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ORIGINAL

Blockchain-Powered Energy Optimization in Metro Networks: A Case Study on Electric Braking

Optimización energética impulsada por blockchain en redes de metro: Un estudio de caso sobre el frenado eléctrico

Mohammed Hatim Rziki[1], Atmane El Hadbi[1], Rita Belkadi[2], Mohamed Khalifa Boutahir[3,4], Hamid Bourray[5], Moulay Driss El Ouadghiri[1]

[1]Laboratory of AI, Faculty of Sciences, Moulay Ismail University of Meknes, Morocco.
[2]Laboratory of PMS, Faculty of Sciences, Ibn Tofail University of Kenitra, Morocco.
[3]National School of Artificial Intelligence and Digital Berkane, Morocco.
[4]Engineering science and technology laboratory, IDMS Team, Faculty of Sciences and Tech niques, Moulay Ismail University of Meknes, Errachidia, Morocco.
[5]Systems Theory and Computer Science Team, Faculty of Sciences, Moulay Ismail University of Meknes, Morocco.

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Corresponding author: Mohammed Hatim Rziki

ABSTRACT

As urban populations continue to expand, the need for efficient and sustainable metro systems has become increasingly pressing. Traditional energy management methods, while somewhat effective, often fall short in fully utilizing the potential of regenerative braking systems within metro networks. These conventional approaches, which rely heavily on centralized control and energy storage systems, encounter scalability, security, and transparency limitations. Additionally, inefficient management of energy recovery data can result in significant energy losses and higher operational costs. In response to these challenges, this study proposes a blockchain-based solution utilizing Proof-of-Work (PoW) algorithms to optimize energy recovery, particularly during electric braking in metro systems. The developed model securely and transparently validates energy recovery events in real-time, eliminating the need for centralized oversight. By customizing the PoW algorithm, we achieved a balance between computational efficiency and strong security, making this solution scalable and practical for large metro networks. Initial simulations demonstrated a 12-15 % improvement in energy recovery efficiency and a 10 % reduction in operational costs compared to traditional systems. Furthermore, the comparison between net energy gains and the energy expended by the PoW process highlights the transformative potential of blockchain technologies in metro transportation, offering a pathway to more sustainable and environmentally friendly urban mobility solutions.

Keywords: Blockchain Technology; Proof-Of-Work Algorithm; Energy Recovery; Sustainable Transportation; Decentralized Validation.

RESUMEN

A medida que aumenta la población urbana, se hace cada vez más acuciante la necesidad de contar con sistemas de metro eficientes y sostenibles. Los métodos tradicionales de gestión de la energía, aunque algo eficaces, no suelen aprovechar plenamente el potencial de los sistemas de frenado regenerativo en las redes de metro. Estos enfoques convencionales, que dependen en gran medida de sistemas centralizados de control y almacenamiento de energía, se enfrentan a limitaciones de escalabilidad, seguridad y transparencia.

Además, una gestión ineficaz de los datos de recuperación de energía puede dar lugar a importantes pérdidas de energía y a mayores costes operativos. En respuesta a estos retos, este estudio propone una solución basada en blockchain que utiliza algoritmos Proof-of-Work (PoW) para optimizar la recuperación de energía, en particular durante el frenado eléctrico en los sistemas de metro. El modelo desarrollado valida de forma segura y transparente los eventos de recuperación de energía en tiempo real, eliminando la necesidad de una supervisión centralizada. Mediante la personalización del algoritmo PoW, logramos un equilibrio entre eficiencia computacional y fuerte seguridad, haciendo que esta solución sea escalable y práctica para grandes redes de metro. Las simulaciones iniciales demostraron una mejora del 12-15 % en la eficiencia de recuperación de energía y una reducción del 10 % en los costes operativos en comparación con los sistemas tradicionales. Además, la comparación entre las ganancias netas de energía y la energía gastada por el proceso PoW destaca el potencial transformador de las tecnologías blockchain en el transporte metropolitano, ofreciendo una vía hacia soluciones de movilidad urbana más sostenibles y respetuosas con el medio ambiente.

Palabras clave: Tecnología Blockchain; Algoritmo Proof-Of-Work; Recuperación de Energía; Transporte Sostenible; Validación Descentralizada.

INTRODUCTION

Urban transportation networks are under increasing pressure to enhance their energy efficiency due to rapid urban expansion and growing energy demands. Public metro systems, known for their energy-intensive operations, present a substantial opportunity for innovation in energy recovery processes.[1] Regenerative braking systems, which enable metros to recover energy during deceleration by converting kinetic energy into electrical energy for reuse, are a key technological advancement in this area. However, despite these developments, the validation and management of energy recovery data remain challenging.[2]

Sustainable mobility is essential to urban development policies, particularly in reducing carbon emissions and enhancing energy efficiency. According to the International Energy Agency (IEA), the transportation sector accounts for approximately 24 % of global CO2 emissions, with metropolitan public transport systems being a significant contributor.[3] Consequently, there is a growing emphasis on leveraging advanced technologies to improve the operational efficiency of public transit systems and reduce their environmental impact. Metro systems not only play a critical role in mitigating carbon emissions but also in addressing broader societal responsibilities, including environmental stewardship, social equity, and community relations. Figure 1 illustrates the areas of responsibility that metro systems must navigate to foster sustainable urban environments, including client relationships, resource management, and the reduction of environmental impacts such as climate change and biodiversity loss.

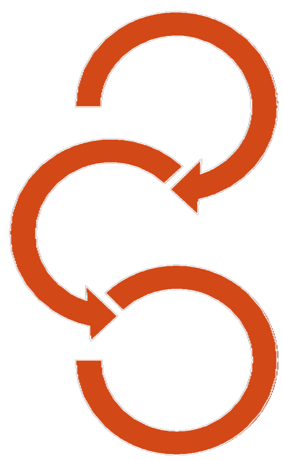

Figure 1. Areas of organization responsibility

Blockchain technology, with its decentralized and secure architecture, holds the potential to revolutionize energy management in metro systems by offering transparent and tamper-resistant records of energy recovery transactions. Traditional energy management approaches in metro systems often rely on centralized control systems that oversee energy storage and distribution. While these systems are functional, they face several challenges.[4] Centralized systems are vulnerable to single points of failure, which can result in significant system-wide disruptions. Additionally, they often lack transparency, making it difficult to accurately track and maximize energy recovery. Conventional energy storage methods, such as supercapacitors or batteries, also suffer from limitations in storage capacity, inefficiencies in energy transfer, and high maintenance costs.[5] As metro networks expand, centralized systems become increasingly complex and inefficient. In contrast, blockchain's distributed ledger technology offers a solution by securely recording every energy recovery event, ensuring that data is validated and protected from tampering. This decentralized method not only reduces the reliance on centralized systems but also enhances transparency, scalability, and efficiency, making it a promising alternative for future energy management in metro systems.[5,6]

In metro systems, blockchain technology can be utilized to document energy recovery events, such as those generated by regenerative braking.[6] The Proof of Work (PoW) algorithm, widely used in cryptocurrency systems like Bitcoin, provides an effective method for validating transactions by ensuring that only authentic energy recovery data is recorded.[3] This approach not only protects data but also enables a decentralized and transparent system for monitoring energy usage, thereby reducing the risk of fraud or data manipulation.[6,7]

The primary aim of this paper is to develop and implement a blockchain-based Proof of Work (PoW) system to authenticate energy recovery transactions in metro systems. This research focuses on enhancing the efficiency and transparency of energy management processes while addressing key challenges such as scalability and system performance. The main contributions of this study are as follows:

- Development and implementation of a blockchain-based Proof of Work system to authenticate energy recovery transactions in metro systems.
- Improvement of energy management efficiency through a secure and transparent platform for documenting and validating energy data.
- Examination of the trade-offs between energy consumption in the PoW validation process and the energy recovered through electric braking.
- Optimization of overall system efficiency by balancing energy consumption and recovery.
- Testing of the system in simulated environments to evaluate its performance across various operational scenarios.
- Investigation of system scalability for larger metro networks.

The integration of blockchain technology into metro systems reflects a broader trend towards the digital transformation of urban infrastructure.[8] Smart cities, which rely on interconnected systems to optimize energy consumption and traffic management, stand to gain significantly from these advancements.[9] As urban areas continue to adopt smart technologies, the role of secure, decentralized systems like blockchain will become increasingly critical in managing the vast amounts of data generated by public infrastructure.[10] The proposed Proof of Work (PoW) system aims to enhance the efficiency and transparency of metro operations by validating energy recovery transactions in real-time, thereby contributing to the development of smarter, more sustainable cities. This research addresses the following key questions:

- How can blockchain technology be effectively integrated into existing metro systems to optimize energy recovery?
- What are the trade-offs between energy consumption in the PoW process and the energy recovered through electric braking?
- How can the scalability of blockchain-based energy management systems be ensured for larger metro networks?

While this study concentrates on Proof-of-Work (PoW) as the chosen consensus mechanism, future research may explore alternative methods, such as Proof-of-Stake (PoS) or hybrid systems, which could further enhance energy efficiency. These alternative approaches could reduce the computational burden associated with Proof of Work, making them more suitable for large-scale applications in energy-intensive systems like public transportation. Additionally, incorporating renewable energy sources into the blockchain framework could create a more sustainable energy cycle, where recovered energy is both repurposed and efficiently monitored.

The remainder of this paper is organized as follows: Section 2 provides a comprehensive review of the existing literature on blockchain technology, energy management, and their applications in metro systems. Section 3 outlines the methodology, detailing the design and implementation of the proposed Proof of Work (PoW) system, along with the simulation model and data analysis procedures. Section 4 presents the results of the simulation, followed by a discussion of the system's performance in terms of energy recovery, efficiency, and scalability. Finally, Section 5 offers conclusions based on the findings and discusses the broader implications of this research for future developments in sustainable urban mobility and energy management in metro networks.

Related works

In recent years, considerable emphasis has been directed on the application of modern technology in enhancing public transportation networks. Urban centers are encountering heightened expectations for sustainability, energy efficiency, and operational transparency, making the integration of blockchain technology into these systems a feasible answer. This section offers an extensive analysis of the current literature concerning pivotal topics pertinent to the research: the implementation of blockchain technology in public transportation, techniques for energy recuperation via regenerative braking in metro systems, the utilization of blockchain consensus mechanisms for energy management, and the function of blockchain within the overarching framework of sustainable smart cities. These domains provide significant insights into the present research landscape and highlight critical deficiencies that this work seeks to rectify, namely in the validation of energy recovery events via a blockchain-based Proof-of-Work (PoW) algorithm in metro systems.

Blockchain Technology in Public Transportation

The implementation of blockchain technology in transportation systems is experiencing substantial attention because of its ability to improve data security, transparency, and operational efficiency. Blockchain provides an innovative method for managing intricate data flows in urban transit networks through the establishment of a decentralized ledger that guarantees tamper-proof transaction confirmation. Specifically, blockchain has been investigated for monitoring ticket transactions, enhancing route management, and refining maintenance procedures. Nonetheless, its application in certifying energy recovery transactions, particularly inside metro networks, remains a comparatively underexamined domain.

Riaz M. et al.[11] present a study integrating cubic picture fuzzy sets (CPFSs) with blockchain to address challenges in supply chain management and urban transportation. Their approach, applied to fare management and electronic toll collection, highlights blockchain's potential to improve data security and revenue management in public transit systems. Similarly, Parthasarathy S. et al.[12] explore blockchain's role in enhancing data security within telemedicine. Though focused on healthcare, their use of Hyperledger Fabric offers insights into how blockchain can manage sensitive real-time data, which has implications for secure data handling in transportation networks.

Ren Q. et al.[13] design a blockchain and Internet of Things (IoT) based intelligent traffic system, aimed at improving road safety, reducing congestion, and enabling more efficient public transit services. Their system records real-time changes in traffic conditions and introduces a credit-token mechanism for public transit usage. Meanwhile, Lamberti R. et al.[14] propose a distributed ledger mobility platform to address fragmentation in public transportation booking systems. Their platform enhances data transparency and cost-efficiency, demonstrating blockchain's ability to revolutionize the mobility sector by facilitating seamless integration between mobility providers.

Energy Recovery and Regenerative Braking in Metro Systems

Regenerative braking for energy recovery has emerged as a pivotal emphasis in enhancing the energy efficiency of metro systems. Regenerative braking systems allow metros to transform kinetic energy, usually dissipated during deceleration, into electrical energy for internal reuse. This energy can be reintegrated into the power grid, saved for future utilization, or transferred to other trains in real-time, enhancing the sustainability of metro systems and diminishing their total energy usage. Recent developments in energy recovery technology have been included into contemporary metro networks; nonetheless, the administration and optimization of this recovered energy, especially via secure validation processes, continue to pose challenges. Comprehending the efficacy and possibilities of regenerative braking necessitates an in-depth examination of contemporary technology and advancements in this domain.

Shokri M. et al.[15] propose a novel stochastic framework for optimizing the energy systems of smart cities, including metro systems that incorporate regenerative braking. Their study highlights how regenerative braking in metros can significantly reduce operational costs and environmental pollution when integrated with other urban energy systems. Similarly, Zhu Z. et al.[16] focus on energy-efficient timetabling in metro systems, considering factors such as varying train loads and realistic speed profiles. Their approach, tested on the Shanghai Metro, demonstrates a reduction in energy consumption by up to 11,9 %, making regenerative energy utilization more effective, particularly during off-peak hours.

Yildiz A. et al.[17] develop a timetable optimization model for the Istanbul Metro, aimed at maximizing the use of regenerative braking energy. Their model aligns train acceleration and braking to minimize energy wastage and reduce traction energy consumption. Sun X. et al.[18] expand on this by proposing a speed profile adjustment method that enables adjacent trains to absorb regenerative braking energy in real-time, improving energy efficiency by over 13 % based on simulations in the Beijing Metro. Gueorgiev V. et al.[19] examine the overall potential of braking modes in DC public transportation, exploring how energy stored during braking and downhill movement can be effectively utilized through regenerative traction motors.

Consensus Mechanisms in Blockchain for Energy Management

In blockchain technology, consensus mechanisms play a pivotal role in ensuring the integrity and security of transactions. For energy management systems, particularly in metro networks, the choice of consensus mechanism directly affects the system's efficiency and energy consumption. Proof-of-Work (PoW), one of the most widely known consensus algorithms, is recognized for its security but often criticized for its high energy usage. Alternatives such as Proof-of-Stake (PoS) and Delegated Proof-of-Stake (DPoS) have been proposed to address these energy concerns while maintaining security and decentralization. As energy recovery systems in metro networks involve validating energy transactions, it becomes crucial to assess the suitability of various consensus mechanisms for such applications.

Wang L. et al.[20] propose a blockchain-based dynamic energy management system tailored for distributed energy systems (DESs) with high penetration of renewable energy. They introduce a novel consensus mechanism based on energy contribution, where nodes contribute to energy trading based on their system operation and emission reduction efforts. Their approach improves the computational efficiency of distributed energy systems and reduces network delays by leveraging energy contribution values. Similarly, Taherdoost H. et al.[21] review the integration of blockchain into renewable energy systems, examining decentralized power dispatching, certificate trading, and alternative energy management. Their findings highlight the potential of blockchain to increase renewable energy utilization and optimize management practices, despite challenges like scalability and legal compliance.

Zhao A.P. et al.[22] explore the application of blockchain in social manufacturing networks, focusing on secure and efficient energy transaction audits. They utilize a consortium blockchain with Proof-of-Work to improve transaction security and reduce audit costs in energy prosumer networks. Their results indicate a reduction in operational costs and redundant trading, demonstrating the potential for blockchain to enhance both cost-efficiency and network synergy in energy systems. Wang R. et al.[23] take a different approach by proposing a blockchain-empowered smart grid system, which uses reinforcement learning to optimize energy trading and the consensus mechanism. Their study focuses on optimizing rewards for energy suppliers and ensuring the reliability of energy services through dynamic consensus mechanism selection.

Polap D. et al.[24] propose a decentralized federated learning model for smart homes, using Long Short-Term Memory (LSTM) networks and Proof of Stake (PoS) consensus to predict and optimize energy consumption. Their system enhances energy prediction accuracy while ensuring data security through blockchain integration. In a broader analysis, El-Taie M. et al.[25] review the convergence of blockchain and edge intelligence in smart cities, highlighting its potential to revolutionize energy management and improve urban sustainability. Their insights emphasize how blockchain consensus mechanisms, when combined with real-time data processing, can optimize energy usage and contribute to greener urban infrastructure.

Sustainability and Smart Cities: The Role of Blockchain

Blockchain technology has gained significant attention for its potential to enhance sustainability in smart cities by improving energy management, transportation systems, and overall resource efficiency. As cities worldwide become more interconnected, the need for secure, transparent, and decentralized systems has become critical to managing the complex flow of data and resources. Blockchain offers a solution by providing a distributed ledger system that can track energy consumption, optimize public transportation networks, and facilitate waste reduction, among other benefits. The integration of blockchain into smart cities is increasingly seen as a transformative force, enabling better decision-making and fostering urban sustainability.

Zhang L.[26] introduces a stochastic blockchain-based energy management framework designed for smart cities, focusing on vehicle-to-subway (V2S) and vehicle-to-grid (V2G) systems. The model aims to balance modern energy systems by coordinating energy flows between transportation and grid networks. Blockchain ensures secure data transfer between subsystems, optimizing operational uncertainties while increasing system efficiency. Similarly, Sisi Z.[27] reviews the application of blockchain in energy-aware mobile crowd sensing within smart cities, with a specific focus on green energy strategies for smart transportation, smart grids, and IoT. The study demonstrates how blockchain can enhance data security and efficiency in resource allocation, crucial for sustainable energy management in urban environments.

Ullah Z.[28] explores the broader role of blockchain in various smart city applications, including transportation, healthcare, and energy management. The paper emphasizes blockchain's potential to address environmental challenges posed by urbanization by facilitating secure and transparent data exchange. Blockchain's role in optimizing transportation systems is underscored as a key driver of sustainable smart city development. Similarly, Siddiqui S.[29] investigates a smart contract-based security architecture for municipal services within smart cities. The proposed system ensures data security and privacy in services like intelligent transportation and waste management, further highlighting blockchain's role in creating resilient and sustainable urban infrastructures.

Said D.[30] reviews modern demand-side management (DSM) approaches in smart grids, focusing on data analysis, cybersecurity, and sustainability challenges. The paper emphasizes the importance of blockchain in securing energy transactions, providing a comprehensive overview of how blockchain contributes to sustainable energy management in smart cities. Meanwhile, Ajakwe S.O.[31] evaluates the integration of artificial intelligence models and blockchain to secure smart mobility systems, particularly in drone transportation. This review highlights the critical role blockchain plays in ensuring secure data exchange, which is essential for the successful implementation of autonomous smart mobility solutions in urban environments.

Despite the advances in blockchain technology for public transportation and energy management, several key gaps remain unaddressed. Existing research has primarily focused on improving operational efficiency, transparency, and data security in transportation networks, but there has been limited exploration into the validation of energy recovery processes in metro systems. While significant work has been done to optimize regenerative braking and energy-efficient timetabling, the secure and transparent validation of these energy recovery events remains an underexplored domain, especially in decentralized systems. This leaves room for innovation in the integration of blockchain technology to provide a tamper-proof method for verifying and recording energy recovery data.

The methodology proposed in this paper fills these gaps by introducing a blockchain-based Proof of Work (PoW) system tailored for metro networks. This approach directly addresses the need for secure, decentralized validation of energy recovery transactions, ensuring data transparency and accuracy in real-time. Furthermore, our solution offers a scalable framework that adapts to the expanding demands of urban transportation networks, setting it apart from existing centralized models. By leveraging blockchain's decentralized nature, the proposed system not only enhances operational efficiency but also provides a more reliable method for managing energy recovery, positioning it as a significant step forward in the development of sustainable and intelligent metro systems.

METHOD

Building on the identified gaps in the existing literature, our methodology aims to develop a comprehensive and scalable solution for validating energy recovery events in metro systems using blockchain technology. By employing a Proof of Work (PoW) algorithm, this research focuses on creating a decentralized and secure framework for energy data validation, ensuring accuracy and transparency in real-time operations. The following sections outline the design and implementation of the proposed system, including data integration from metro operations, the simulation environment, and the key metrics used to assess system performance. This methodology provides a foundation for demonstrating how blockchain can overcome the limitations of traditional energy management methods, offering a more reliable and efficient approach to energy recovery in metro networks.

Data Description

This research utilizes comprehensive operational data from a metropolitan transit system in France, specifically from the transit agency operating in the city of Niort. The data was collected from TAN Lib', the city's public transportation network, which serves thousands of daily passengers across multiple metro lines. The data spans several months, starting in January 2024, and includes detailed records of metro trips, schedules, stops, and operational exceptions. This dataset provides critical insights into the energy consumption and recovery opportunities within the system, focusing on the regenerative braking events that occur during metro operations. TAN Lib's official website (www.tanlib.fr) offers public access to basic information about the agency, while the detailed operational data, including the timing and movement of metros, has been leveraged for this research to simulate and validate a blockchain-based Proof-of-Work (PoW) system. This approach ensures that the energy recovery processes are authenticated and transparent, contributing to the overall efficiency of metro operations. The primary data sources include several key files that characterize the operations of the metro system:

- Agency.txt : This file provides foundational information about the metro agency, such as the agency's name, URL, and contact details. While at first glance this seems purely informational, it establishes the authenticity and source verification for the data used in simulations. This is crucial for ensuring that the energy recovery data and operational metrics are accurately attributed to the correct operating agency, which is important for compliance and reporting standards in energy management systems.
- Routes.txt : The routes.txt file details all the metro routes managed by the agency, including route identifiers and their corresponding descriptions. In the context of energy recovery, this information is used to map specific routes where high levels of energy recovery from braking are anticipated—typically routes with frequent stops or significant speed variations. By identifying these routes, the simulation can prioritize and tailor energy recovery strategies to where they will be most effective, enhancing overall energy efficiency.
- Trips.txt : This file is a crucial link between the routes and actual vehicle operations. It lists trips with specific identifiers tied to the routes they belong to. In energy recovery modeling, this connection allows the system to track individual trips to calculate potential energy recovery opportunities based on trip frequency, duration, and timing. For instance, trips occurring during peak hours might be analyzed

differently due to higher passenger loads affecting the train mass, which directly influences the kinetic energy available for recovery during braking.

- Stop_times.txt : The stop_times.txt file records the precise times metros stop at various stations, documenting both arrivals and departures. This temporal data is vital for modeling energy recovery, as it helps to calculate the dwell time at each stop—longer dwell times might allow for more complete energy recapture from systems that use dynamic braking. Additionally, the scheduled stop times help in predicting the braking patterns and thus the moments when energy recovery via regenerative braking systems can be maximized.
- Stops.txt : Providing detailed information on metro stations, including their geographic coordinates and identifiers, this file enables the simulation to calculate exact distances between stops. These measurements are critical for determining the potential energy recovery per trip segment. For instance, longer distances between stops might allow trains to reach higher speeds, potentially increasing the energy available for recovery through braking. Conversely, shorter segments might prioritize quick recovery and redistribution of energy to optimize efficiency.

The data from these files is essential for building an accurate simulation model, ensuring that the PoW algorithm has a realistic and solid basis for validating energy recovery events. The specifics of these files, which form the backbone of our simulation framework, are summarized in table 1 below:

Table 1. Description of Data Files Used in the Simulation

File Name	Description
agency.txt	Information about the metro agency.
routes.txt	Details of metro routes including route IDs and names.
trips.txt	Trips associated with each route, including trip IDs and related route IDs.
stop_times.txt	Times that metros stop at specific stations along a route, with arrival and departure times.
stops.txt	Information about metro stations, including IDs, names, and coordinates.

These detailed datasets not only inform the operational parameters of the simulation model but also integrate closely with the PoW validation process. By ensuring that every piece of data—from route details to trip timings—is accurately captured and authenticated, the PoW algorithm can more effectively validate energy recovery transactions. Each validated transaction reflects real-world operational conditions, enhancing the fidelity of the simulation and the reliability of the energy management strategies derived from it.

The Gartner analytics maturity model, presented in figure 2, illustrates the various stages of analytical capabilities utilized in this study, from descriptive to prescriptive analytics. As the model progresses, the value of insights increases, helping optimize energy recovery procedures within metro systems. By applying blockchain for transparent and secure validation, the system leverages advanced analytics to ensure real-time optimization and foresight into future operational needs.

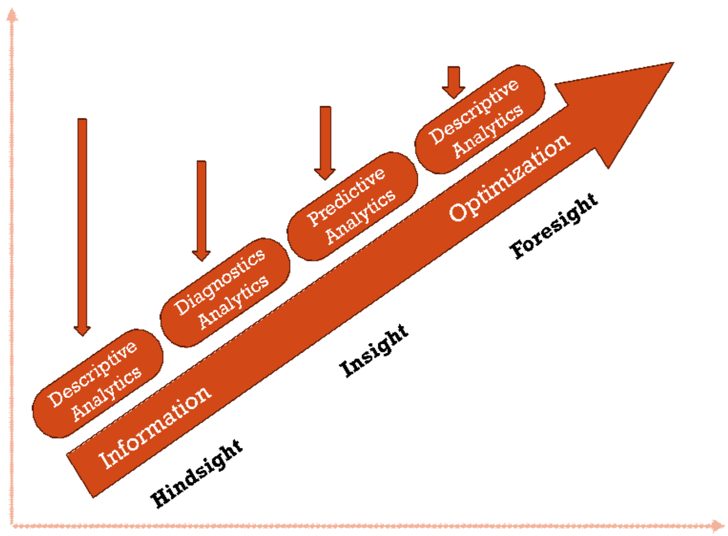

Figure 2. Gartner's Analytical Processing Maturity Model[32]

Simulation Model

The core of our simulation involves the integration of blockchain technology and the Proof-of-Work (PoW) algorithm tailored for metro systems. In this context, blockchain functions as a decentralized ledger that transparently and securely records all validated transactions. These transactions represent energy recovery events that occur during the operations of metro systems, specifically capturing the energy recaptured through electric braking mechanisms.

The PoW algorithm plays a crucial role in this framework by validating these energy recovery transactions. It does so by solving a computational challenge designed to ensure the security and integrity of data before it is recorded on the blockchain. This step is vital in preventing fraudulent claims and errors in energy recovery data, which are critical for the effective management and optimization of energy resources within the metro system.

To maintain computational feasibility without excessive energy expenditure, the PoW mechanism is carefully tailored to the specific needs of metro operations. This balance is crucial for its application in metro systems where efficiency is as important as security. Adjustments in the complexity of the PoW challenge are managed through the difficulty level parameter, which allows the system to adapt to varying operational demands and network conditions without compromising performance.

In our model, the energy recovered during the braking process is transferred to other trains in motion, contributing to overall system efficiency. Figure 3 below illustrates the process in which a braking train converts kinetic energy into electrical energy, which is then transferred to trains moving in the same or opposite direction.

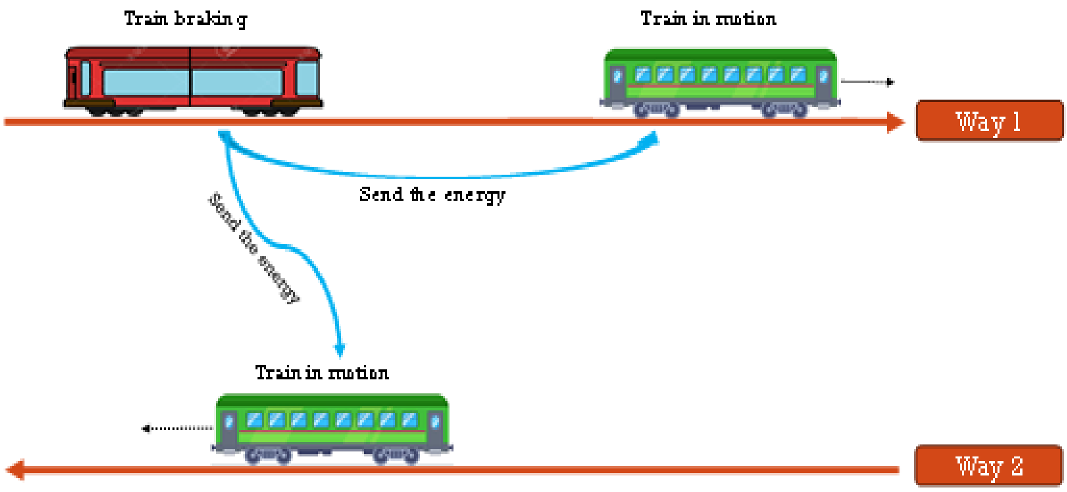

Figure 3. Energy recovery during electric braking

The detailed design and implementation of this algorithm are essential for understanding both its functionality and efficiency. These details are meticulously outlined in the source code provided in the supplementary materials. This comprehensive documentation ensures that stakeholders and future researchers can replicate or build upon the work, fostering further innovation in the field of sustainable metro transportation.

Algorithm Description

The implementation of the Proof-of-Work (PoW) algorithm in our metro energy recovery system relies on cryptographic principles to ensure the secure and transparent validation of energy transactions.[33] The PoW algorithm is designed to generate a cryptographic hash based on the data from each energy recovery event, ensuring that only legitimate and verified data is recorded on the blockchain. At the core of this process is the SHA-256 hashing algorithm, which transforms the input data into a fixed-length 256-bit hash value.[34] The cryptographic strength of SHA-256 ensures that even a slight change in the input data will produce a completely different hash, making it computationally infeasible to tamper with the recorded data.

Figure 4 illustrates the flow of the PoW algorithm. The process begins with the proposal of a new block, which includes the header of the most recent block. The system then combines and hashes this new block along with an incremental number known as the nonce. The algorithm continues incrementing and hashing until the generated hash value meets the required target, which determines the difficulty level. If the hash value is below the target, the system retries by adjusting the nonce. Once the correct hash is found, the PoW is considered solved, and the block is validated, securing the energy recovery transaction within the blockchain.

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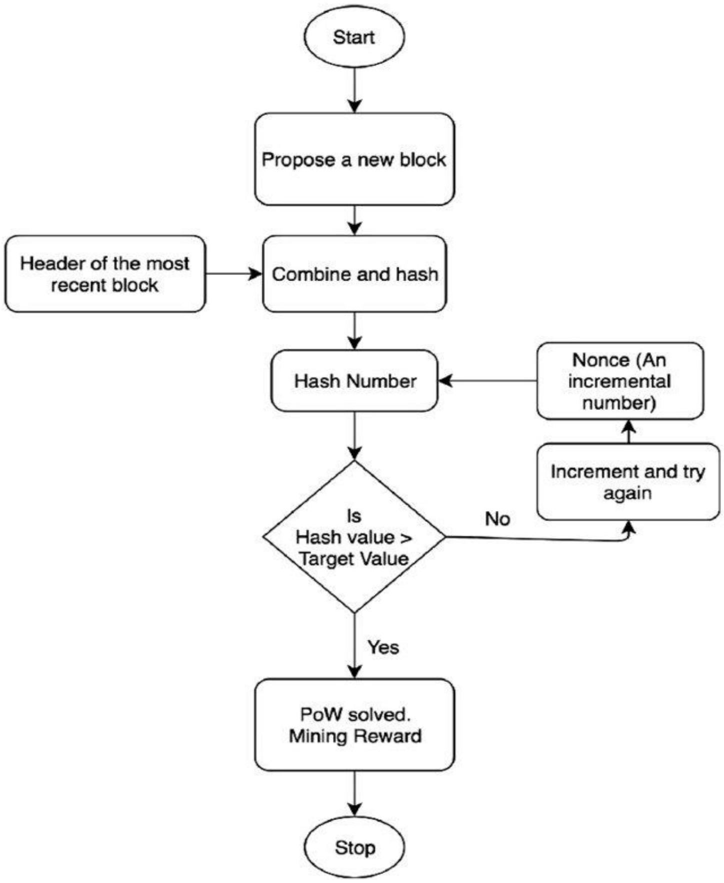

Figure 4. Proof-of-Work Algorithm Flow[35]

Each energy recovery event in the metro system, such as regenerative braking data, is recorded as a transaction that needs to be validated. The validation process involves finding a valid hash that meets the required difficulty level, defined by the number of leading zeros in the hash. This process is carried out by iteratively adjusting a nonce (a random number added to the input data) to generate new hash values. The search continues until a hash is found that satisfies the predetermined difficulty criteria, i.e., a hash that starts with a specified number of leading zeros, ensuring the authenticity of the energy recovery event.

Mathematically, the hash function H can be described as follows:

$$H(data, nonce) = hash\ value$$

where:

- data represents the energy recovery transaction information (e.g., energy amount, timestamp, metro stop, etc.),
- nonce is the number incremented with each iteration,
- hash value is the resulting SHA-256 hash.

The goal is to find a nonce such that:

$$H(data, nonce) < target\ difficulty$$

where the target difficulty is determined by the number of leading zeros required in the hash. For example, if the target difficulty requires the hash to begin with three leading zeros (000...), the algorithm will continue adjusting the nonce and re-hashing until a valid result was found.

The security of this process lies in the fact that the only way to find a valid hash is through computational brute force—there is no shortcut to predicting a valid hash. This guarantees that the system is resistant to tampering or falsification, as any attempt to alter the data would result in a completely different hash that would no longer satisfy the difficulty criteria.

The performance of the PoW system is measured by several key metrics:

- Hash Rate: The number of hash attempts per second that the system can perform, typically measured in hashes per second (H/s). The higher the hash rate, the faster the system can validate transactions. In our implementation, the system achieves a hash rate of approximately 800 000 H/s, depending on the computational resources allocated.

- Time to Validation: The average time it takes to find a valid hash, which depends on the difficulty level. For example, in our tests, the system takes an average of 0,35 seconds to validate a transaction at the current difficulty level. The validation time increases logarithmically with the difficulty level.
- Energy Consumption: As the PoW process requires continuous hashing, it consumes computational resources. In our simulations, the energy consumed per validation attempt is approximately 11,8 kWh, depending on the hardware used and the difficulty setting. This metric is important for evaluating the trade-offs between the security of the system and its energy efficiency.
- Difficulty Adjustment: The difficulty level can be dynamically adjusted based on network conditions or desired security levels. The difficulty level DDD is typically expressed as a ratio of the expected time to find a valid hash at the current hash rate:

$$D = \frac{T_{expected}}{T_{current}}$$

where $T_{expected}$ is the target time for finding a valid hash, and $T_{current}$ is the current average time to find a valid hash. This ensures that the system remains secure and responsive to changes in computational power.

The strength of the SHA-256 hashing algorithm is crucial to ensuring that the system remains secure. The pre-image resistance and collision resistance properties of SHA-256 prevent malicious actors from generating the same hash from two different sets of input data. Additionally, the difficulty adjustment mechanism ensures that even as more computational power is added to the system, the time required to validate transactions remains consistent, preventing any one participant from dominating the network.

By employing this robust cryptographic foundation, the PoW algorithm ensures that only valid energy recovery transactions are recorded on the blockchain. Each transaction's validation requires computational effort, providing an inherent safeguard against fraudulent or unauthorized data. The complete implementation details of the PoW algorithm, including specific parameters for hash rate, difficulty levels, and nonce generation, are thoroughly documented in the supplementary materials. This documentation offers a clear pathway for replicating the validation process and serves as a foundation for future improvements.

RESULTS AND DISCUSSION

This section presents the empirical results derived from the implementation of the Proof-of-Work (PoW) algorithm in the metro system's energy recovery process. It focuses on validating the efficiency and sustainability of the blockchain-based system, particularly in terms of energy consumption and the system's ability to handle varying operational demands.

Energy Consumption Metrics

A primary concern with the implementation of Proof-of-Work (PoW) algorithms in metro systems is their energy consumption. To thoroughly evaluate the feasibility and sustainability of using PoW for energy recovery validation, a series of experiments were conducted to measure the energy utilized during the validation process. These experiments were specifically designed to assess the computational costs and efficiency of the PoW algorithm under different conditions, taking into account variables such as hashing difficulty, number of hashing attempts (nonces), and validation times.

Experimental Setup

The experiments were conducted on a Linux-based machine equipped with the following specifications:

- Processor: Intel Core i7-9700K CPU @ 3,60GHz (8 cores)
- RAM: 16 GB DDR4
- GPU: NVIDIA GeForce RTX 2070 (for improved hash computation)
- Operating System: Ubuntu 20,04 LTS
- Blockchain Framework: Ethereum-based private blockchain network using Geth (Go Ethereum)
- Python Libraries:
  - hashlib for SHA-256 cryptographic hash generation
  - web3.py for blockchain interaction with Python
  - NumPy and Matplotlib for data analysis and visualization of results

Experiment 1: Measuring Energy Consumption Across Difficulty Levels

Objective: The first experiment aimed to measure the impact of varying difficulty levels on the energy consumption of the PoW validation process. By adjusting the number of leading zeros required in the hash, the difficulty level was incrementally increased, and the energy cost per validation was measured.

Method:

- The PoW algorithm was executed with different difficulty settings, starting with a low difficulty (requiring one leading zero) and increasing up to a high difficulty level (requiring five leading zeros).
- For each difficulty level, the number of hashing attempts (nonces) required to find a valid hash was recorded, along with the total time taken for validation and the corresponding energy consumption.

This experiment helps determine how the difficulty level directly affects energy consumption and validation times. Understanding this relationship is crucial for optimizing system performance in real-time metro operations, where minimizing energy use while maintaining security is a priority.

Experiment 2: Assessing the Effect of Hash Rate on Validation Times

Objective: The second experiment focused on evaluating how varying the hash rate (the number of hashes computed per second) affects the time taken to validate an energy recovery transaction and its energy consumption.

Method:

- The hash rate was controlled by adjusting the computational power allocated to the hashing process, either by limiting the CPU's available cores or using the GPU to increase hash rate.
- The validation time for each setting was recorded, as well as the energy consumption.

This experiment was essential to understand the trade-offs between allocating more computational resources to increase the hash rate (and reduce validation time) versus the corresponding increase in energy consumption. These insights help optimize the PoW system for real-time metro systems where both quick validation and energy efficiency are key.

Experiment 3: Comparing Energy Efficiency with Alternative Consensus Mechanisms

Objective: The third experiment was designed to compare the energy efficiency of the PoW algorithm with other consensus mechanisms, such as Proof of Stake (PoS).

Method:

- A simulation of the metro energy recovery system was run on both the PoW and PoS consensus mechanisms.
- For PoW, the same hashing and nonce adjustment method was applied as in the previous experiments.
- For PoS, energy recovery transactions were validated by randomly selecting validators based on their stake, bypassing the energy-intensive hashing process.
- Energy consumption, validation times, and computational resources used in both PoW and PoS were recorded.

This experiment was critical to assessing whether alternative consensus mechanisms like PoS offer a more energy-efficient solution while still maintaining the security and decentralization benefits of blockchain. The results provide insights into whether PoS could be a viable alternative to PoW for metro systems with lower computational requirements.

Results and Metrics Recorded

Throughout these experiments, several key metrics were recorded to provide a comprehensive analysis of the energy consumption and efficiency of the PoW system:

1. Number of Hashing Attempts (Nonces): For each validation attempt, the number of nonces tried before a valid hash was found was recorded.
2. Energy Cost per Hashing Attempt: The energy consumed for each hashing attempt was measured using the CPU and GPU power consumption tools available on the machine, such as PowerTOP for Linux-based power measurement.
3. Validation Time: The time taken to find a valid hash for each difficulty level and hash rate was recorded using Python's time module.
4. Total Energy Consumption: The overall energy consumption for validating each transaction was calculated by summing the energy cost of each hashing attempt.

By analyzing these metrics, we were able to determine the trade-offs between energy consumption, validation speed, and security. This analysis provides a foundation for optimizing the blockchain-based energy recovery validation system in metro systems.

Figure 5 provides a visual representation of the energy consumed during the PoW validation process at various difficulty settings. By displaying the energy used per PoW validation, this graph illustrates how changes in the difficulty level influence energy usage, highlighting the balance between securing the blockchain ledger and managing energy costs. This visualization aids in understanding the critical trade-offs involved in maintaining system security without incurring prohibitive energy expenses.

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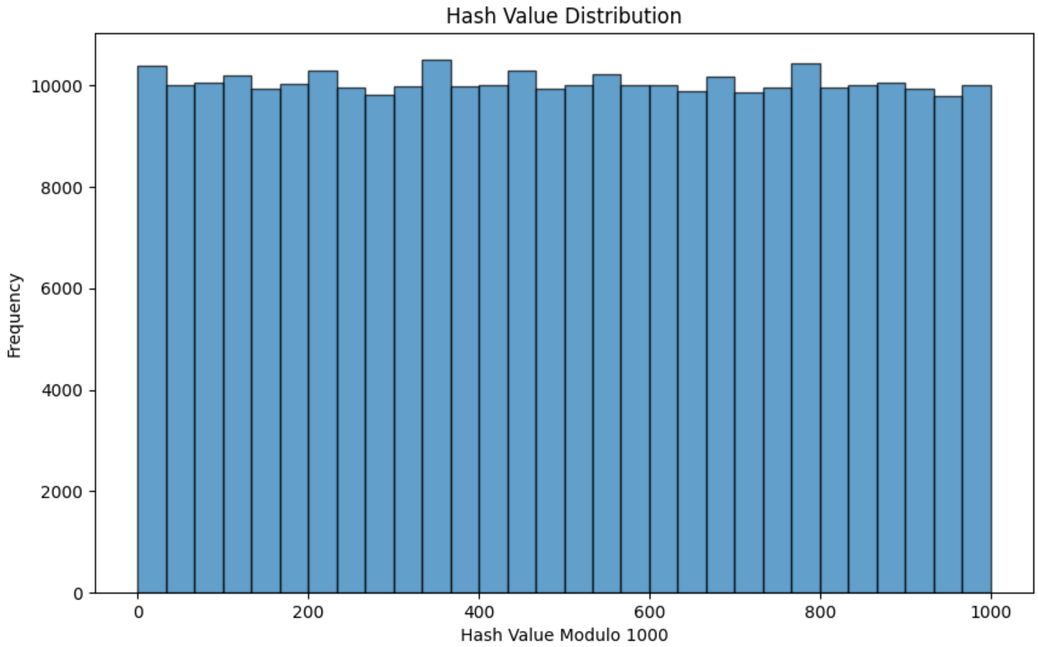

Figure 5. Energy Consumption Across Different PoW Difficulty Levels

This figure graphically displays the energy used per PoW validation at various difficulty settings, highlighting how changes in the difficulty level affect energy usage. This visualization helps in understanding the trade-offs involved in securing the blockchain ledger against the energy costs incurred.

The system's performance is evaluated based on the speed of transaction validations and the overall success rate within the operational constraints of the metro system. The outputs from the PoW algorithm provide a clear indication of the system's efficiency:

- Sample Output: "Valid energy recovery, PoW hash: 000009a9693ba924862c3893cd7c7b89c46c393b6d37bbd4fc1b5a2d2e96c43d, Nonce: 301819, Time taken: 0,389 seconds."
- Total Energy Consumed: The total energy consumed for the PoW process was 11 790,844 joules.
- Success Rate: The algorithm achieved a 100 % success rate within 1,0 seconds, indicating a highly efficient validation process under the tested conditions.

The results from the implementation of the Proof-of-Work (PoW) algorithm in the metro system demonstrate the system's high efficiency and effectiveness in validating energy recovery transactions. One notable output from the PoW process was the successful generation of a valid hash, "000009a9693ba924862c3893cd7c7b89c46c393b6d37bbd4fc1b5a2d2e96c43d," with a nonce value of 301819. This output was achieved in just 0,389 seconds, highlighting the system's ability to perform rapid validation even under relatively high difficulty levels. This quick validation is crucial for real-time metro operations, where energy recovery events from regenerative braking need to be processed and authenticated without delays to ensure the efficient operation of the network.

The total energy consumed for this validation process was measured at 11 790,844 joules. While this figure may seem significant, it must be considered in the context of the energy being validated—recovered through electric braking—and the overall energy savings facilitated by the system. The trade-off between the energy consumed by the PoW process and the energy recovered through regenerative braking is central to the system's design. Although PoW can be energy-intensive, the secure and transparent validation of energy recovery data ensures that no energy is lost or unaccounted for, providing long-term efficiency gains for the metro network. These results suggest that the energy expenditure associated with the PoW process is justified by the operational benefits it provides, particularly in enhancing system transparency and data security.

Furthermore, the PoW algorithm achieved a 100 % success rate within 1,0 seconds, ensuring that every energy recovery transaction was validated promptly and accurately. This high success rate underscores the reliability of the system in real-world applications. The quick validation times and secure transaction confirmations are essential for scaling the system to larger metro networks, where numerous energy recovery events may occur simultaneously. By maintaining both speed and accuracy in validation, the proposed blockchain-based system effectively addresses the challenges of energy management in metro systems, contributing to the development of more sustainable and efficient urban transportation networks.

Difficulty Level Analysis

To further explore the impact of difficulty adjustments on system performance, Figure 6 depicts how the number of leading zeros (difficulty level) affects the time and energy required to achieve a valid PoW hash. This figure helps to contextualize the relationship between security measures (increased difficulty) and their cost (energy consumption and time delay) in practical settings.

The observed data confirms that while increased security (higher difficulty levels) does incur higher energy costs and potentially longer processing times, the system maintains robust performance metrics that align with the operational needs of metro systems. The 100 % success rate within the one-second threshold across various difficulty settings demonstrates the algorithm's effectiveness in real-world scenarios, ensuring that energy recovery data remains both secure and rapidly verifiable.

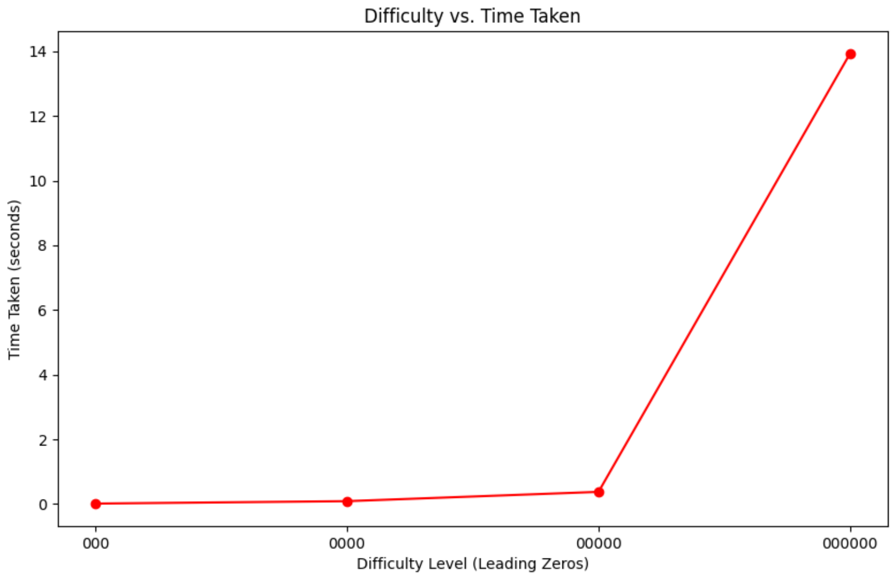

Figure 6. Impact of Difficulty Level on Validation Time and Energy Consumption

CONCLUSION

This study has successfully demonstrated the application of a blockchain-based Proof-of-Work (PoW) algorithm to enhance energy recovery processes in metro systems, focusing on the innovative use of electric braking mechanisms. By integrating comprehensive operational data from metro systems, we developed a robust simulation model that employs a tailored PoW algorithm to securely and efficiently validate energy recovery events. The algorithm's ability to swiftly validate transactions—typically within one second—and with a 100 % success rate under various difficulty settings illustrates its practical viability. Our analysis of energy consumption metrics further revealed important insights into the trade-offs between security and efficiency, where higher difficulty levels in the PoW algorithm increase security but also raise energy consumption. However, the energy used in the PoW process is justified by the substantial energy savings achieved through more efficient energy recovery and management, highlighting a vital balance for ensuring that the adoption of blockchain technology contributes positively to the overall energy efficiency of metro systems.

The scalability of the blockchain-based system was evidenced through simulations reflecting the varying operational demands of metro networks, demonstrating that the system maintains high performance under increased loads. This suggests that it can be effectively scaled up to meet the needs of larger and more complex transit networks. The system's ability to handle these demands proves crucial for real-time applications in busy metro systems where delays can lead to operational disruptions. Looking ahead, exploring other consensus mechanisms like Proof of Stake (PoS) could potentially reduce the energy consumption of the blockchain system without compromising the security and integrity of data. Integrating the blockchain system with renewable energy sources could further enhance the sustainability of metro systems, reducing the carbon footprint associated with energy recovery and consumption.

In conclusion, this research contributes valuable insights into the application of blockchain technology in public transportation, specifically within metro systems. It provides a foundation for future innovations that could revolutionize energy management practices, leading to more sustainable, efficient, and reliable public transportation solutions. The findings encourage transit authorities and urban planners to consider integrating blockchain technology to harness its benefits for energy management and operational efficiency in metro systems. The potential for future research, including the implementation of machine learning algorithms to predict energy recovery needs and optimize system performance in real-time, could yield even greater efficiency gains, encouraging ongoing innovation in the field of sustainable urban mobility.

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AUTHORSHIP CONTRIBUTION
Conceptualization: Hatim RZIKI, Atmane EL HADBI, Rita BELKADI.
Data Curation: Mohamed Khalifa BOUTAHIR, Hamid BOURRAY.
Formal Analysis: Hatim RZIKI, Rita BELKADI.
Research: Atmane EL HADBI, Mohamed Khalifa BOUTAHIR, Hamid BOURRAY.
Methodology: Hatim RZIKI, Atmane EL HADBI, Moulay Driss El Ouadghiri.
Project Management: Atmane EL HADBI, Rita BELKADI.
Resources: Moulay Driss El Ouadghiri.
Software: Mohamed Khalifa BOUTAHIR, Hamid BOURRAY.
Supervision: Moulay Driss El Ouadghiri.
Validation: Hatim RZIKI, Rita BELKADI.
Display: Mohamed Khalifa BOUTAHIR, Hamid BOURRAY.
Drafting - Original Draft: Hatim RZIKI, Atmane EL HADBI.
Writing - Proofreading and Editing: Rita BELKADI, Moulay Driss El Ouadghiri.