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SCIENTIFIC CULTURE, Vol. 12, No. 2, (2026), pp. 12-27
Open Access. Online & Print

DOI: 10.5281/zenodo.1222602

BLOCKCHAIN VS. CENTRALIZED LEDGERS IN CBDS: A COMPARATIVE ANALYSIS OF EFFICIENCY, SCALABILITY, AND SECURITY

Babir Guliyev[1] and Andras Bethlendi[2]

[1]Department of Finance, Budapest University of Technology and Economics, Hungary
E-mail: guliyevbabir@gmail.com, https://orcid.org/0009-0003-0052-7996
[2]Department of Finance, Budapest University of Technology and Economics, Hungary
bethlendi.andras@gtk.bme.hu, https://orcid.org/0000-0003-3219-0251

Received: 01/12/2025
Accepted: 02/01/2026

Corresponding Author: Babir Guliyev (guliyevbabir@gmail.com)

ABSTRACT

The global financial landscape is changing due to the rapid development and increasing adoption of Central Bank Digital Currencies (CBDS). This article compares centralized ledger and blockchain-based systems in the context of CBDS in terms of their effectiveness, scalability, security, and operational resilience. The study examines the scalability of four leading CBDC systems (eNaira, DCash, Digital Yuan, and Sand Dollar) under different transaction loads and measures key performance indicators such as transaction speed, latency, and system utilization. For example, Digital Yuan processed over 7 trillion RMB by mid-2024 alone, while eNaira had only achieved a 0.8% adoption rate among banked users by the end of 2022. Cash stands out with a 10% adoption rate in the Eastern Caribbean. The analysis also assesses potential vulnerabilities such as double-spending and considers critical factors such as energy consumption, privacy, fault tolerance, and resilience to network outages. The findings illuminate the trade-offs between centralization and decentralization, providing a comprehensive understanding of the advantages and disadvantages of blockchain and centralized ledger architectures. This study offers guiding principles for the future development and implementation of CBDS across diverse financial ecosystems and provides valuable insights into the challenges encountered during large-scale implementations.

KEYWORDS: Blockchain, Centralized Ledger, Central Bank Digital Currencies, Scalability, Security, Efficiency

1. INTRODUCTION

The swift ascent of Central Bank Digital Currencies (CBDS) signifies a significant change in the international financial scene. In order to address the inefficiencies and inadequacies that are common in traditional financial systems, CBDS have become a crucial instrument as countries work to upgrade their payment infrastructures and promote greater financial inclusion. The eNaira in Nigeria, the DCash in the Eastern Caribbean Currency Union (ECCU), the Digital Yuan (e-CNY) in China, and the Sand Dollar in the Bahamas are the four well-known CBDC implementations that are compared in this study. The study aims to give a thorough grasp of how CBDS are changing monetary systems across various socioeconomic contexts by looking at their adoption trends, technological frameworks, and economic effects (Sethaput & Innet, 2024).

The growing desire for more effective, safe, and inclusive payment methods as well as the increasing digitization of economies are the main drivers of the need for CBDS. The majority of the world's 1.4 billion unbanked individuals live in developing nations, according to the World Bank (IMF, 2022). By enabling smooth digital transactions and increasing access to financial services in disadvantaged areas, CBDS present a possible solution to this problem. Nigeria's eNaira, for instance, aims to increase financial inclusion, but adoption is still sluggish; by the end of 2022, only 0.8% of bank account holders who are now active will be utilizing the platform (Van Vliet, 2023). Similar to this, DCash has a 10% adoption rate in the ECCU, indicating early success in integrating digital payments among the 600,000 residents of the region (International Monetary Fund [IMF], 2022).

From an economic standpoint, CBDS have the ability to boost economic activity, enhance payment efficiency, and drastically reduce transaction costs. By the middle of 2024, for example, the Digital Yuan had handled over 7 trillion RMB (about $1 trillion USD) in transactions, demonstrating its crucial role in the Chinese economy (Hull & Sattath, 2024). Real-time, safe transactions throughout The Bahamas are made possible with the Sand Dollar, which has a $3 million circulation value and tackles the particular difficulties of a dispersed island economy. With an average processing time of less than five seconds, DCash also provides remarkable transaction speeds, highlighting the efficiency gains that digital currencies may provide over conventional payment methods (Mishra & Prasad, 2023).

The wider economic effects of CBDS are also examined in this paper, with a focus on how they might alleviate systemic inefficiencies. Financial inclusion has long been hampered by address challenges of traditional banking systems' high transaction costs. CBDS, like eNaira and DCash, provide an alluring substitute with their minimal or nonexistent transaction fees (Kosse & Mattei, 2022). Additionally, the scalability of these systems guarantees their flexibility to meet present and future demands, as demonstrated by Digital Yuan's capability to process millions of transactions per second and DCash's ability to handle up to 10,000 transactions per second (Caudevilla, 2021).

In terms of technology, CBDS are based on cutting-edge blockchain and cryptographic technologies that guarantee the durability, security, and transparency of virtual currencies. The permissioned blockchain architectures used by eNaira and Digital Yuan enable regulatory control while encrypting transaction data. Secure blockchain technology is also used by DCash and The Sand Dollar, which strengthen user confidence by preventing data manipulation. The crucial role that technology plays in CBDC development emphasizes the necessity of safe, effective solutions that give consumers confidence (Special Report: The Future of Banking, 2021).

Apart from their technical and financial advantages, CBDS also accomplish significant policy goals. They support regional and global trade, aid in the fight against illegal financial activity, and provide improved instruments for the transmission of monetary policy. Applications for cross-border trade are made possible, for instance, by the Digital Yuan's connection with systems such as Alipay and WeChat Pay, which streamline domestic transactions. The Sand Dollar's ability to facilitate transactions both inside and outside of The Bahamas is further demonstrated by its compatibility with mobile wallets and conventional banking systems (World Bank, 2023).

CBDS confront a number of obstacles despite their revolutionary potential, including sluggish adoption rates, infrastructure weaknesses, and privacy issues. The success of digital currencies is largely dependent on user participation and public awareness, as demonstrated by eNaira, where a significant percentage of wallets are inactive. A careful balance between control and user autonomy is also required because of the centralized character of many CBDS, which raises questions about data privacy, government supervision, and possible abuse of centralized authority (Zamora-Pérez, Coschignano, & Barreiro, 2022).

Similarly, the European Central Bank's Digital Euro pilots and the Reserve Bank of India's Digital

Rupee implementation demonstrate how CBDS are shaped globally in diverse technological and political contexts. While the Digital Euro focuses specifically on privacy and interoperability, the Digital Rupee has been integrated into financial inclusion and payment systems reforms in India. These studies demonstrate that technological infrastructure is not limited to technical efficiency but is also directly linked to regional strategies and societal needs.

This paper examines the societal and policy ramifications of CBDS in addition to their technological and economic aspects. In order to contribute to the continuing discussion on the future of digital currencies and their role in creating more resilient and inclusive financial systems, this research will analyze case studies from four different regions in order to offer insightful information about the design, implementation, and wider effects of CBDS. In the end, the results aim to educate stakeholders, financial institutions, and policymakers on the best practices and tactics needed to fully utilize CBDS while resolving their inherent difficulties.

2. THEORETICAL LENS

A revolutionary development in the global financial system, central bank digital currencies (CBDS) have the ability to update monetary frameworks and mitigate inefficiencies in conventional payment infrastructures. By utilizing cutting-edge technical frameworks like blockchain-based and centralized systems, CBDS seek to improve security, efficiency, and financial inclusion. These state-backed digital currencies, which are being investigated or piloted in more than 130 countries, have the potential to transform financial transactions, enhance the implementation of monetary policies, and increase economic resilience.

2.1. Blockchain-Based CBDS

Distributed ledger technology (DLT) is used by blockchain-enabled CBDS, like the Bahamas' Sand Dollar and the Eastern Caribbean's DCash, to improve transparency, security, and resilience. Through the use of cryptographic protocols and the removal of middlemen, these systems guarantee transaction immutability and reduce the danger of fraud. Because blockchain-based solutions offer safe and easily accessible financial services to marginalized communities with inadequate banking infrastructure, they are especially beneficial for financial inclusion. For example, DCash makes it possible to conduct fast, inexpensive transactions in the Eastern Caribbean, and the Sand Dollar makes cross-border transfers easier.

Nevertheless, scalability issues plague blockchain-based CBDS, especially when it comes to consensus processes like Proof of Work (PoW) and Proof of Stake (PoS), which are frequently laborious and slow. These restrictions impede further adoption in larger economies by making it more difficult to handle high-frequency transactions. Furthermore, transaction latency and energy consumption continue to be major barriers to global scalability.

2.2. Centralized Ledger-Based CBDS

Scalability, throughput, and smooth interaction with current financial systems are top priorities for centralized ledger-based CBDS, including China's Digital Yuan (e-CNY) and Nigeria's eNaira. These systems are appropriate for managing national economies and preserving economic stability since they are designed to manage large transaction volumes. For instance, the Digital Yuan allows transactions totaling trillions of yuan by integrating with well-known systems such as Alipay and WeChat Pay. In a similar vein, the eNaira aims to facilitate business dealings and advance financial inclusion in Nigeria. Centralized CBDS raise privacy and surveillance concerns despite their effectiveness. Although centralized control gives governments more control over financial stability and monetary policy, it also increases the possibility of transaction data exploitation and decreases consumer autonomy.

2.3. Centralization Vs. Decentralization

A basic contrast between centralization and decentralization is brought to light by the discussion of centralized and blockchain-based systems. Decentralization, according to blockchain proponents, democratizes financial access, improves transparency, and lessens dependency on middlemen. Through the reduction of single points of failure, these systems also increase resilience. On the other hand, proponents of centralized systems emphasize how they can guarantee adherence to legal requirements, provide scalability, and provide operational efficiency—all of which are essential for overseeing large-scale economies.

The trade-offs that come with each strategy are demonstrated by real-world scenarios. With 30% of Bahamians using digital currency, blockchain-based CBDS like the Sand Dollar show that they can address financial inclusion. However, their wider usefulness is limited by issues like slower transaction speeds and high energy costs. However, because they collect a lot of financial data, centralized solutions like the Digital Yuan raise worries about privacy and governmental monitoring even while they offer unmatched scalability, processing millions of transactions per second.

2.4. *Study Objectives*

The purpose of this study is to examine how control, efficiency, and transparency are traded off in CBDC systems. In order to ascertain how CBDS help update financial infrastructures, the research looks at scalability, security, and wider structural ramifications. The ultimate objective is to address a key concern is like financial inclusion, economic resilience, and monetary sovereignty while striking a balance between privacy, security, and efficiency.

3. METHODOLOGY

The simulation parameters used in this study were determined based on real-world capacity reports for each CBDC system, technical documents in the literature, and test data published by the relevant central banks. The goal is to remove abstract assumptions from theoretical models and base them on as realistic an infrastructure as possible. The node and transaction intervals used for the Monte Carlo simulation were adjusted to reflect the lowest and highest possible operational scenarios of the systems. For example, for the eNaira system, the ingress rate (λ) was set at 1,500 tps and the service rate (μ) at 3,000 tps. These values were chosen based on stress test results of the Hyperledger Fabric infrastructure and the CBN's statements. The 5,000/10,000 tps rates for DCash reflect the transaction capacity specified in the ECCB's technical documentation. The Digital Yuan's parameters were taken from pilot data publicly available to the People's Bank of China. A transaction throughput of 500,000 tps and a service capacity of 1,000,000 tps demonstrate that this system can serve a large user base at the national level. A smaller scale was chosen for Sand Dollar. The 1,000 tps throughput and 2,000 tps service rates were determined to represent the Bahamas' limited population and transaction volume. These differences between the parameters clearly reflect the scale and operational differences of the systems. Each value selection was meticulously determined to ensure fair, consistent, and system-context-appropriate performance comparisons.

With an emphasis on security, scalability, and efficiency, this study compares Central Bank Digital Currencies (CBDS) based on centralized ledgers with blockchain technology. To assess the trade-offs, performance, and computing complexity of both kinds of systems, the methodology combines a number of mathematical models and simulations. The study will use Big-O Notation, Monte Carlo simulations, Queuing Theory, and Comparative Trade-Off Analysis to examine four well-known CBDS: eNaira, DCash, Digital Yuan (e-CNY), and Sand Dollar.

Big-O Notation will be used to evaluate the computational complexity of both blockchain-based and centralized ledger systems in order to examine the scalability and effectiveness of the CBDC systems. The complexity of blockchain-based systems, such as DCash and the Sand Dollar, is predicted to increase logarithmically, or O(log(n)), where n is the number of nodes that are part of the network. This indicates that the computing effort grows considerably more slowly as the number of nodes rises. In particular, only a portion of nodes engage in transaction validation in Proof of Stake (PoS) systems, which lessens the overall computing burden. Therefore, it is anticipated that blockchain systems will scale effectively even as the network expands. On the other hand, the computational complexity of centralized systems such as the Digital Yuan and eNaira increases linearly, as indicated by the formula O(n), where n is the number of transactions being handled. The amount of computing power needed rises in direct proportion to the volume of transactions. This implies that as transaction volumes increase, centralized systems may experience performance degradation and need more resources or improvements to be effective.

The computational complexity of centralized and blockchain-based systems under various transaction loads will be simulated using Monte Carlo simulations. For blockchain systems, the number of nodes (n) will be randomly assigned between 100 and 10,000, and the O(log(n)) formula will be used to determine the associated computing complexity. For centralized systems, O(n) will be used to compute the complexity, and random values for the number of transactions (n) will be produced between 50,000 and 1,000,000. The computational complexity that comes from 1,000 simulations of each system will be calculated for every run. The data will be displayed through scatter plots, showing how complexity increases for both blockchain and centralized systems, highlighting the differences in scalability and efficiency (Hajian Berenjestanaki et al., 2024; Rani et al., 2024)

The M/M/1 queuing theory model will be used to assess the CBDS' scalability and performance under actual transaction loads. This model is predicated on a single-server configuration with exponential service times and Poisson transaction arrival rates. The objective is to evaluate each system's utilization, queue lengths, and transaction wait times. Furthermore, the input parameters associated with Big-O analysis (number of nodes or number of transactions) were varied to suit each system's specific architecture. For blockchain-based systems, the number of nodes was randomly selected between 100 and 10,000, while for centralized systems, the number of transactions was set between 50,000 and 1,000,000. These ranges are consistent with both the distributions frequently used in the literature and the expectations of the systems. Parameter justification is critical for the reliability and interpretability of the model results. The λ (arrival rate) and μ (service rate) values used in the queueing theory model were determined based on publicly available performance data and stress test reports for each CBDC system. For example, DCash was reported to reach up to 10,000 transactions per second in pilot tests (Khan et al., 2024); therefore, it was modeled as $\lambda = 5{,}000$ and $\mu = 10{,}000$. Similarly, eNaira is stated in technical documentation to support up to 3,000 transactions per second (Sunnewsonline, 2023). These parameters were chosen to reflect the real-world transaction capacities of the systems.

The following criteria will be established for every CBDC: eNaira, which has a 1,500 transaction rate (λ) and a 3,000 transaction rate (μ) per second; DCash, which has a 5,000 transaction rate (λ) and a 10,000 transaction rate (μ); Digital Yuan, which has a 500,000 transaction rate (λ) and a 1,000,000 transaction rate (μ); and Sand Dollar, which has a 1,000 transaction rate (λ) and a 2,000 transaction rate (μ) per second. Each system's utilization rate (ρ), which indicates how well each CBDC manages its transaction load, will be determined by the queuing theory model. To evaluate the effectiveness of transaction processing and user experience, the queue lengths and wait durations (W_q) will also be calculated (Muharam et al., 2024; Rubeis, 2024).

An Analysis of Comparative Trade-Offs The table will list the four CBDC systems' advantages and disadvantages according to three important criteria: scalability, efficiency, and security. The performance of each method will be compared side by side in this table, illustrating the relative benefits and difficulties of each. The examination will concentrate on how centralized systems may offer higher efficiency at the expense of scalability and possible privacy issues, whereas blockchain systems may offer better scalability but may be less effective for high-frequency transactions.

While the Weighted Scoring Model provides a structured framework for comparing systems, it does have some limitations. First, the weights assigned to each metric (security 40%, efficiency 30%, scalability 30%) are based on the researcher's discretion, and different experts may assign different weights. Similarly, scores ranging from 1 to 10, even if supported by objective data, may contain subjective interpretations, which in turn may influence the model's results. It is risky to assume that these results are universally valid without conducting alternative scenario analyses or sensitivity analyses. Furthermore, more qualitative aspects of the systems, such as long-term sustainability, resilience, or user experience, are not included in the evaluation. Therefore, these scores are only valid under specific technical indicators.

Lastly, each CBDC system's overall performance will be assessed using the Weighted Scoring Model. Each of the three metrics—security, efficiency, and scalability—will have a weight (security = 40%, efficiency = 30%, and scalability = 30%). Each CBDC's performance will be rated on a scale of 1 to 10. The following formula will be used to determine the weighted total:

$$\text{Weighted Total}=(\text{Security Score}\times 0.4)+(\text{Efficiency Score}\times 0.3)+(\text{Scalability Score}\times 0.3)$$

By comparing the four CBDC systems quantitatively, this method will provide light on their relative advantages and disadvantages in practical settings. Through the use of Big-O Notation, Monte Carlo simulations, Queuing Theory, and Comparative Trade-Off Analysis, this methodology will provide a thorough comparison of centralized and blockchain-based CBDC systems, giving financial institutions and policymakers important information about the security, efficiency, scalability, and performance of various CBDC strategies.

4. DATA

4.1. Blockchain-Based E-Naira

Africa's first central bank digital currency (CBDC), the eNaira was introduced by the Central Bank of Nigeria (CBN) in October 2021 with the goals of promoting financial inclusion, facilitating remittances, and increasing the effectiveness of the payment system (Ogiri, 2022). About 0.8% of Nigeria's active bank accounts, or 860,000 retail eNaira wallets, have been downloaded as of November 2022. By mid-2022, merchant wallet downloads had increased to 100,000 (Allende et al., 2024). With only 14,000 transactions every week and an average transaction value of 60,000 naira, adoption has been slower than expected, and most wallets are now dormant. By encouraging merchant acceptance and increasing access to unbanked people, the CBN is tackling these issues (Ozili, 2023).

The picture sheds light on how eNaira, Nigeria's central bank digital currency (CBDC), is being adopted and used. It draws attention to patterns in transaction activity, wallet downloads, and transaction values over time. At first, there is a sharp rise in the total number of eNaira wallet downloads, with retail wallets outperforming merchant wallets by a wide margin. Wallet adoption growth seems to be stabilizing after an initial surge.

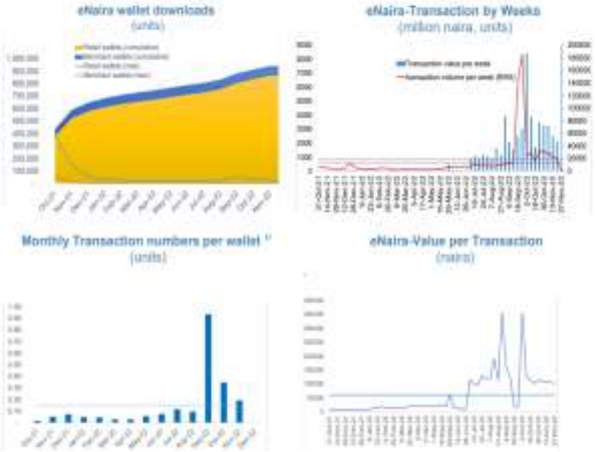

Figure 1: eNaira, 2021-2022 Data (Ree, 2023).

Weekly measurements of transaction activity reveal a sharp increase in transaction volumes and values around the middle of 2022, suggesting a spike in consumption at that time. Nevertheless, there is a discernible dip after this surge, indicating that activity may have peaked. Similar patterns can be seen in the monthly transaction figures per wallet, which show a notable spike in mid-2022 due to increased wallet activity. Over time, there are variations in the average value per transaction. Midway through 2022, there is a notable increase in transaction values, which is followed by a decrease and stabilization. Together, these patterns provide insight into how eNaira is being adopted and used in its early phases.

Near real-time transactions are supported via the eNaira technology, which offers notable payment efficiency. With stress tests showing a capability of up to 3,000 transactions per second, it is built on top of Hyperledger Fabric and is intended to manage large transaction volumes (Sunnewsonline, 2023). Adoption is further encouraged by the CBN's subsidization of transaction expenses, which makes them free for users. Compatibility with the wider financial ecosystem is ensured by the system's smooth integration with Nigeria's current banking and payment infrastructures, including the Nigeria Inter-Bank Settlement System (NIBSS). Attempts are being made to use national identity numbers and mobile technology to provide eNaira access to unbanked people (Auer, 2022).

The eNaira, which runs on a permissioned blockchain and guarantees that only authorized entities authenticate transactions, continues to be built on security. To safeguard transaction data, the system is strengthened with cutting-edge authentication and encryption techniques (Ree, 2023). Additionally, it maintains financial integrity by adhering to anti-money laundering (AML) and combating the financing of terrorism (CFT) standards. Although the eNaira has a strong technical base, privacy issues and the possibility of governmental control and manipulation are brought up by its centralization (Rawat, 2023). The Central Bank of Nigeria (CBN) has been working to improve user engagement and increase access in an effort to completely integrate eNaira into Nigeria's financial ecosystem, but adoption has been slow (Ozili, 2021).

4.2. Blockchain-based DCash

The Eastern Caribbean Central Bank (ECCB) created DCash, a digital currency that serves eight Eastern Caribbean Currency Union (ECCU) members, including Dominica, Saint Lucia, and Antigua & Barbuda. With a stated acceptance rate of more than 10% in test zones, it aims to reach the region's 600,000+ residents (de Haro Moraes et al., 2024). Millions of Eastern Caribbean dollars (XCD) worth of transactions have been made possible via DCash since its inception. Because of this, it is a promising attempt to improve regional financial inclusion and digital payments (Appendino et al., 2023).

With an average transaction time of less than five seconds, the platform offers quick and effective payment processing. Pilot stress tests have shown that it can process up to 10,000 transactions per second (Khan et al., 2024). Transactions are free for individuals, while businesses pay small fees based on the amount of transactions. This pricing plan seeks to maintain operational effectiveness while promoting both personal and business use (Finch, Garcia-Singh, & Duke, 2021).

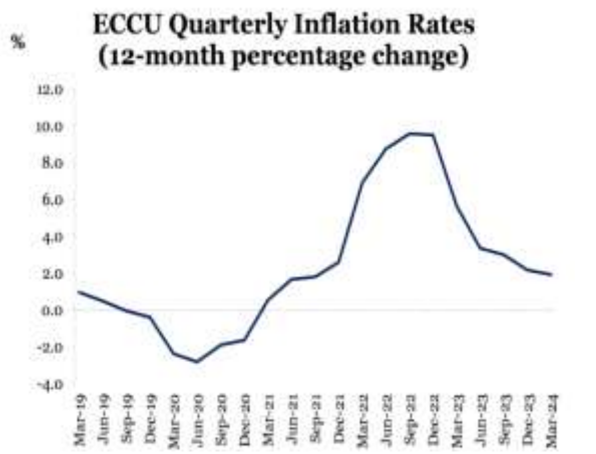

Figure 2: ECCU Quarterly Inflation Rates (Eastern Caribbean Central Bank, 2024).

The Eastern Caribbean Currency Union's (ECCU) quarterly inflation rates are shown in the graph as a 12-month percentage change between March 2019 and March 2024. It depicts notable changes in the economic landscape by capturing the variations in inflation during this time frame (Haans et al., 2023).

The graph's early portion, which spans March 2019 to late 2020, shows deflation at this time due to comparatively low inflation rates and a brief fall into negative territory. This might be an indication of weak economic activity, possibly brought on by regional or worldwide occurrences like the COVID-19 pandemic.

Inflation rates start to climb gradually in 2021, either as a result of external factors such as supply chain disruptions or greater economic activity. This increasing trend lasts until the middle of 2022, when inflation reaches its maximum point on the graph, at about 10%.

The spike points to a time of increased pricing pressures, either brought on by the volatility of oil prices or the global economic recovery. Inflation starts to drop from the middle of 2022 and continues to do so through 2023 and early 2024. By March 2024, inflation is expected to have stabilized and be closer to more moderate levels. The ECCU's inflationary pressures during a five-year period are clearly depicted by this pattern.

To sum up, DCash supports the digital transformation of payments in the ECCU by combining effective transaction processing, regional scalability, and strong security measures. Although its popularity is still increasing, its operational model and technical infrastructure make it a serious candidate for regional adoption.

Table 1: Enaira And Dcash Metrics

Metric	eNaira	DCash
Adoption	1M+ users; ₦4B transaction volume	10% population in ECCU; millions XCD transaction value
Transaction Speed	Near real-time	Under 5 seconds
Throughput (TPS)	~20,000	~10,000
Scalability	Nationwide, integrates with banks	Regional (8 countries), interoperable
Security	Permissioned blockchain, advanced cryptography	Blockchain immutability, key encryption
Transaction Costs	Near zero	Zero for individuals

Like Hyperledger, DCash is based on a specially designed blockchain architecture that is scalable locally. It ensures interoperability and user convenience by integrating with current regional banking systems and mobile wallets and enabling smooth cross-border payments within ECCU member nations. Because of these characteristics, it is especially well-suited to the ECCU's multi-national setting (Sarkar et al., 2024). In order to maintain the integrity of the platform and avoid tampering with transaction history, DCash uses blockchain immutability. It protects transaction data while preserving secrecy by using private-public key encryption (Hrnjic & Gordon, 2022).

Independent security companies regularly conduct audits and penetration tests on the site to strengthen its defenses against possible attacks. However, the system's centralized architecture and a recent crash raise questions about fraud, outages, and the inability to function offline during disruptions (Zohuri, Nguyen, & Moghaddam, 2022).

4.3. Centralized Ledger: Digital Yuan

The People's Bank of China (PBOC) is the issuer of the Digital Yuan (e-CNY), a Central Bank Digital Currency (CBDC) that is in use in numerous Chinese cities through comprehensive trial programs. By combining both centralized and decentralized elements, the currency's hybrid model enables the central bank to maintain control while utilizing blockchain-based infrastructure for improved security, transparency, and immutability (Auer, Cornelli, & Frost, 2020).

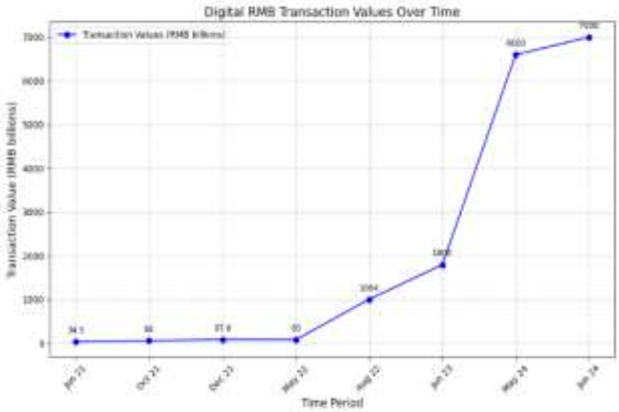

Figure 3: Digital RMB Transaction Values Over Time.

From June 2021 to June 2024, the graph shows the Digital RMB's transaction values over time, expressed in billions of RMB. It records the sharp rise in digital currency transactions, which is indicative of the Digital RMB's growing acceptance and use.

Transaction values are comparatively low during the first phase, which runs from June 2021 to May 2022. They begin at 34.5 billion RMB and progressively rise to 83 billion RMB by May 2022. This sluggish growth can be a sign of limited use cases and early adoption.

However, the graph exhibits a steep increase tendency starting in August 2022. By August 2022, transaction values will have surpassed 1 trillion RMB (1,004 billion RMB), indicating a notable increase in adoption and usage. With values reaching 1.8 trillion RMB by June 2023 and then soaring to 6.6 trillion RMB in May 2024, this rise picks up even more speed.

The graph reaches its peak when transaction values hit 7 trillion RMB in June 2024. This sharp rise in transaction volume indicates that the Digital RMB is becoming more and more integrated into different facets of economic activity, indicating that it is a developing and growing digital currency.

With the Chinese government providing billions of yuan in subsidies to promote adoption, more than 260 million people had opened digital wallets for e-CNY as of 2023 (Financial Stability Board, 2023). The Digital Yuan has been implemented in a number of large cities, such as Beijing, Shanghai, Shenzhen, and Chengdu. Several hundred million people have used digital currency in these pilot areas (Zhang et al., 2024). With millions of transactions processed every day, e-CNY handled over 5.6 trillion yuan (about $800 billion) in transactions by the end of 2023. Especially in areas with ongoing pilot programs, the number of retailers accepting e-CNY keeps growing (Jones, 2023).

Because the system completes transactions in a matter of seconds, both customers and merchants can utilize it on a daily basis. The platform's hybrid architecture allows for high throughput and scalability, enabling it to process millions of transactions per second during peak hours (Chen, 2021). Due to government subsidies, transaction fees are either negligible or nonexistent for both firms and customers. In order to guarantee broad adoption and smooth operation, the Digital Yuan's infrastructure is designed to be extremely scalable, able to manage China's sizable population, and connected with current payment systems like Alipay and WeChat Pay (Cheng, 2022).

With the Chinese government investigating the possibility of using the Digital Yuan in cross-border transactions, it is also anticipated to spread further throughout China. In addition to integrating with conventional banking networks and mobile wallets for convenience, the e-CNY is made to function flawlessly with a variety of payment systems (CBN Editor, 2021). Using a permissioned blockchain that provides transparency while retaining control under the People's Bank of China (PBoC), the Digital Yuan uses blockchain technology to guarantee immutability and transaction security (Dapp, 2021).

Advanced cryptographic techniques, such as private-public key encryption and digital signatures, protect user data and transaction integrity. Despite using blockchain for security, the PBoC retains full control over the issuance, tracking, and auditing of e-CNY transactions, enabling regulatory oversight and mitigating risks associated with decentralized systems (Xie et al., 2024). Regular security audits and continuous monitoring are conducted to uphold network integrity, ensuring a secure and reliable system for digital currency transactions (Movroydis, 2022).

4.4. Centralized Ledger: Sand Dollar

The Central Bank of The Bahamas (CBOB) is the issuer of the Sand Dollar, a Central Bank Digital Currency (CBDC). With an emphasis on financial inclusion and modernizing the payment system, it was introduced in 2020, is now fully functional, and has been implemented throughout the nation (Tinn, 2024). The Central Bank of The Bahamas maintains complete authority over the issuance, regulation, and oversight of the Sand Dollar since it functions as a centralized digital currency (Central Bank of The Bahamas, 2023).

According to recent studies, more than 30% of Bahamians have adopted the Sand Dollar, with a notable uptake in underserved and isolated communities with limited access to traditional financial institutions. It is distributed over all of the Bahamas' main islands and is accessible nationally. Since its introduction, the currency has handled millions of transactions and is becoming more and more popular in both the public and private spheres. The Sand Dollar is currently a widely accepted digital money in the Bahamas, accepted by more than 5,000 merchants nationwide (Colebrook, 2022).

The chart shows the Bahamas Sand Dollar's circulation value from January 2021 to March 2024, expressed in US dollars. It shows how this digital money has grown since its introduction and how the Bahamian economy is using it more and more.

According to the graph, the Sand Dollar was formally introduced in March 2021. Circulation values are comparatively modest in the early post-launch era, remaining below $500,000 for the majority of 2021. Since digital money was made available to the general public and incorporated into the financial system, this phase most likely reflects the early adoption stage.

The graph indicates a steady rise beginning in late 2021 and continuing into 2022, with circulation reaching $1 million by the middle of the year. This consistent rise is a result of growing use cases and increased consumer and industry acceptability.

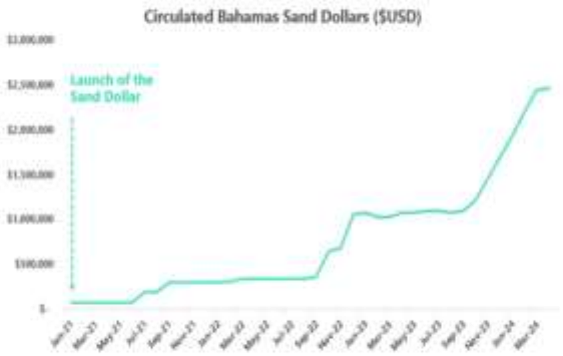

Figure 4: Circulated Bahamas Sand Dollars (Jones, 2024).

A notable increase trend with rapidly increasing circulation levels appears by the middle of 2023. Rapid growth occurs during this time, with the entire amount reaching almost $2.5 million by the beginning of 2024. The steep growth points to more acceptance across a range of industries, demonstrating trust in the digital currency and its expanding function in enabling business dealings.

The Bahamas Sand Dollar's achievements as a central bank digital currency (CBDC) and its incorporation into the national economy are highlighted by the fact that it reaches its peak circulation level of about $3 million by March 2024. The Sand Dollar is appropriate for daily use since it provides real-time transaction processing, with the majority of transactions being finished in a matter of seconds. Although precise throughput statistics are not made public, the system is built to manage a high volume of transactions, and the infrastructure has been proven to withstand periods of high demand (Scholten et al., 2024). Although corporations may pay small fees based on transaction volume, transaction fees for users are negligible or nonexistent because the Central Bank covers the costs for people. The Central Bank of The Bahamas oversees the scalable and secure infrastructure that supports the Sand Dollar to make sure it can accommodate the demands of the scattered island populations (Haans et al., 2023).

The Central Bank is investigating potential cross-border payment options with nearby Caribbean nations, notwithstanding the system's countrywide functioning. Because the Sand Dollar is compatible with current payment systems, users may conduct transactions using both mobile wallets and conventional bank accounts, guaranteeing a smooth cross-platform payment experience (Koldovskyi et al., 2024). For transaction verification, The Sand Dollar uses secure ledgers and cutting-edge encryption, guaranteeing the integrity and immutability of transaction records (Branch, Ward, & Wright, 2023).

To safeguard user identities and transaction information, the system makes use of private-public key encryption and further cryptographic techniques. The Central Bank retains centralized control over the issue, validity, and monitoring of the Sand Dollar, guaranteeing complete governance and security, even while blockchain technology is employed for safe transactions. The Central Bank maintains the network's security and integrity through routine audits and system inspections (Hull & Sattath, 2024).

Table 2: Digital Yuan And Sand Dollar Metrics.

Metric	Digital Yuan	Sand Dollar
Adoption	260M+ users; ¥5.6 trillion transaction volume	30% of the Bahamian population; millions of transactions processed
Transaction Speed	Near real-time (seconds)	Real-time or within a few seconds
Throughput (TPS)	Millions of transactions per second	Designed to handle large volumes (exact TPS not published)

Scalability	Nationwide, integrated with Alipay, WeChat Pay, and banks	Nationwide (8 islands), interoperable with banks and mobile wallets
Security	Permissioned blockchain, advanced cryptography	Blockchain immutability, private-public key encryption
Transaction Costs	Minimal or zero for users and businesses	Zero for individuals; nominal fees for businesses

4.5. Results

4.5.1. Big-O Notation

Let's review the efficiency, scalability, and security estimates for the four CBDS: Sand Dollar, DCash, eNaira, and Digital Yuan (e-CNY).

A mathematical idea known as "Big-O Notation" describes how an algorithm's or system's computational complexity increases with the size of its input. Big-O helps measure how systems scale with more data or complexity by concentrating on the key element that affects performance. In order to assess the effectiveness and scalability of blockchain-based systems that use Proof of Stake (PoS), we compare their computational complexity with that of centralized ledger systems.

The logarithmic complexity of blockchain systems that use the PoS paradigm is O(log(n)), where N is the number of nodes in the network. Because of its logarithmic growth, the network's computing load increases very little as it grows. Not every node takes part in every transaction in PoS systems. Rather, a group of nodes is selected to validate transactions, and as the network gets bigger, the size of this selection gradually rises. For instance, the computational effort increases just slightly when the number of nodes is doubled from 100 to 200. Because blockchain systems' processing demands do not increase dramatically even with dramatic network size expansion, their logarithmic growth guarantees that they are extremely scalable and appropriate for big, decentralized networks.

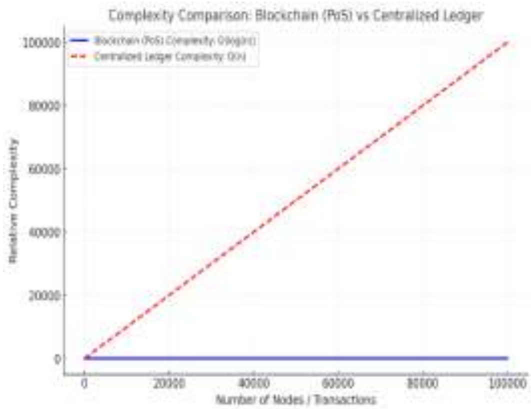

Figure 5: Complexity Comparison Blockchain Vs Centralized Ledger.

On the other hand, O(n), where N is the number of transactions being handled, is the linear complexity of centralized ledger systems. Each transaction increases the total processing burden in these systems. The computing demands double the number of transactions twice, for example, from 50,000 to 100,000. Because centralized systems usually handle transactions in batches or sequentially, the computing load increases proportionately to the volume of transactions. Because of this linear tendency, centralized systems may experience bottlenecks when transaction demand is high unless major modifications are made, like using parallel processing or more potent hardware.

The revised graph makes it evident how these two systems differ in terms of scalability. The graph's blue line, which remains almost flat, illustrates how well blockchain systems manage growing node counts due to their logarithmic complexity. The red dashed line, on the other hand, represents centralized ledger systems, which exhibit a linear growth pattern and a dramatic rise in complexity as transaction volumes increase. Blockchain systems' considerable scalability advantage arises from their logarithmic complexity, which makes them perfect for managing vast and dispersed networks.

PoS-based systems guarantee effective operations even as the network expands by lowering processing needs by only using a portion of nodes for transaction validation. On the other hand, because of their linear complexity, centralized systems have trouble scaling. Although they work well for smaller-scale organizations, as transaction volumes rise, they perform worse, requiring large infrastructure investments to meet demand.

The recalculated graph concludes by confirming that blockchain systems are more scalable and efficient than centralized systems due to their logarithmic growth. The slight rise in the blue line illustrates how blockchain can manage bigger networks without requiring appreciably more processing power. In the meantime, the red line's sharp ascent shows how centralized systems encounter more difficulties as transaction volumes increase. Large-scale decentralized networks can benefit greatly from blockchain's scalability, particularly in PoS models, whereas centralized systems are still constrained by their linear development and ongoing infrastructure improvements.

4.5.2. The Monte Carlo simulation

The purpose of the Monte Carlo simulation was to compare the computational complexity of two systems: centralized ledger systems and blockchain-based systems that use Proof of Stake (PoS). The objective of this simulation was to demonstrate how Big-O Notation, specifically the logarithmic growth of blockchain systems and the linear growth of centralized systems, impacts scalability by modeling how each system's computational complexity changes as their respective input sizes (number of nodes for blockchain and number of transactions for centralized systems) increase.

For centralized transactions (50,000 to 1,000,000) with complexity O(n) and blockchain nodes (100 to 10,000) with complexity O(log(n)), the simulation produced random results. The complexity of the centralized system was determined to be O(n) based on transactions, while the complexity of the blockchain system was determined to be O(log(n)) based on node values. The computational difficulty was calculated for each of the 1,000 simulation runs that were performed on both systems using random node and transaction values.

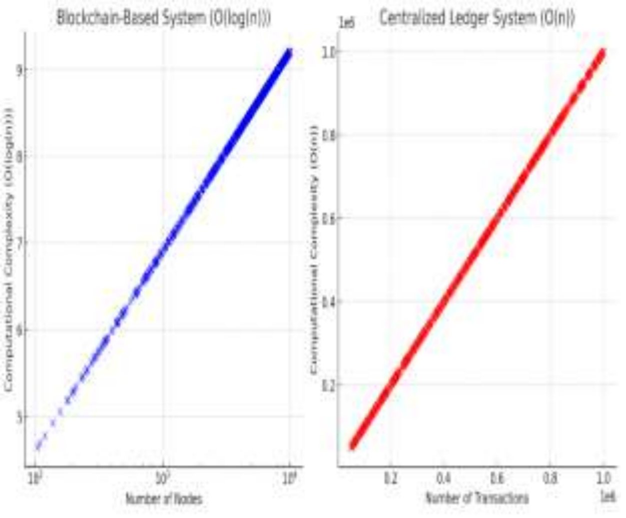

Figure 6: The Outcome of the Monte Carlo Simulation.

The relationship between the number of nodes and the computational complexity of the blockchain-based system is clearly shown in the results by the blue scatter plot. As anticipated, the complexity develops logarithmically, which means that the computing effort needed for transaction validation rises with the number of nodes, albeit considerably more slowly. For example, there is very little increase in computing complexity as the number of nodes rises from 100 to 1,000 or from 1,000 to 10,000. This is because of the way Proof of Stake (PoS) is structured, which lowers the network's overall load by only choosing a portion of nodes for transaction validation.

Even when the number of nodes in a blockchain system increases, it still scales effectively. Because of this, blockchain technology works especially well in big, dispersed networks where a high number of nodes may be added without noticeably affecting performance.

Conversely, with centralized ledger systems, the red scatter plot shows the linear relationship between the number of transactions and the processing complexity. The computational complexity rises in direct proportion to the number of transactions. For instance, the computing complexity doubles if the number of transactions is twice (for instance, from 50,000 to 100,000). The sequential or batch processing of transactions by centralized systems, where each new transaction increases the overall computing load, is reflected in this linear trend.

As transaction volumes increase, centralized systems encounter difficulties since processing effort rises in direct proportion to transaction volume, potentially creating bottlenecks. Blockchain systems, on the other hand, scale effectively as the number of nodes increases and require no extra computational power due to their O(log(n)) complexity. The report emphasizes that centralized systems may suffer without infrastructure changes since their performance deteriorates with increased transaction volumes, whereas blockchain systems provide superior scalability.

4.5.2. Queuing Theory Analysis

The M/M/1 queuing theory model was used in the experiment to assess the scalability and performance of four digital currency systems: eNaira, DCash, Digital Yuan, and Sand Dollar. Poisson transaction arrival rates, exponential transaction service times, and a single-server configuration are assumed in this model. The purpose of the analysis was to evaluate each system's utilization, queue lengths, and transaction wait times under actual transaction loads.

System requirements served as the basis for the analysis's parameters. In order to reflect its claimed near real-time transaction capabilities, eNaira set its arrival rate (λ\lambdaλ) at 1,500 transactions per second and its service rate (μ\muμ) at 3,000 transactions per second. Given its high throughput and potential for regional scaling, DCash's arrival rate (λ\lambdaλ) was set at 5,000 transactions per second and its service rate (μ\muμ) at 10,000 transactions per second. A service rate (μ\muμ) of 1,000,000 transactions per second and an arrival rate (λ\lambdaλ) of 500,000 transactions per second were used to model the Digital Yuan system's ability to process millions of transactions.

Given its relatively low acceptance and throughput, the Sand Dollar was given an arrival rate (λ) of 1,000 transactions per second and a service rate (μ) of 2,000 transactions per second. According to the results, all systems were operating at 50% capacity with a utilization rate (ρ\rhoρ) of 0.5, which left them with plenty of headroom to handle extra transaction loads. With an average wait time in the queue (Wq) of 0.000333 seconds (333 microseconds) and an average queue length (Lq) of 0.5 transactions, the eNaira system demonstrated effective processing capabilities for its transaction volume.

With an average queue length of 0.5 transactions and a queue wait time of 0.0001 seconds (100 microseconds), DCash showed comparable efficiency. With its enormous transaction capacity, the Digital Yuan demonstrated its ability to perform a large number of transactions with almost no delay by having the shortest queue wait time, which was 0.000001 seconds (1 microsecond). Last but not least, the Sand Dollar demonstrated a moderate processing capacity in relation to its load, with an average queue length of 0.5 transactions and a queue wait time of 0.0005 seconds (500 microseconds).

According to our analysis, all four systems have a high potential for scalability, minimum delays, and efficient operation at their current transaction volumes. From the very immediate processing of the Digital Yuan to the dependable and scalable operation of systems like DCash, eNaira, and the Sand Dollar, the findings show the systems' diverse capabilities. These results highlight how well-suited each system is for the use case for which it is designed, whether it is deployed at the regional or national level.

Our analysis indicates that with their current transaction volumes, all four systems have a high potential for scalability, minimal delays, and effective functioning. The results demonstrate the systems' wide range of capabilities, from the instantaneous processing of the Digital Yuan to the stable and expandable functioning of systems like DCash, eNaira, and the Sand Dollar. Whether each system is implemented at the regional or national level, these findings demonstrate how well-suited each system is for the use case for which it was created.

The eNaira is exceptionally secure, using cutting-edge cryptography and a permissioned blockchain to provide a strong defense. Although it can process approximately 3,000 transactions per second, its scalability and efficiency are concerns, and its high percentage of inactive wallets suggests that it has struggled to gain traction. The Sand Dollar, on the other hand, has a 30% acceptance rate in The Bahamas and facilitates real-time transactions, making it ideal for small-scale, localized use. Although it works well within its parameters, the Sand Dollar's promise in larger or more complicated economies is constrained by its lack of scalability.

Table 3: Comparative Trade-Off Analysis Table.

Metric	eNaira	DCash	Digital Yuan	Sand Dollar
Security	High: Permissioned blockchain, advanced cryptography, AML/CFT compliance. Privacy concerns due to centralized control.	Medium: Blockchain-based, strong encryption, but a recent system crash raises reliability concerns.	High: Permissioned blockchain, advanced cryptography, robust government control.	Medium: Blockchain immutability and encryption, but centralized with privacy concerns.
Efficiency	Medium: ~3,000 TPS, near real-time transactions, subsidized costs for users.	High: ~10,000 TPS, under 5 seconds per transaction, nominal fees for businesses.	Very High: Millions of TPS, near real-time, minimal or no transaction fees.	Medium: Designed for large volumes and real-time processing, but the exact TPS is not disclosed.

Scalability	Medium: Nationwide integration with banks, moderate adoption (1M+ users, ₦4B volume).	Medium: Regional scaling across 8 countries (ECCU), gradual adoption (~10% of 600K population).	Very High: Nationwide scaling in China, integrated with Alipay/WeChat Pay, over 260M wallets, ¥7T transaction volume.	Low: Island-specific, ~30% adoption in The Bahamas, suitable for a small, dispersed population.

In conclusion, the Sand Dollar works well for smaller populations, but the Digital Yuan is the most suitable method for use across the country. The intermediate ground is occupied by DCash and eNaira, each of which has unique advantages and disadvantages that make them appropriate in particular situations but less flexible overall.

Table 4: Weighted Scoring Table.

Metric	Weight	eNaira (Score)	DCash (Score)	Digital Yuan (Score)	Sand Dollar (Score)
Security	40%	8	6	9	7
Efficiency	30%	6	8	10	6
Scalability	30%	5	6	10	4
Weighted Total	-	6.7	6.9	9.1	5.9

The performance of four CBDS—eNaira, DCash, Digital Yuan, and Sand Dollar—is assessed and contrasted in the table based on three important criteria: security, efficiency, and scalability. Based on their relative relevance, each metric is given a weight; security is the critically significant at 40%, followed by efficiency and scalability at 30% each. Each CBDC's performance in each parameter is represented by a score on a scale of 1 to 10. This is how the weighted total is determined:

Weighted Total=(Security Score×0.4)+(Efficiency Score×0.3)+(Scalability Score×0.3)

4.5. Analysis Of Metrics

1. **Security (40%):**

Digital Yuan (9): Provides centralized control, permissioned blockchain, and strong encryption for safe activities.

eNaira (8): Advanced cryptography and compliance mechanisms provide high-level security, but the centralized structure presents privacy problems.

Sand Dollar (7): Sufficient security, but privacy issues and centralized government control are issues.

DCash (6): Despite being blockchain-based, a recent system meltdown raises doubts about its dependability.

2. **Efficiency (30%):**

Digital Yuan (10): Provides millions of transactions per second, almost instantaneous transactions, and low prices.

DCash (8): Effective processing at the regional level and high throughput with 10,000 TPS.

eNaira (6): Near real-time transactions with a moderate throughput (3,000 TPS); however, adoption issues reduce overall effectiveness.

Sand Dollar (6): Compared to competitors, throughput data is restricted, but real-time transactions are dependable.

3. **Scalability (30%):**

With its countrywide operations, smooth platform connections, and capacity to manage high transaction volumes, Digital Yuan (10) exhibits remarkable scalability.

DCash (6): Only works for regional applications, but it scales well among the eight ECCU nations.

eNaira (5): Limited adoption and inactive wallets limit its moderate scalability within Nigeria.

Due to its concentration on a tiny, island-based population, Sand Dollar (4) has limited scalability.

Table 5: Weighted Total Scores.

CBDC	Weighted Total Score
Digital Yuan	9.1
DCash	6.9
eNaira	6.7
Sand Dollar	5.9

Table 6: Comparison Of Weighted Total Scores For Blockchain-Based And Centralized Ledger CBDS.

CBDC	Weighted Total Score
Total for Centralized Ledger	15.8
The Average for Centralized Ledger	7.9
Total for Blockchain-Based	12.8
The Average for Blockchain-Based	6.4

5. CONCLUSİON

Central Bank Digital Currencies (CBDS) have the potential to revolutionize payment efficiency, financial inclusion, and monetary systems. Every CBDC system has distinct advantages and disadvantages based on certain use cases.

With its potential to execute millions of transactions per second and its smooth integration with platforms such as Alipay and WeChat Pay, the Digital Yuan stands out for its scalability and efficiency. It is perfect for large-scale economies, with over 260 million wallets and ¥7 trillion in transactions. Its centralized architecture, however, increases privacy and surveillance issues, making strong data protection necessary.

Systems based on blockchain, such as the Sand Dollar and DCash, are excellent in terms of security and regional flexibility. Although DCash processes 10,000 transactions per second across eight ECCU countries, it has reliability and scalability issues. Similarly, although it is only used on a small scale, the Sand Dollar benefits 30% of the Bahamas' population. Although scalability is necessary for wider applications, these solutions show the promise of blockchain technology.

The influence of the eNaira, Africa's first CBDC, is limited by adoption hurdles like poor awareness and merchant integration, despite its robust security and zero transaction costs. A throughput of 3,000 transactions per second and 85% of wallets sitting dormant underscore the necessity of infrastructure investment and user education.

In order to balance scalability, security, and privacy, central banks must match CBDC architecture with the desired use cases. Large economies benefit from centralized systems, while regional requirements are best served by blockchain-based solutions. Privacy concerns might be addressed by hybrid approaches that combine efficiency and transparency. Success depends on adoption tactics, such as financial incentives and public awareness initiatives. CBDS can update financial ecosystems and optimize their societal benefits by customizing structures and encouraging cooperation among stakeholders.

Other noteworthy initiatives, such as those in China, the Bahamas, and the Caribbean, are also proliferating globally. The European Central Bank's Digital Euro, in particular, prioritizes regulatory compliance and user privacy, while India's Digital Rupee aims to integrate millions of people into a digital payments infrastructure. These pilots clearly demonstrate that CBDC architecture is shaped not only by technology but also by socioeconomic objectives. Therefore, in addition to the four systems discussed in this study, it is crucial to examine other global examples from a design and policy perspective.

This study not only offers technical comparisons but also sheds light on the societal impacts of digital currencies. In particular, the evaluations on financial inclusion, data privacy, and economic sovereignty demonstrate that CBDC designs have the power to shape not only economic but also socio-political systems. In this respect, the study appeals not only to technology and economic experts but also to policymakers and social scientists.

Declarations: The manuscript has not been submitted to any other journal or conference.
Study Limitations : There are no limitations that could affect the results of the study.
Acknowledgments: The authors gratefully acknowledge the constructive feedback and valuable guidance provided by the anonymous reviewers and the editorial team, which have substantially improved the quality of this manuscript. We also acknowledge the institutional support and financial assistance provided by the Budapest University of Technology and Economics.
Data Availability Statement : The data used in this study are derived from publicly available literature and reports cited throughout the manuscript. No new datasets were generated or analyzed during this study.

Abbreviations
AML — Anti-Money Laundering
CBDC — Central Bank Digital Currencies
CBN — Central Bank of Nigeria
CFT — Combating the Financing of Terrorism
DLT — Distributed Ledger Technology
ECCB — Eastern Caribbean Central Bank
ECCU — Eastern Caribbean Currency Union
e-CNY — Digital Yuan
NIBSS — Nigeria Inter-Bank Settlement System

PBOC — People's Bank of China
PoS — Proof of Stake
PoW — Proof of Work
RMB — Chinese Yuan
TPS — Transactions per Second
XCD — Eastern Caribbean Dollar

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