science - Research and Development, 33(1-2), 207-214.

[12]. Islam, N., Rahman, M. S., Mahmud, I., Sifat, M. N. A., & Cho, Y.-Z. (2022). A Blockchain-Enabled Distributed Advanced Metering Infrastructure Secure Communication (BC-AMI). Appl. Sci., 12(14), 7274. https://doi.org/10.3390/app12147274.

[13]. Bronski, P., Creyts, J., Gao, S., Hambridge, S., Hartnett, S., Hesse, E., Morris, J., Nanavatty, R., & Pennington, N. (2018). "The Decentralized Autonomous Area Agent (D3A) Market Model: An Implementation Framework for Transactive Energy Based on Blockchain for the 21st Century Grid", Energy Web Foundation. Retrieved from https://energyweb.org/D3A.

[14]. Pichler, M., Meisel, M., Goranovic, A., Leonhartsberger, K., Vallant, H., Lettner, G., Marksteiner, S., Chasparis, G., & Bieser, H. (2019). "Decentralized Energy Networks Based on Blockchain: Background, Overview and Concept Discussion" in W. Abramowicz & A. Paschke (Eds.), BIS 2018 Workshops (LNBIP 339, pp. 244–257). Springer Nature Switzerland AG. https://doi.org/10.1007/978-3-030-04849- 5_22.

[15]. Aclara, "TWACS Net Server with TWACS OC Software", Hubbell, 2008. [Online]. Available: https://www.hubbell.com/aclara/en/solutions/twacs. [Accessed: May 16, 2024].

[16]. G. Reyes, "Enterprise Management Systems for Database Administration Focused on Invoicing Processes", Master's thesis, Facultad de Contaduría Administración e Informática, Universidad Autónoma del Estado de Morelos, Cuernavaca, Morelos, Noviembre 2014.

[17]. Aggarwal, S., Chaudhary, R., Aujla, G.S., Kumar, N., Choo, K.K.R., & Zomaya, A.Y. (2019). Blockchain for smart communities: Applications, challenges and opportunities. J. Netw. Comput. Appl., 144, 13–48.

[18]. Liu, Z., Luong, N.C., Wang, W., Niyato, D., Wang, P., Liang, Y.-C., & Kim, D.I. (2019). A survey on applications of game theory in blockchain. arXiv, arXiv:1902.10865.

[19]. Wang, S, Ouyang, L., Yuan, Y., Ni, X., Han, X., & Wang, F.Y. (2019). Blockchain-enabled smart contracts: Architecture, applications, and future trends. IEEE Trans. Syst. Man Cybern. Syst., 49, 2266–2277.

[20]. Graf, M., Küsters, R., & Rausch, D. (2020). Accountability in a permissioned blockchain: Formal analysis of hyperledger fabric. In Proceedings of the 2020 IEEE European Symposium on Security and Privacy (EuroS&P), Genoa, Italy, 7–11 September 2020.

[21]. Zhao, W., Qi, Q., Zhou, J., & Luo, X. (2023). Blockchain-Based Applications for Smart Grids: An Umbrella Review. Energies, 16(6147). https://doi.org/10.3390/en16176147.

[22]. Méndez, J. I., Medina, A., Ponce, P., Peffer, T., Meier, A., & Molina, A. (2022). Evolving Gamified Smart Communities in Mexico to Save Energy in Communities through Intelligent Interfaces. Energies, 15(5553). https://doi.org/10.3390/en15155553.

[23]. Carr, D., & Thomson, M. (2022). Non-Technical Electricity Losses. Energies, 15(6), 2218. https://doi.org/10.3390/en15062218.

[24]. Djamali, A., Dossow, P., Hinterstocker, M., Schellinger, B., Sedlmeir, J., Völter, F., & Willburger, L. (2021). Asset logging in the energy sector: A scalable blockchain-based data platform. In Proceedings of the 10th DACH+ Conference on Energy Informatics (pp. 1-14). Virtual Conference.

[25]. Miao, S., Zhang, X., Asamoah, K.O., Gao, J., Qi, X. (2021). E-Chain: Blockchain-Based Energy Market for Smart Cities. In: Liu, Q., Liu, X., Shen, T., Qiu, X. (eds) The 10th International Conference on Computer Engineering and Networks. CENet 2020. Advances in Intelligent Systems and Computing, vol 1274. Springer, Singapore. https://doi.org/10.1007/978-981-15-8462-6_176.

[26]. R. B. Chakraborty, M. Pandey, and S. S. Rautaray, "Managing Computation Load on a Blockchain-based Multi-Layered Internet-of-Things Network", in Proc. Comput. Sci., vol. 132, pp. 469-476, 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1877050918312400.

[27]. Y. Lin and C. Zhang, "A Method for Protecting Private Data in IPFS", in Proceedings of the 2021 IEEE 24th International Conference on Computer Supported Cooperative Work in Design (CSCWD), Nanjing, China, 2021, pp. 1-4. DOI: 10.1109/CSCWD49262.2021.9437830.

[28]. Fernando Rebollar Castelán. "Un Modelo Multicapas Basado en Blockchain que Fortalece la Integridad y Seguridad de Información Pública". Tesis doctoral, Doctorado en Ciencias de la Ingeniería, Universidad Autónoma del Estado de México, México, 2021.

[29]. CFE Esquema tarifario vigente. [Online]. Disponible en: https://app.cfe.mx/Aplicaciones/CCFE/Tarifas/TarifasCRENegocio/Negocio.aspx [Access: 4 may 2024].

[30]. Secretaría de Energía. "Avanza el proceso de separación de la CFE y su grupo corporativo". [Online]. Available: https://www.gob.mx/sener/prensa/avanza-el-proceso-de-separacion-de-la-cfe-y-su-grupo-corporativo. [Accessed: July 03, 2016].

[31]. Rousseau, "La reforma energética (2013-2014) a la luz de la nueva legislación sobre los impactos sociales de los proyectos", Foro int, vol. 60, no. 2, pp. 853-887, 2020. DOI: 10.24201/fi.v60i2.2740. [Online]. Available: http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S0185-013X2020000200853&lng=es&nrm=iso. Accessed on May 05, 2024.

[32]. Instituto Nacional de Electricidad y Energías Limpias, 'Reforma 113, Palmira, 62490 Morelos, Teléfono: (777) 3623811'. [En línea]. Disponible en: https://www.gob.mx/ineel/en#10052. [Access: 4 may 2024]."

Информация об авторах / Information about authors

Рене ГАРСИЯ-РЕЙЕС – аспирант последнего года на факультете программирования Мексиканского Национального центра исследований и технологических разработок (CENIDET). Его научные интересы включают децентрализованные технологии, криптографию, передовую измерительную инфраструктуру (AMI), науки о данных, методы добычи данных, Интернет энергии (IoE), облачные вычисления и визуализацию.

René GARCÍA-REYES – Final-year PhD student at the Computer Science Department of the National Center for Research and Technological Development (CENIDET) in Mexico. His research interests include decentralized technologies, cryptography, advanced metering infrastructure (AMI), data science, data mining, Internet of Energy (IoE), cloud computing, and virtualization.

Хавьер ОРТИС-ЭРНАНДЕС имеет степень PhD по автоматизации и программированию, штатный профессор факультета программирования Национального центра исследований и технологических разработок (Мексика). Сфера научных интересов: цифровая трансформация, инженерия требований, моделирование бизнес-процессов.

Javier ORTIZ-HERNANDEZ – PhD in Automation and Computer Science, full professor at the Computer Science Department of the National Center for Research and Technological Development in Mexico. Research interests: digital transformation, requirements engineering, business process modeling.

Рито МИХАРЕС имеет степень PhD по электрической и электронной инженерии. Профессор Мексиканского Национального института электроэнергии и чистой энергетики. Сфера научных интересов: цифровая обработка сигналов, встроенные системы, неразрушающее тестирование, ультраакустика.

Rito MIJAREZ – PhD in Electrical and Electronics Engineering, a full-time researcher at the Instituto Nacional de Electricidad y Energías Limpias in Mexico. Research interests: digital signal processing, embedded systems, non-destructive testing, ultrasonics.

Ясмин ЭРНАНДЕС имеет степень PhD по программированию от Технологического университета Монтеррей, профессор и факультета программирования Национального центра исследований и технологических разработок (Мексика). Научные интересы: искусственный интеллект, интеллектуальные обучающие системы, интеллектуальный анализ данных в образовании, аффективные вычисления, обработка естественного языка, человеко-машинное взаимодействие, машинное обучение.

Yasmín HERNÁNDEZ – PhD in Computer Science from Tecnológico de Monterrey and a full-time professor and researcher at the Computer Science Department of the National Center for Research and Technological Development (CENIDET) in Mexico. Her areas of expertise include artificial intelligence, intelligent tutoring systems, educational data mining, affective computing, natural language processing, human-computer interaction, and machine learning.

Хосе Альберто ЭРНАНДЕС-АГИЛАР имеет степень PhD по техническим и прикладным наукам от Центра исследований в области техники и прикладных наук при Автономном университете штата Морелос (UAEM). Член Мексиканской Национальной системы исследователей (SNI) 1-го уровня и является автором нескольких исследовательских и научно-популярных статей, а также трех книг. Его научные интересы включают интеллектуальный анализ данных, машинное обучение, глубокое обучение, алгоритмы оптимизации на графических процессорах (GPU) и прикладной искусственный интеллект.

José Alberto HERNÁNDEZ-AGUILAR – PhD of Engineering and Applied Sciences from the Center for Research in Engineering and Applied Sciences at the Autonomous University of the State of Morelos (UAEM). His research interests include data mining, machine learning, deep learning, optimization algorithms on Graphics Processing Units (GPUs), and applied artificial intelligence. Dr. Hernández Aguilar is a Level 1 member of the National System of Researchers (SNI) and has authored several research and outreach articles, as well as three books.