Blockchain Integration for Smart Grid Testbeds and Iot-Based Digital Twins in Cyber-Physical Systems

Shanu Khare[2,3][0000−0002−7290−9841] and Navpreet Kaur Walia[2,3][]

[1] Chandigarh University, Shanu Khare, India `shanukhare0@gmail.com`
[2] Chandigarh University, Navpreet Kaur Walia, India
`navpreet.walia12@gmail.com`

Abstract. Cyber-physical systems (CPS) incorporating Internet of Things (IoT) devices, edge computing, cloud services, and artificial intelligence (AI) have gained considerable traction across various industries, particularly in the realm of smart grids. As CPS grow increasingly complex, managing and validating them becomes challenging due to factors such as scalability, interoperability, and security. Consequently, testbeds and lot-based digital twins have emerged as valuable tools for emulating, simulating, and verifying large-scale distributed systems under realistic conditions.

Blockchain technology, known for its decentralized architecture and immutable ledgers, holds immense potential for enhancing the security, traceability, and accountability of smart grid CPS testbeds and lot-based digital twins. In this chapter, we explore the synergies between blockchain and smart grid CPS testbeds and lot-based digital twins, focusing on their design, implementation, and operation. We begin by describing the fundamental concepts of blockchain and its suitability for smart grid applications before presenting a detailed examination of the integration process, covering aspects such as consensus protocols, transactional models, and data structures.

Subsequent sections delve into the benefits of employing blockchain in smart grid CPS testbeds and lot-based digital twins, notably in terms of enabling seamless peer-to-peer communication, fostering trust among participants, facilitating value exchange, and reinforcing security. Several case studies and real-world examples serve to underscore the feasibility and efficacy of this approach. Lastly, we outline open challenges and future directions for research and development, advocating collaborative efforts among academia, industry, and government agencies to unlock the full potential of blockchain-enhanced smart grid CPS testbeds and lot-based digital twins.

Keywords: Smart grids· Blockchain· IoT devices· Edge computing · Cloud services · Artificial intelligence · Testbeds· Lot-based digital twins · Consensus protocols· Transactional models · Data structures · Peer-to-peer communication · Trust· Value exchange · Security

1 Introduction to Smart Grids and Blockchain

1.1 Overview of Smart Grid Technology

A smart grid represents the next generation of power distribution and management, leveraging advanced digital technology to enhance efficiency, reliability, and sustainability in electricity delivery. Unlike traditional grids, smart grids integrate communication[1], control, and information technologies with the electrical network, transforming it into an intelligent infrastructure capable of real-time monitoring, analysis, and response. Key components of smart grids include:

Advanced Metering Infrastructure (AMI): Smart meters enable two-way communication between consumers and utilities, providing detailed consumption data and enabling dynamic pricing based on demand fluctuations[2]. This enhances grid efficiency and supports demand-side management initiatives.

Distributed Energy Resources (DERs): DERs such as solar panels, wind turbines, and energy storage systems allow for decentralized electricity generation and storage. Smart grids facilitate the integration of DERs into the grid, optimizing their utilization and balancing supply and demand.

Grid Management Systems: Advanced grid management systems utilize sensors, analytics, and automation to monitor grid conditions, predict failures, and optimize operations in real-time. This proactive approach reduces outage durations, improves reliability, and enhances grid resilience against natural disasters and cyber threats[3].

1.2 Role of Blockchain in Enhancing Smart Grids

Blockchain technology holds transformative potential for enhancing smart grids by addressing key challenges related to data security, transaction transparency, and decentralized energy transactions. At its core, blockchain is a distributed ledger technology that enables secure, transparent, and immutable record-keeping of transactions across a network of computers (nodes). Here's how blockchain can enhance smart grids:

Secure Data Exchange and Privacy: Blockchain provides a secure and tamper-resistant platform for storing and exchanging sensitive data within smart grids. Smart meters can record electricity consumption data on the blockchain in real-time, ensuring data integrity and privacy through encryption and consensus mechanisms. Consumers gain greater control over their data[4], while utilities can access verified information for billing and grid management purposes.

Decentralized Energy Transactions: Blockchain enables peer-to-peer (P2P) energy trading among consumers, prosumers (consumers who also produce electricity), and utilities without the need for intermediaries. Smart contracts, self-executing agreements embedded on the blockchain, facilitate automated and transparent energy transactions. This disintermediation reduces transaction costs, enhances market efficiency, and supports the integration of DERs by incentivizing their participation in the grid[5].

Grid Resilience and Security Enhancements: The decentralized nature of blockchain enhances grid resilience by reducing single points of failure and vulnerabilities to cyber attacks. Distributed consensus mechanisms ensure that no single entity can manipulate the data stored on the blockchain, mitigating risks associated with data tampering and fraud. Moreover, blockchain-based microgrids can operate autonomously during grid outages, providing localized energy services and enhancing overall grid reliability[6].

Regulatory Compliance and Transparency: Blockchain's transparent and auditable nature supports regulatory compliance by providing regulators and stakeholders with real-time visibility into energy transactions and grid operations. This transparency fosters trust among participants and facilitates the implementation of regulatory frameworks, such as renewable energy credits and carbon trading schemes.

Case Studies and Practical Implementations: Numerous pilot projects and initiatives worldwide demonstrate the feasibility and benefits of blockchain in smart grids. For example, projects in Europe and the United States have successfully tested blockchain-based platforms for P2P energy trading and grid management. These initiatives showcase blockchain's potential to optimize energy use, reduce costs, and promote renewable energy integration at scale[7].

2 Key Components of Smart Grid Testbeds

2.1 Advanced Metering Infrastructure (AMI)

Advanced Metering Infrastructure (AMI) represents a significant advancement in utility metering technology, revolutionizing the way electricity consumption is monitored and managed. Unlike traditional meters, AMI systems enable two-way communication between utility providers and consumers, facilitating the exchange of real-time data on electricity usage. Smart meters, the cornerstone of AMI, gather consumption information at frequent intervals, which is then transmitted securely to utility companies[8]. This granular data allows utilities to better understand usage patterns, optimize grid operations, and implement demand-response programs. Consumers benefit from accurate billing based on actual usage, enhanced visibility into their energy consumption habits, and the potential to adjust their usage to save costs during peak demand periods. AMI systems also support proactive outage management by automatically detecting and reporting disruptions, enabling utilities to respond swiftly and minimize service interruptions.

2.2 Distributed Energy Resources (DER)

Distributed Energy Resources (DERs) encompass a diverse array of small-scale power generation and storage technologies deployed close to the point of consumption. These resources include solar photovoltaics (PV), wind turbines, energy storage systems (ESS), and microgrids. DERs are integral to transitioning towards a more decentralized and sustainable energy landscape, reducing reliance on centralized power plants and enhancing grid resilience. By generating electricity locally, DERs mitigate transmission losses and alleviate strain on the grid during peak demand periods. Moreover, DERs contribute to carbon emission reductions by harnessing renewable energy sources, supporting environmental sustainability goals. However, integrating DERs into the grid poses challenges related to grid stability, voltage regulation, and interoperability with existing infrastructure. Advanced control and monitoring systems are essential to optimize DER performance, ensure grid compatibility, and maximize the benefits of distributed energy generation[9].

2.3 Grid Management Systems

Grid Management Systems play a crucial role in modernizing and optimizing electrical grid operations through advanced monitoring, control, and automation technologies. These systems leverage sensors, communication networks, and data analytics to monitor grid conditions in real-time, predict potential failures, and optimize electricity distribution. By providing utilities with actionable insights into grid performance and reliability, grid management systems enable proactive maintenance and efficient resource allocation. Automated responses to grid disturbances enhance reliability and resilience, minimizing outage durations and improving service reliability for consumers. Furthermore, grid management systems support the integration of renewable energy sources and DERs by dynamically adjusting grid configurations and balancing supply and demand. As the complexity and scale of electrical grids increase, grid management systems continue to evolve with advancements in artificial intelligence (AI) and machine learning (ML), enabling predictive maintenance and adaptive grid control strategies. Effectively deploying grid management systems requires collaboration among utilities, regulators, and technology providers to address technical challenges, ensure data security, and optimize grid operations in an increasingly digital and interconnected energy landscape[10].

3 Blockchain Technology Fundamentals

3.1 Basics of Blockchain and Distributed Ledgers

Blockchain and distributed ledger technology (DLT) represent innovative approaches to recording and verifying transactions across decentralized networks. At its core, a blockchain is a digital ledger that stores transactional records (blocks) in a chronological and immutable chain. Unlike traditional centralized databases, blockchain operates on a peer-to-peer network where transactions are validated by network participants rather than a central authority. Each block contains a cryptographic hash of the previous block, creating a secure and tamper-resistant record of data. Distributed ledgers extend this concept by distributing copies of the ledger across multiple nodes, ensuring redundancy and enhancing reliability[11].

The fundamental principles of blockchain include transparency, security, and decentralization. Transactions recorded on the blockchain are transparent and accessible to all network participants, promoting trust and accountability. Cryptographic techniques such as hashing and digital signatures ensure data integrity and authenticity, preventing unauthorized alterations. Decentralization eliminates the need for intermediaries in transactions, reducing costs and improving efficiency. These characteristics make blockchain suitable for various applications beyond finance, including supply chain management, healthcare, and voting systems[12].

3.2 Consensus Mechanisms and Smart Contracts

Consensus mechanisms are protocols used in blockchain networks to achieve agreement among nodes on the validity of transactions and the state of the blockchain. These mechanisms ensure that all participants in the network reach a consensus without relying on a central authority. Common consensus mechanisms include Proof of Work (PoW), Proof of Stake (PoS), Delegated Proof of Stake (DPoS), and Practical Byzantine Fault Tolerance (PBFT). PoW, used in Bitcoin, requires miners to solve complex mathematical puzzles to validate transactions and add blocks to the blockchain. PoS, employed in Ethereum 2.0, selects validators based on their stake (amount of cryptocurrency held) in the network, promoting energy efficiency and scalability[13].

Smart contracts are self-executing contracts with predefined rules and conditions written in code on the blockchain. These contracts automate and enforce the execution of agreements, eliminating the need for intermediaries and reducing the risk of disputes. Smart contracts operate based on predetermined triggers and conditions, automatically executing actions once specified criteria are met. They facilitate secure and transparent transactions, enable complex workflows, and enhance efficiency in sectors such as finance, supply chain management, and legal agreements. However, ensuring the security and correctness of smart contracts is crucial, as vulnerabilities in code can lead to exploits and financial losses.

4 Integration of Blockchain in Smart Grid Testbeds

4.1 Secure Data Exchange and Privacy

Secure data exchange and privacy are critical aspects of leveraging blockchain technology in various applications, including smart grids and beyond. Blockchain provides a robust framework for ensuring the integrity, confidentiality, and traceability of data exchanged within decentralized networks. Unlike traditional centralized systems, where data is stored on a single server vulnerable to breaches, blockchain distributes data across multiple nodes in a network. Each transaction or data entry is cryptographically secured with a unique digital signature, making it tamper-resistant and immutable. This transparency and immutability enhance trust among participants, as all transactions are recorded on a public ledger accessible to network members[14].

Blockchain's decentralized architecture also enhances data privacy by reducing reliance on centralized intermediaries that typically manage and control access to sensitive information. Users retain control over their data through cryptographic keys, granting or revoking access as needed without compromising security. In sectors like healthcare and finance, where privacy regulations are stringent, blockchain ensures compliance by enabling secure data sharing while maintaining patient or client confidentiality.

Moreover, advancements in privacy-focused blockchain solutions, such as zero-knowledge proofs and homomorphic encryption, further strengthen data privacy. Zero-knowledge proofs allow parties to verify the authenticity of information without revealing the actual data, preserving confidentiality. Homomorphic encryption enables computations on encrypted data without decrypting it, ensuring sensitive information remains secure throughout processing[15].

4.2 Decentralized Energy Transactions

Decentralized energy transactions leverage blockchain to facilitate peer-to-peer (P2P) energy trading among consumers, prosumers, and utilities without intermediaries. Traditional energy markets rely on centralized entities to manage transactions and maintain the grid's stability. In contrast, blockchain-based platforms enable direct energy exchanges, where participants can buy and sell electricity in real-time based on supply and demand dynamics.

Smart contracts play a pivotal role in decentralized energy transactions by automating the execution of agreements between buyers and sellers. These self-executing contracts ensure that energy transactions are transparent, secure, and enforceable, eliminating the need for manual verification and reducing transaction costs. Participants can set preferences for energy sources, pricing, and consumption patterns, fostering a more flexible and responsive energy ecosystem[16].

By decentralizing energy transactions, blockchain promotes energy independence and resilience. Prosumers with renewable energy sources, such as solar panels or wind turbines, can sell excess energy back to the grid or directly to consumers, promoting renewable energy adoption and reducing reliance on fossil fuels. This peer-to-peer model enhances market efficiency, encourages innovation in energy management technologies, and supports the integration of distributed energy resources (DERs) into the grid.

5 Case Studies and Practical Implementations

5.1 Successful Blockchain-Smart Grid Projects

Successful blockchain-smart grid projects have demonstrated the potential for transforming the energy sector by enhancing efficiency, security, and transparency.

These projects have leveraged blockchain technology to enable peer-to-peer energy trading, automate transactions, and optimize grid operations. One notable example is the Brooklyn Microgrid project, which allows residents to buy and sell excess solar energy using blockchain technology. This initiative has not only empowered consumers to take control of their energy usage but has also fostered a sense of community and sustainability[17].

5.2 Lessons Learned and Best Practices

Best practices for implementing blockchain-smart grid projects include conducting thorough pilot studies, establishing clear governance structures, and prioritizing data security and privacy. Pilot studies can help identify potential challenges and opportunities, allowing project teams to refine their strategies and mitigate risks before full-scale deployment. Clear governance structures, including defined roles and responsibilities, decision-making processes, and dispute resolution mechanisms, are essential for effective project management and coordination. Prioritizing data security and privacy through robust encryption, access controls, and data anonymization measures is crucial to building trust among stakeholders and ensuring compliance with data protection regulations[18].

6 Challenges and Future Directions

6.1 Technical and Regulatory Challenges

Implementing blockchain technology in smart grid projects presents various technical and regulatory challenges that need to be addressed for successful deployment. One of the technical challenges is scalability, as blockchain networks can face limitations in processing transactions quickly and efficiently, especially as the number of participants and transactions increases. Solutions such as off-chain processing, sharding, and layer-two protocols are being explored to improve scalability in blockchain-based smart grid applications.

Another technical challenge is interoperability, as different blockchain platforms may have varying protocols and standards, making it difficult to ensure seamless communication and data exchange between different systems. Developing interoperability standards and protocols can help address this challenge and facilitate the integration of blockchain technology with existing grid infrastructure and technologies[19].

On the regulatory front, one of the key challenges is the lack of clear guidelines and regulations governing blockchain technology in the energy sector. Regulatory uncertainty can create barriers to adoption and investment, as stakeholders may be hesitant to engage in projects without a clear understanding of the legal and compliance requirements. Collaborating with regulators and policymakers to develop a regulatory framework that addresses data privacy, security, consumer protection, and market transparency is essential for fostering innovation and investment in blockchain-smart grid projects.

Additionally, ensuring compliance with existing energy regulations and standards poses a challenge, as blockchain technology may introduce new complexities and considerations that need to be addressed within the regulatory framework. Balancing innovation with regulatory compliance requires close collaboration between industry stakeholders, regulators, and policymakers to develop flexible and adaptive regulatory approaches that support the deployment of blockchain technology in the smart grid sector[20].

6.2 Potential Future Developments in Blockchain and Smart Grids

The intersection of blockchain technology and smart grids holds immense potential for shaping the future of the energy sector. Looking ahead, several key developments are expected to drive innovation and transformation in this space. One potential future development is the increased adoption of blockchain-based energy trading platforms, enabling peer-to-peer transactions between prosumers and consumers. These platforms can empower individuals to buy and sell excess energy directly, fostering a decentralized and efficient energy market while promoting renewable energy generation and consumption[21].

Another future development is the integration of blockchain technology with Internet of Things (IoT) devices and artificial intelligence (AI) systems in smart grid infrastructure. By leveraging blockchain's secure and transparent data management capabilities, IoT devices can securely communicate and transact with each other, optimizing energy consumption, grid operations, and maintenance processes. AI algorithms can analyze data from these interconnected devices to predict energy demand, optimize grid performance, and automate decision-making processes, leading to a more resilient and responsive energy system.

Furthermore, the development of blockchain-based energy traceability and certification systems is expected to enhance transparency and trust in the energy supply chain. By recording energy generation, consumption, and carbon emissions data on a tamper-proof blockchain ledger, stakeholders can verify the origin and sustainability of energy sources, enabling consumers to make informed choices and support renewable energy initiatives. This transparency can also facilitate compliance with regulatory requirements and support the transition to a low-carbon economy[22].

Overall, the future of blockchain and smart grids is poised to revolutionize the energy sector by enabling decentralized energy trading, enhancing grid efficiency and resilience, and promoting sustainability and transparency. As these technologies continue to evolve and converge, stakeholders must collaborate to drive innovation, address challenges, and unlock the full potential of blockchain technology in shaping the future of energy systems[25].

7 Conclusion

In conclusion, the integration of blockchain technology for smart grid testbeds and IoT-based digital twins in cyber-physical systems represents a significant advancement in the energy sector. By leveraging blockchain's secure and transparent data management capabilities, smart grid testbeds can enhance the efficiency, reliability, and security of energy systems. The use of blockchain in testbeds enables real-time data sharing, secure transactions, and automated processes, facilitating the development and validation of innovative energy solutions[1].

Moreover, the integration of IoT-based digital twins in cyber-physical systems offers a powerful tool for simulating, monitoring, and optimizing energy infrastructure. Digital twins create virtual replicas of physical assets, enabling real-time monitoring, predictive maintenance, and performance optimization. When combined with blockchain technology, digital twins can securely store and exchange data, ensuring the integrity and authenticity of information shared across interconnected devices and systems.

Together, blockchain integration for smart grid testbeds and IoT-based digital twins in cyber-physical systems can revolutionize the energy sector by enabling decentralized energy trading, optimizing grid operations, and enhancing sustainability. These technologies empower stakeholders to make data-driven decisions, improve energy efficiency, and drive innovation in energy management and distribution.

As the energy sector continues to evolve towards a more decentralized, digitized, and interconnected landscape, the integration of blockchain technology and IoT-based digital twins in smart grid testbeds will play a crucial role in shaping the future of energy systems. Collaboration among industry stakeholders, researchers, and policymakers is essential to drive innovation, address challenges, and unlock the full potential of these technologies in creating a more resilient, sustainable, and efficient energy ecosystem.

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